ISSN: 3065-7865

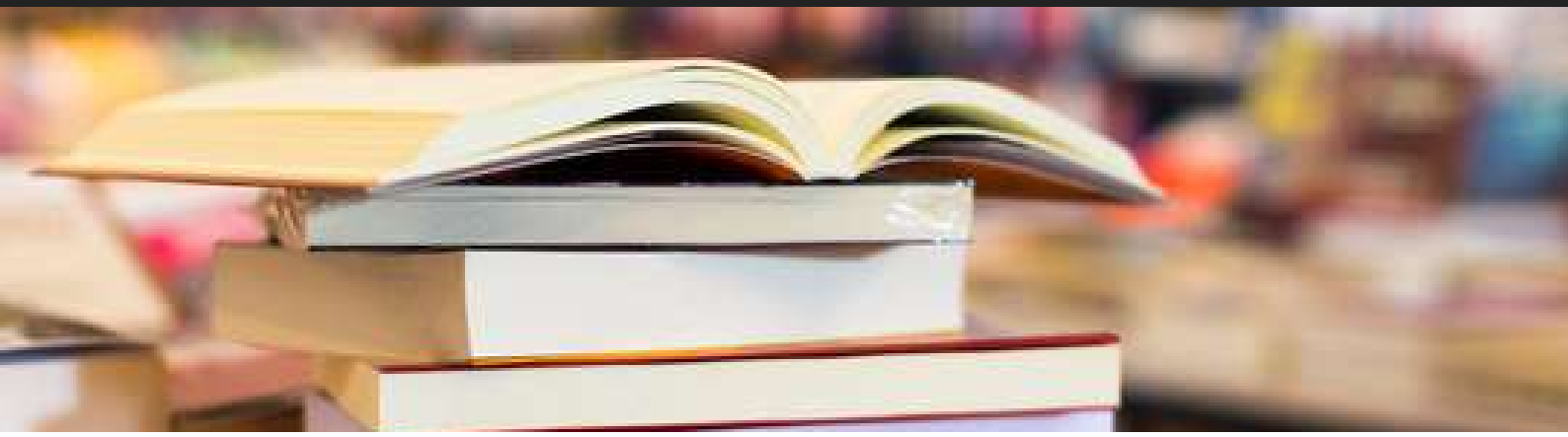
BULLETIN OF NEXUS

SEPTEMBER 2026, VOLUME-3 ISSUE- 9 (II)

Double-blind peer-reviewed /refereed, open access online International journal

Chief Editor

Dr. F. M. Nadaf



ISSN: 3065-7865 SEPTEMBER 2026, VOLUME-3 ISSUE- 9(II)

DOUBLE-BLIND PEER-REVIEWED /REFEREED, OPEN ACCESS ONLINE INTERNATIONAL JOURNAL



BN
RIG LLC

BN
2024
MULTIDISCIPLINARY
INTERNATIONAL RESEARCH JOURNAL

Publisher
Royal International Global LLC

JOURNAL PARTICULARS

Name of Journal	Bulletin of Nexus
Frequency	Monthly (Jan to Dec)
e-ISSN	3065-7865
Publisher	Royal International Global LLC 16192 Coastal Highway, County of Sussex, Lewes, Delaware 19958 USA
Chief Editor	Dr. F. M. Nadaf
Copy right	Royal International Global LLC
Starting Year	October 2024
Subject	Multi-Disciplinary
Review Process	Double Blind Review Process
Language	English
Publication Format	online
Access	Open Access
License	Creative Commons Attribution 4.0 International
Phone No.	(+1) 3023033026
Email	bulnexus@gmail.com
Journal Website	https://bnir.us
Registered office Address	CEO Royal International Global LLC 16192 Coastal Highway, County of Sussex, Lewes, Delaware 19958 United States of America (USA)
Admin. Office Address	CEO Royal International Global LLC 16192 Coastal Highway, County of Sussex, Lewes, Delaware 19958 United States of America (USA)

Bulletin of Nexus

(International Multidisciplinary Research Journal)

ISSN: 3065-7865
Volume-3, Issue-9(II), September 2026
Publication Language – English
Periodicity of Publication- Monthly
Website: https://bnir.us Email: bulnexus@gmail.com

CHIEF EDITOR

Dr. F. M. Nadaf
Professor,
Dept. of Geography
DPM's Shree Mallikarjun College, Canacona-Goa
Email- fmnadaf@shreemallikarjuncollege.ac.in

EDITOR BOARD

Dr. A. G. Amarasinha
Head/ Department of Geography, Faculty of Social Sciences
University of Kelaniya, Dalugama, Sri Lanka
E- Mail - amarageo@kln.ac.lk

Dr. Praveen G. Saptarshi
Dr. Praveen G. Saptarshi
Visiting Faculty
Salisbury University, United States
Email: praveen.saptarshi@gmail.com

Dr. Ranjit Gurav
Ingram School of Engineering,
Texas State University, United States
Email- ranjit.g@txstate.edu

Dr. Lal Mervin Dharmasiri
Senior Professor and Chair
Head of Geography
University of Kelaniya, Sri Lanka
Email- mervin@kln.ac.lk

Dr. Sambhaji. D. Shinde
Professor,
Head Department of Geography,
Shivaji University, Kolhapur
Maharashtra, India
Email- sds_geo@unishivaji.ac.in

Dr. Vinayak P. Dhulap
Dr. Vinayak P. Dhulap
Director, School of Earth Sciences,&
Head, Department of Environmental Science,
Punyashlok Ahilyadevi Holkar Solapur University, Solapur - 413 255 (Maharashtra) India
Email: vpdhulap@sus.ac.in

Dr. Devidas S. Gejage
I/C Principal
Sameer Gandhi Kala Mahavidyalaya, Malshiras.
Dist. Solapur, State. Maharashtra, India,
Pin. 413107
Email- sgacprincipal@sus.ac.in

PUBLISHER
Royal International Global LLC
16192 Coastal Highways, County of Sussex, Lewes, Delaware 19958
United States of America (USA)
Email: ceo@royaligllc.us Website: https://royaligllc.us Mob: Mob: (+1) 3023033026

Index

Sr. No.	Paper Title	Page No.
1	AI and Digital Economy: Pathway to Sustainable Development and Viksit Bharat 2047 **Dr. Vijaykumar A. Patil**	1-9
2	The Relevance of Shivaji-Era Technology in the Modern Period **Dr. Uma Uttam Patil**	10-14
3	Indian diaspora and the Voice of Bharati Mukherjee **Dr. D. R. Khanderao**	15-18
4	Comparative Biochemical Profiling of Mucus from Five Selected Marine Fish Groups **Supriya Pramod Sawant, Vinda Manjramkar**	19-22
5	A Study of Web 1.0 To Web 4.0: Evolution, Technologies, Applications and Future Directions **Dr. Kamlesh Ravikumar Patil**	23-27
6	The AI Lexicon: Exploring Neologism and Contemporary Word Formation Processes **Dr. Salama Khwaja Attar, Dr. Khaja Dada Atar, Nida Adam Inchanalkar**	28-32
7	UNDP–SDG Framework - Impact of Smart Technologies on Tamil Nadu Warehousing Corporation **Dr. V. Pattammal**	33-38
8	Gender Disparity in India: Determinants, Implications and Remedial Measures **Dr. Yuvraj Pandharinath Jadhav**	39-43
9	Comparative Evaluation of Universal 16S rDNA TaqMan and SYBR Green Real-Time PCR for Bacterial Load Determination in Bacterial Meningitis **Bhagchandani S. P., Motwani D. R.**	44-47
10	AI and Responsible Innovation: Technology, Society and Governance in the Technorapid Age for Viksit Bharat 2047. **Gupta Dinesh Kumar NP., Kiran Save**	48-52
11	First-Principles Calculation of Lattice Energy and Structural Properties of $CuInX_2$ (X = S, Se, Te) Semiconductors using Quantum ESPRESSO **Dr. Ajay Kumar Sharma**	53-61
12	The Dual-Edged Sword: The Integrated Influence of Mindfulness and Digital Detention on Mental Health and Procrastination in Generation Z **Jagdish Appasaheb Sardesai, Dr. Amol Appaso Kamble**	62-69
13	Geographical Analysis of Agricultural Development and Regional Disparities in Maharashtra **Dr. Santosh P. Mane**	70-73
14	The Confluence of AI and Eco-Innovation: Shaping the Future of Multidisciplinary Research **Dr. Syed Saleha Javed Abbas**	74-79
15	A Study of Financial Instruments for the Development of Primary Education in Kolhapur District: Integrating AI and Smart Technologies for Sustainable Development and Viksit Bharat 2047 **Ravi Shivaji Chavan, Dr. M. K. Kamble**	80-85
16	Nutritional Value and Health Benefits of Lotus (Nelumbo nucifera): A Short Review **Pawade R. S.**	86-89
17	Corporate Governance and ESG Compliance in India: A Critical Analysis of Emerging Business Law **Nikhil Kashinath Naik**	90-94
18	AI-Driven Smart Materials for Sustainable Energy Applications: Advancing Smart Technologies for Viksit Bharat 2047 **Aaditi Prakash Patil**	95-100

19	Fintech Adoption in India and Its Role in Banking Sector Development: Strategic Challenges and Future **Prashant Prakash Deshmukh**	**101-105**
20	Two-Wheeler Mechanic as a Small Business: A Socio-Economic Perspective **Sujata Sakharam Koli, Dr. M. K. Kamble**	**106-110**
21	Application of Artificial Intelligence in Mathematics Teaching and Learning: Opportunities, Challenges and Future Prospects **Shri Uttam Balaso Pawar**	**111-114**
22	Sports Ethics and Values in the Indian Knowledge Tradition in Relation to Sports Education **Dr. Chand Khan Safdar Khan**	**115-117**
23	Post-Human Canvas: Literature As a Moral Compass for AI Integration and National Growth **Dr. Geetika Patni**	**118-122**
24	Jyoti Lanjaware's Mother: A Depiction of Dalit Women's Ethos **Dr. Tenkale Mahadev Nagnath**	**123-125**
25	AI-Driven Precision Agriculture and Crop Resilience: Integrating Artificial Intelligence, IoT and Remote Sensing for Climate-Resilient Indian Agriculture: A Vision for Viksit Bharat 2047 **Twinkal Prakash Sawant**	**126-133**
26	Role Of Fintech in Indian Banking Industry **Aishwarya Jaysingrao Thorat patil**	**134-138**
27	English Language and Artificial Intelligence: Future Prospects for Viksit Bharat 2047 **Harishchandra Sugriv Shirsat**	**139-141**
28	Green Chemistry Approaches in Pharmaceutical Synthesis: Sustainable Methods, Challenges and Future Perspectives **Sayali Sahadev Sakhare**	**142-145**
29	Artificial Intelligence-Driven Advances in Analytical Chemistry: Methods, Applications, and Future Perspectives **Dr. Achut R. Shinde**	**146-152**
30	Developments in the Field of Photography and the Integration of Artificial Intelligence and Smart Technologies in a Developed India **Dr. Mangesh Krishnarao Raut**	**153-158**
31	Public Libraries and Reading Culture in The Vision of Viksit Bharat @2047 **Rajesh Shankar Shelke**	**159-163**
32	AI-Assisted Integration of Midgut Digestive Enzymes and Gut Microbiota in Samia ricini: A Predictive Framework for Sustainable Eri-Silk Production **Pradnya Prakash Kamble**	**164-172**
33	Renewable Energy Innovation: Emerging Technologies, Challenges, Opportunities and Its Role in Sustainable Development **Dr. Prasad Laxman Pagdhare**	**173-180**
34	Transforming Library Services through Smart Technologies **Dr. Sainath Shivaji Lokhande**	**181-186**
35	Sustainable Chemical Techniques for Clean energies and Vikasit Bharat 2047 **Tabbu Salim Kavathekar**	**187-189**
36	Artificial Intelligence in Sustainable Chemistry: Applications, Challenges and Future Perspectives towards Viksit Bharat @2047 **Diksha krushnat Kamble**	**190-194**
37	A Study of Investment Preferences of Working Women in India **Rahul Prakash Udasi**	**195-198**
38	AI-Driven Green Chemistry for Sustainable Development: A Comprehensive Review Towards Viksit Bharat @2047	**199-205**

	Sourabh Mahadev Wagare	
39	Role of E-Commerce in Enhancing the Performance and Market Reach of Small Businesses **Atish P. Waghchaure**	**206-210**
40	Impact of Digital Business on Global Market: A Study **Dr. Dhanaji Baburao Ingawale**	**211-215**
41	A Brief Study of Tenets of Russian formalism **Dr. Bharat Arvind Tupere**	**216-219**
42	Assessment of the development of Road infrastructure in Maharashtra **Dr. Shridevi Patil, Nisha Mydeo**	**220-225**
43	The Nalanda-Takshashila Paradigm of Indian Knowledge Systems (IKS): Reimagining Cultural Governance in Contemporary Libraries **Dr. Sanadi Dinesh Annappa**	**226-229**
44	Technology in Agriculture: A Comprehensive Review of Digital Transformation, Precision Farming and Sustainable Agricultural Development **Dr. Sabahat Anjum Qureshi**	**230-235**
45	Building Career Opportunities by Improving Communication Skills in English **Dr. B. S. Savase**	**236-239**
46	Advances in Circular Economy Frameworks for Textile Waste Management and Next-Generation Bio-Based Fibers **Dr. Manju Indrakumar Donode (Kathane)**	**240-242**
47	AI-Driven Development of Smart Chemical Sensors for Rapid Detection of Environmental Pollution **Pushpa Kailas Kondare**	**243-251**
48	Artificial Intelligence for Sustainable & Environmentally Benign Chemical Science **Sangramsinh Shahajirao Bhosale**	**252-256**
49	Social Realism and the Representation of Marginalized Lives: A Comparative Study of Munshi Premchand and Mulk Raj Anand **Sushant Thakur**	**257-262**
50	Potential of Vertical Farming as a Sustainable Livelihood Diversification Strategy for Small and Marginal Farmers in Beed District of Maharashtra **Pardeshi Poonam Dashrath, Dr. Meenal Annachhatre**	**263-266**

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI and Digital Economy: Pathway to Sustainable Development and Viksit Bharat 2047

Dr. Vijaykumar A. Patil
Principal Department of Economics Shripatrao Chougule Arts & Science College, Malwadi-Kotoli. Tal. Panhala, Dist. Kolhapur

Manuscript ID: BN-2026-030901

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 1-9

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909046
DOI link: https://doi.org/10.5281/zenodo.22909046

Abstract

Artificial Intelligence (AI) and the Digital Economy are increasingly shaping India's economic transformation. Their applications in agriculture, manufacturing, services, banking, education, healthcare, governance and entrepreneurship have the potential to improve productivity, reduce transaction costs, expand access to services and strengthen innovation. This study examines the economic role of AI and digitalisation with particular reference to sustainable development and the vision of Viksit Bharat 2047. The study is based on secondary data and follows a descriptive and analytical approach. Official statistics on internet connectivity, digital payments and the IndiaAI Mission are used to provide a quantitative dimension to the analysis. The evidence shows rapid expansion of India's digital ecosystem: internet subscribers reached 1,028.61 million by December 2025, while rural internet subscribers stood at 407.69 million in March 2025. UPI processed 22,716.07 million transactions worth ₹28,92,138.67 crore in June 2026. The IndiaAI Mission, approved with an outlay of ₹10,371.92 crore, has expanded compute capacity beyond its initial 10,000-GPU target. The study concludes that AI and digitalisation can support productivity, financial inclusion, entrepreneurship, sustainable resource use and public-service delivery. However, digital inequality, skill gaps, data privacy, cybersecurity, employment restructuring and environmental costs require policy attention. Inclusive infrastructure, human-capital development, responsible AI and sustainable digital practices are therefore essential for Viksit Bharat 2047.

Keywords: *Artificial Intelligence, Digital Economy, Digital Transformation, Sustainable Development, Financial Inclusion, Employment, Viksit Bharat 2047.*

Introduction

The 21st century is characterised by rapid technological and economic transformation. Artificial Intelligence, big data, cloud computing, automation, digital platforms and mobile connectivity are changing the way production, consumption, finance and public services are organised. The digital economy has reduced geographical barriers and enabled businesses and citizens to interact through increasingly integrated digital platforms.

For India, the significance of AI and digitalisation is particularly high because of the country's large population, expanding digital infrastructure, young workforce and growing entrepreneurial ecosystem. AI can support decision-making, forecasting, automation and innovation, while digital platforms can reduce transaction costs and widen market access. The study therefore considers AI and the Digital Economy not merely as technological developments but as components of a broader process of structural economic transformation.

Need and Significance of the Study

India's transition towards a technology-driven economy creates both opportunities and risks. The expansion of digital connectivity, digital payments and AI infrastructure indicates a rapidly changing economic environment.

Creative Commons *(CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Vijaykumar A. Patil, Principal Department of Econamics Shripatrao Chougule Arts & Science College, Malwadi-Kotoli. Tal. Panhala, Dist. Kolhapur
Email: drvapatil024@gmail.com

How to cite this article:
Patil, V. A. (2026). AI and Digital Economy: Pathway to Sustainable Development and Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 1–9. https://doi.org/10.5281/zenodo.22909046

Quick Response Code:

Website: https://bnir.us

At the same time, access to technology remains unequal across regions and social groups. The study is significant because it links technological change with economic development, employment, inclusion and sustainability.

- Understanding how AI can improve productivity and efficiency.
- Examining the role of digitalisation in financial and economic inclusion.
- Assessing changes in employment and skill requirements.
- Understanding the contribution of digital technologies to sustainable development.
- Evaluating the role of AI and digitalisation in Viksit Bharat 2047.

Objectives of the Study

1. To explain the concepts of Artificial Intelligence and the Digital Economy.
2. To examine their contribution to India's economic development.
3. To analyse their role in agriculture, industry and services.
4. To study employment and skill-related changes.
5. To examine digital financial inclusion and digital payments.
6. To assess their contribution to sustainable development.
7. To identify major technological, social and economic challenges.
8. To examine their role in Viksit Bharat 2047.
9. To suggest policy measures for inclusive and sustainable digital transformation.

Research Methodology

The study is based on secondary information. Government reports, official statistical releases, institutional publications, policy documents and relevant academic literature are considered. The analytical framework is descriptive and interpretative, with selected quantitative indicators used to demonstrate the scale of digital transformation.

Document Analysis and Content Analysis are used to classify information under major themes such as AI, digital economy, productivity, employment, financial inclusion, sustainability and Viksit Bharat 2047. The study does not include a primary field survey; therefore, its conclusions are based on available secondary evidence.

Concept of Artificial Intelligence

Artificial Intelligence refers to computational systems capable of performing tasks associated with human intelligence, including learning, pattern recognition, prediction, language processing, problem-solving and decision support. AI can analyse large datasets at high speed and can therefore support both routine automation and complex decision-making.

In the economic context, AI is relevant to demand forecasting, fraud detection, predictive maintenance, personalised services, agricultural planning, logistics, healthcare, education and public administration.

Concept of the Digital Economy

The Digital Economy refers to economic activities enabled or significantly transformed by digital technologies. It includes digital payments, e-commerce, online banking, digital marketing, cloud services, platform businesses, digital public infrastructure and technology-enabled services.

Its key economic characteristics include speed, scalability, data-driven decision-making, lower transaction costs and wider market access. AI and the Digital Economy are complementary: digital systems generate data, while AI can analyse that data and convert it into predictions, recommendations and automated decisions.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Conceptual Framework

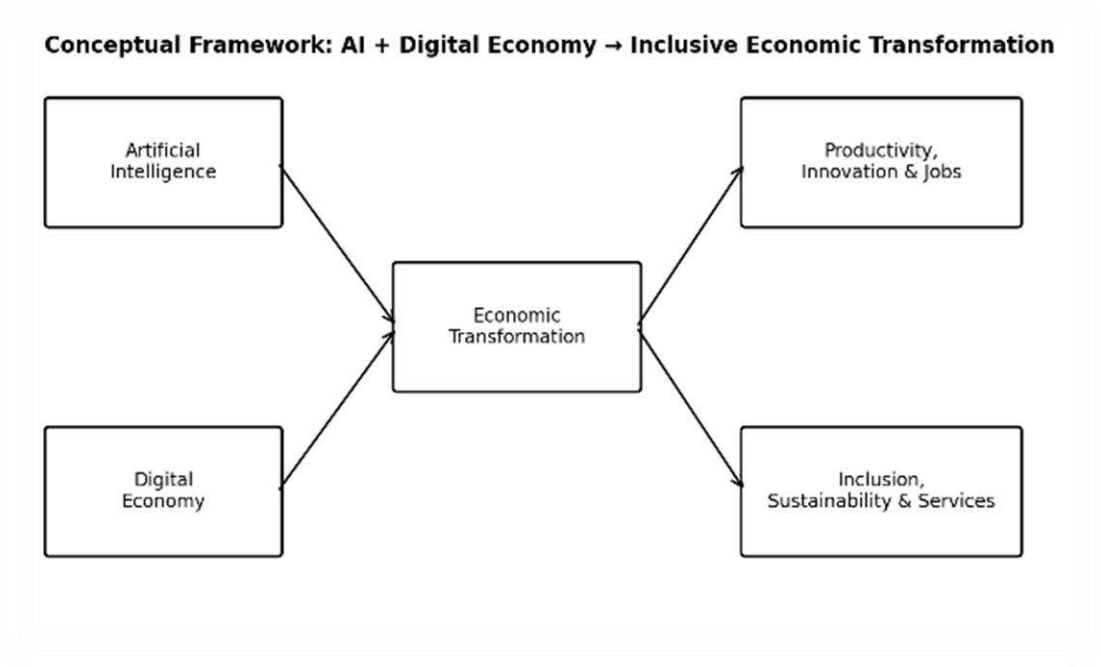


Figure 1. Conceptual framework of AI and Digital Economy-led economic transformation.

Statistical Profile of India's Digital Transformation

Official telecom data show continued expansion of internet connectivity. Total internet subscribers increased from 969.10 million in March 2025 to 1,002.85 million in June 2025, 1,017.81 million in September 2025 and 1,028.61 million in December 2025.

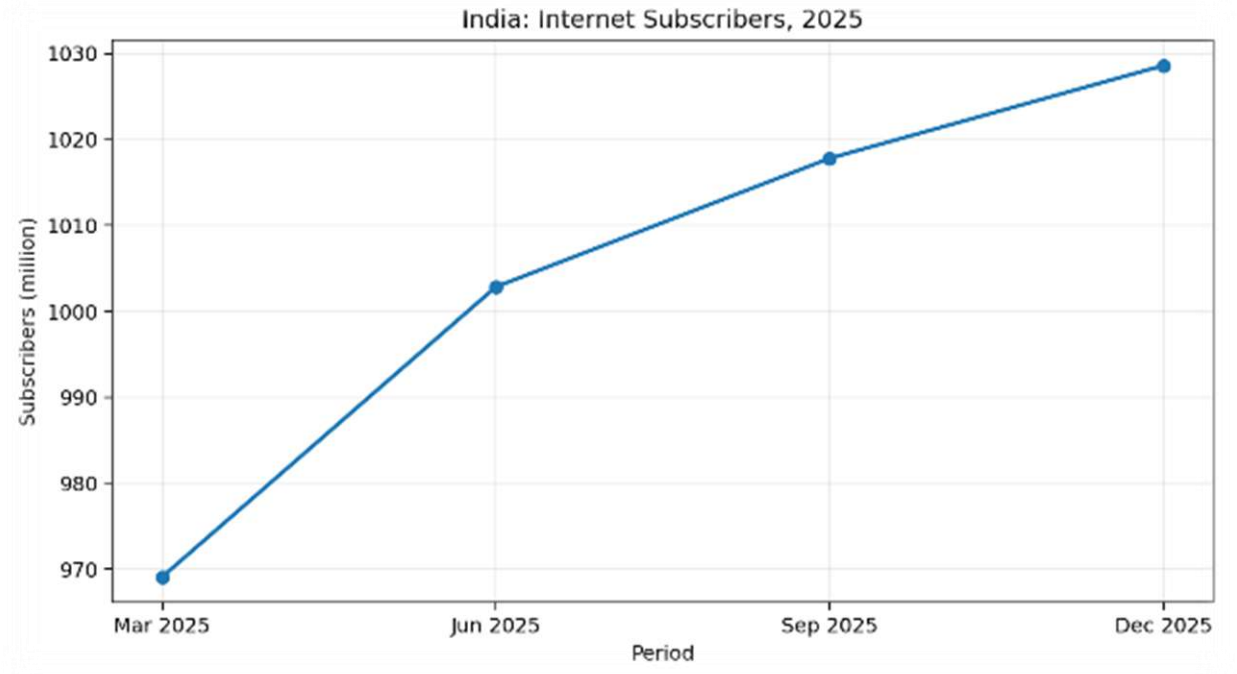


Figure 2. India: Internet subscribers during 2025 (million).

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Indicator	Period	Value	Interpretation
Internet subscribers	Mar 2025	969.10 million	Large national digital base
Internet subscribers	Dec 2025	1,028.61 million	Crossed one billion
Broadband subscribers	Mar 2025	944.12 million	Broadband dominates access
Rural internet subscribers	Mar 2025	407.69 million	Significant rural participation
Urban internet subscribers	Mar 2025	561.42 million	Higher urban concentration

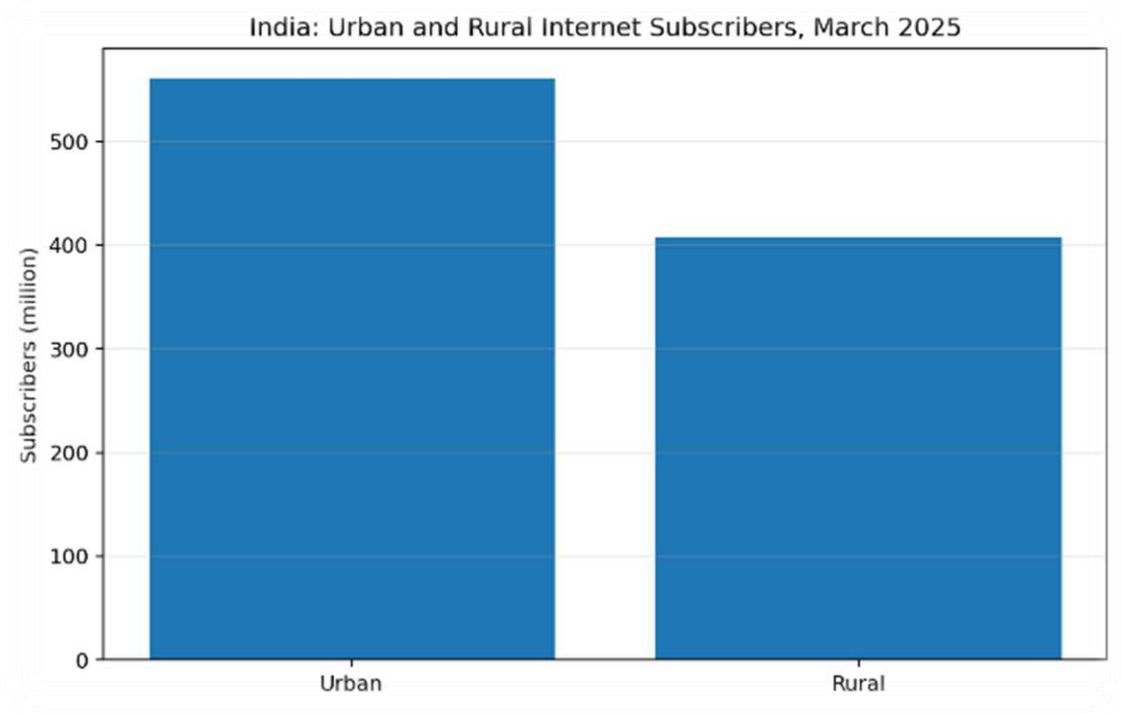


Figure 3. Urban and rural internet subscribers, March 2025 (million).

The March 2025 data also show an important inclusion challenge. Rural internet subscribers were 407.69 million compared with 561.42 million urban subscribers. Internet subscribers per 100 population were 45.03 in rural areas and 110.79 in urban areas, indicating a substantial digital access gap.

Digital Payments and UPI

UPI has become a major component of India's digital payment ecosystem. NPCI statistics show 22,346.80 million UPI transactions in April 2026, 23,201.93 million in May 2026 and 22,716.07 million in June 2026. The corresponding transaction values were ₹29,02,988.05 crore, ₹29,90,424.21 crore and ₹28,92,138.67 crore respectively.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

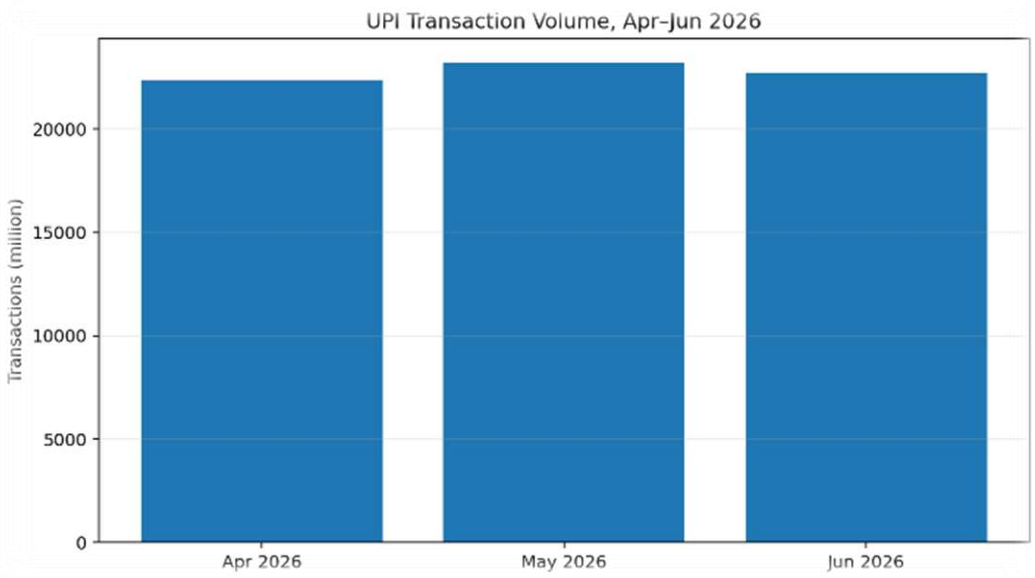


Figure 4. *UPI transaction volume, April–June 2026 (million).*

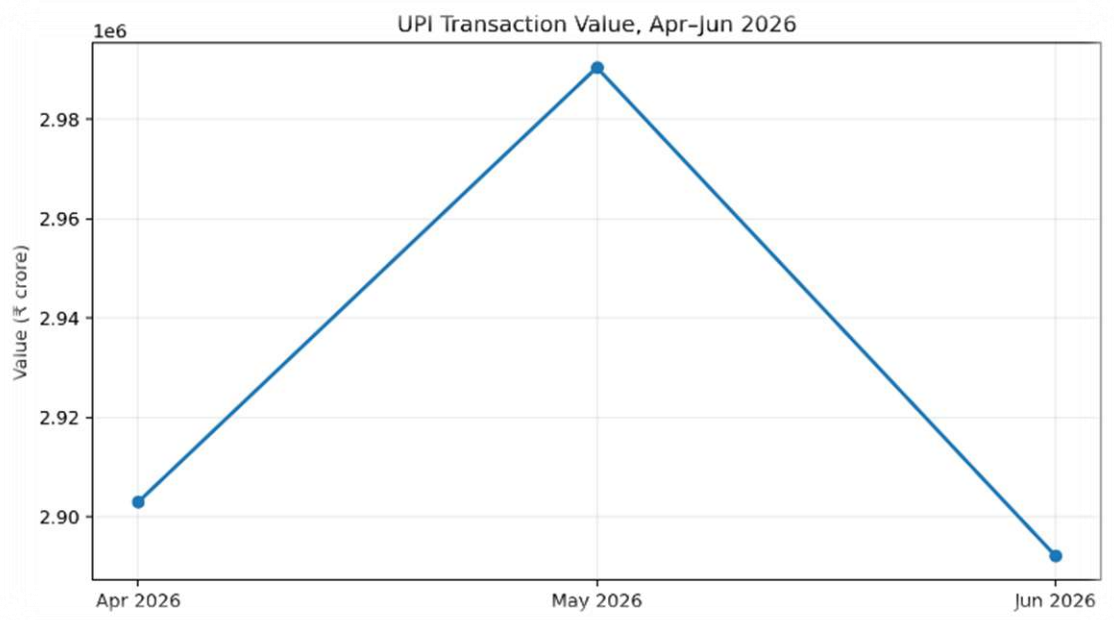


Figure 5. *UPI transaction value, April–June 2026 (₹ crore).*

These figures demonstrate the scale at which digital payments are integrated into everyday economic activity. Digital payments can reduce transaction friction and improve convenience, but financial literacy, fraud prevention, cybersecurity and consumer protection remain essential.

AI and Agriculture

AI can support agriculture through weather forecasting, crop monitoring, soil analysis, precision irrigation, pest detection, yield prediction and market information. Digital platforms can connect farmers with information on prices, government schemes, weather and agricultural services.

The benefits, however, depend on connectivity, affordability, digital literacy, local-language interfaces and the availability of reliable agricultural data. Technology should therefore complement rather than replace farmer knowledge and institutional support.

AI and Industrial Development

AI, automation, robotics and analytics can improve production planning, quality control, predictive maintenance, inventory management and supply-chain efficiency. These technologies can increase productivity and reduce avoidable downtime. MSMEs may face barriers such as technology costs, limited access to specialised talent and lack of internal digital capacity. Policy support,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

shared technology facilities, affordable finance and training can help smaller firms adopt digital tools.

AI and the Services Sector

Banking, insurance, healthcare, education, retail, logistics, tourism and professional services are increasingly using digital platforms and AI-based systems. AI can improve customer support, fraud detection, recommendation systems, data analysis and operational efficiency.

India's expanding digital infrastructure creates opportunities for technology-enabled services, including services delivered across geographic boundaries. The long-term benefit will depend on skills, trust, interoperability and cybersecurity.

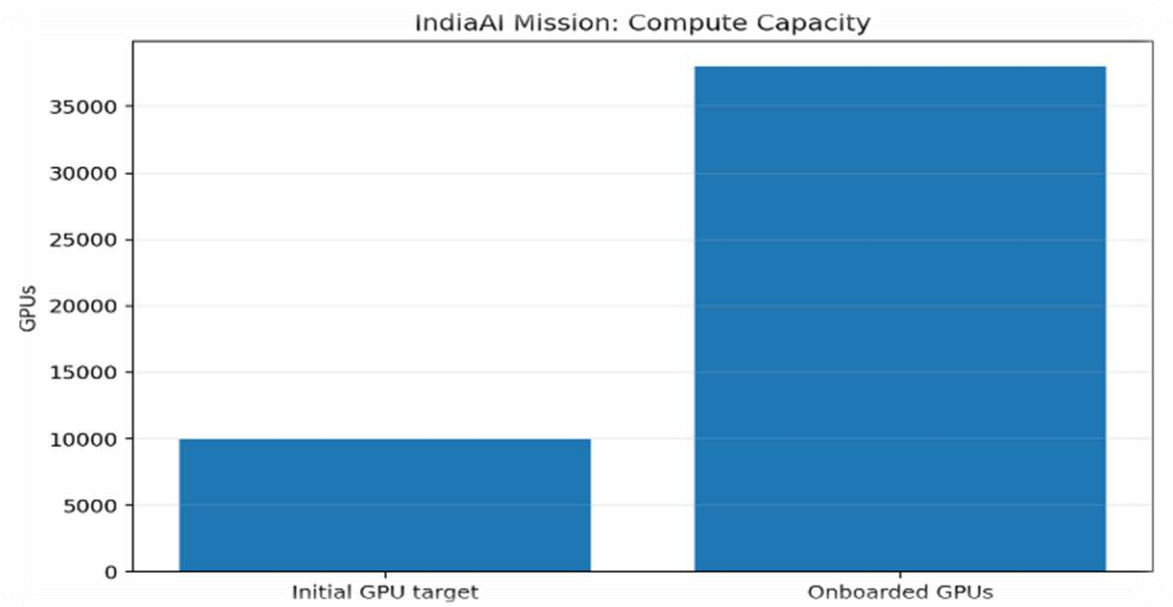
Employment and Skill Development

AI and automation are changing the composition of employment. Routine and repetitive tasks are more susceptible to automation, while demand is growing for digital, analytical, creative and technology-management skills. The appropriate response is therefore to strengthen reskilling and upskilling rather than treat technological change only as a threat to employment.

- Digital literacy and foundational computing skills.
- Data analysis and AI-related competencies.
- Cybersecurity and data protection skills.
- Communication, problem-solving and adaptability.
- Industry-linked vocational and higher-education programmes.
- Continuous lifelong learning and reskilling.

Digital Entrepreneurship and Innovation

Digital platforms have lowered entry barriers for many entrepreneurs. E-commerce, fintech, digital marketing, online education and technology-enabled services provide new business opportunities. AI can further support entrepreneurs through customer analytics, demand forecasting, automation and personalized services.



The India AI Mission was approved with an outlay of ₹10,371.92 crore over five years. Its initial public AI compute target was 10,000 or more GPUs; official 2026 information reports that more than 38,000 GPUs have been onboarded, indicating substantial expansion of national AI computing capacity.

Figure 6. IndiaAI Mission: initial GPU target versus GPUs onboarded.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

15. AI and Sustainable Development

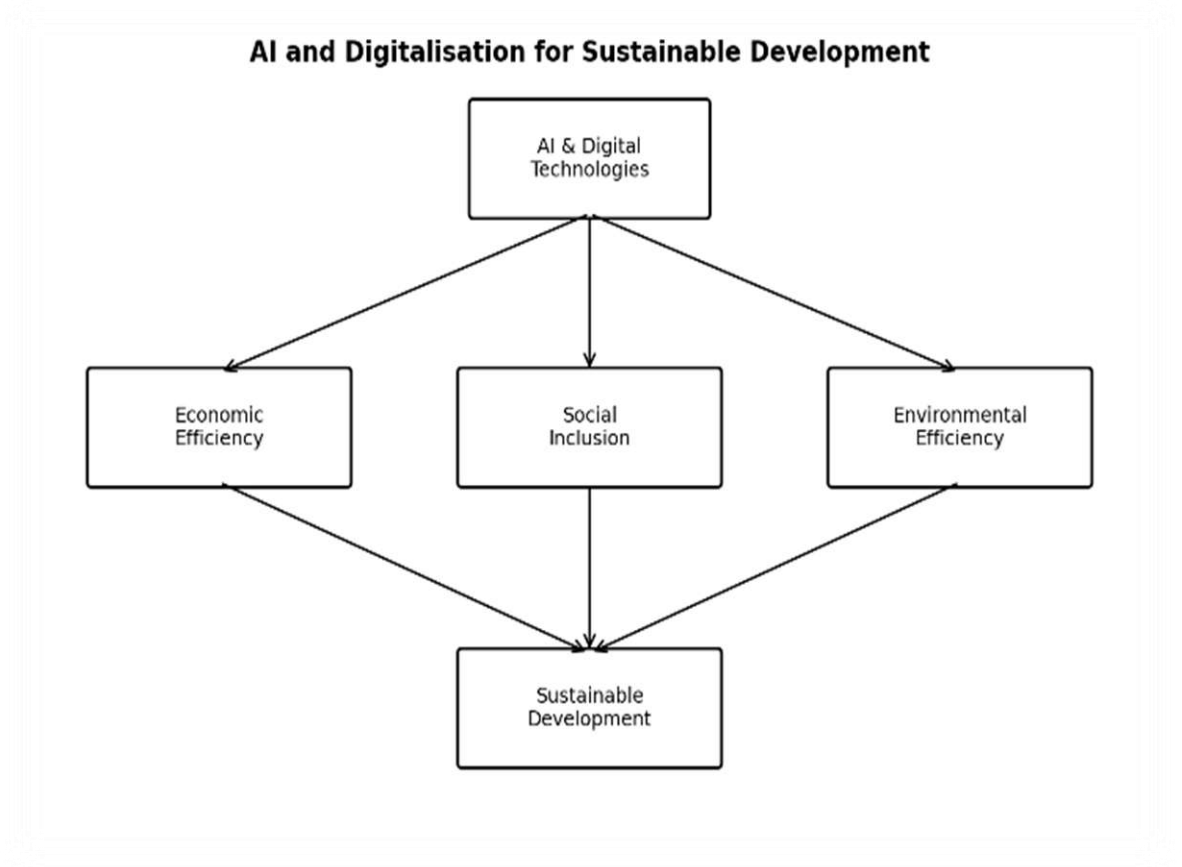


Figure 7. *AI and digitalisation as enablers of sustainable development.*

AI and digital technologies can support sustainable development by improving the efficiency of water, energy, land and transport systems. Applications include precision agriculture, smart energy management, environmental monitoring, intelligent transport, waste management and paperless public services.

At the same time, digital infrastructure creates environmental costs, including energy consumption and electronic waste. Sustainable digitalisation therefore requires energy-efficient infrastructure, responsible hardware use, recycling systems and lifecycle-based environmental assessment.

Major Challenges

1. Digital divide between urban and rural populations.
2. Skill shortages and unequal access to advanced training.
3. Employment restructuring due to automation.
4. Data privacy and cybersecurity risks.
5. Digital fraud and consumer protection challenges.
6. High technology adoption costs for MSMEs.
7. Ethical issues, bias and accountability in AI systems.
8. Concentration of digital platforms and market power.
9. Electronic waste and energy consumption.
10. Need for coordinated regulation and governance.

AI, Digital Economy and Viksit Bharat 2047

Viksit Bharat 2047 requires sustained economic growth together with social inclusion, technological capability, human-capital development and environmental sustainability. AI and digitalisation can contribute through higher productivity, modern agriculture, advanced manufacturing, digital services, financial inclusion, entrepreneurship, innovation and efficient public administration.

The policy challenge is to ensure that digital transformation is not concentrated in a limited number of firms, regions or skilled groups. Broad-based connectivity, affordable access, education, skills, responsible AI and data protection are therefore central to the Viksit Bharat vision.

Major Findings

1. India's digital infrastructure has expanded rapidly, with internet subscriptions exceeding one billion by December 2025.
2. Broadband forms the dominant component of internet access.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

3. Rural digital participation is substantial but remains below the urban level.
4. UPI operates at a very large scale and has become an important component of digital commerce.
5. AI can improve productivity, forecasting, automation and decision support across sectors.
6. Agriculture can benefit from precision and data-driven technologies.
7. Industry can gain through automation, quality control and predictive maintenance.
8. Services are increasingly dependent on digital platforms and data.
9. Employment is undergoing structural change, increasing the importance of reskilling.
10. Digital entrepreneurship creates opportunities for startups and MSMEs.
11. Cybersecurity, privacy and responsible AI are essential for trust.
12. Sustainable digitalisation requires attention to energy use and e-waste.
13. Inclusive digital transformation is necessary for Viksit Bharat 2047.

Policy Recommendations

1. Expand affordable broadband and mobile connectivity, particularly in underserved regions.
2. Strengthen digital literacy and local-language digital services.
3. Scale up AI, data, cybersecurity and advanced technology skill programmes.
4. Create stronger reskilling and upskilling systems linked with industry needs.
5. Support MSMEs through affordable technology, training and shared digital infrastructure.
6. Strengthen data protection, cybersecurity and consumer protection.
7. Promote transparent, accountable and responsible AI.
8. Increase public and private investment in AI research and innovation.
9. Encourage AI applications in agriculture, healthcare, education and public administration.
10. Promote environmentally sustainable data centres, hardware use and e-waste management.
11. Use digital public infrastructure to improve service delivery and inclusion.
12. Integrate digital transformation with the long-term objectives of Viksit Bharat 2047.

Conclusion

Artificial Intelligence and the Digital Economy have the potential to become major drivers of India's economic transformation. The available statistical evidence shows rapid expansion of internet connectivity, digital payments and national AI computing capacity. These developments can improve productivity, market access, financial inclusion, entrepreneurship and public-service delivery.

However, technological progress by itself cannot guarantee inclusive development. Digital inequality, skill gaps, cybersecurity, data privacy, employment restructuring and environmental costs require systematic policy responses. India's digital strategy should therefore combine technological innovation with human-capital development, inclusion, responsible AI and sustainability.

For Viksit Bharat 2047, the central objective should be to ensure that technology creates broad-based economic opportunity. The desired approach can be summarised as: Technology with Inclusion, Innovation with Responsibility, and Growth with Sustainability.

Acknowledgment

The author sincerely expresses gratitude to all those who contributed directly or indirectly to the completion of this research paper. Special thanks are extended to the institutions, government departments, and official agencies whose reports, statistical data, policy documents, and publications provided valuable secondary information for this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. NITI Aayog. (2018). National Strategy for Artificial Intelligence: AI for All. Government of India.
2. NITI Aayog. Responsible AI for All: Principles for Responsible Management of AI in India. Government of India.
3. Ministry of Electronics and Information Technology (MeitY). Digital India Programme. Government of India.
4. Telecom Regulatory Authority of India (TRAI). Indian Telecom Services Performance Indicators, 2024–25 and quarterly reports.
5. National Payments Corporation of India (NPCI). UPI Product Statistics.
6. Government of India. IndiaAI Mission: official releases and programme information.
7. Government of India. Economic Survey and related policy documents.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

8. World Bank. Reports on Digital Development and the Digital Economy.
9. United Nations. Reports on Digital Economy and Sustainable Development.
10. Relevant national and international research articles, journals and academic literature.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

The Relevance of Shivaji-Era Technology in the Modern Period

Dr. Uma Uttam Patil
Head, Department of History, Shripatrao Chougule Arts and Science College, Malwadi, Kotoli

Manuscript ID:
BN-2026-030902

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 10-14

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909489
DOI link:
https://doi.org/10.5281/zenodo.22909489

Abstract

The technological practices of the Shivaji period extended well beyond military weapons and fortification. In seventeenth-century Maharashtra, planners made effective use of mountains, passes, rainfall, the coastline, locally available materials, and accumulated human experience. These conditions shaped systems for defence, water conservation, storage, settlement, movement, and maritime protection. This paper re-examines the principles behind such practices and considers their possible application to present-day challenges including water scarcity, climate-related risks, environmentally sensitive architecture, disaster preparedness, heritage conservation, and sustainable development. The study draws upon historical literature, digital library material, Government of Maharashtra information, fort-related tourism resources, and selected Marathi newspaper reports. The objective is not to reproduce historical methods literally, but to understand and scientifically reinterpret their core principles, particularly local resource efficiency, water security, geographical planning, multi-layered protection, and community involvement.

Keywords: *Shivaji-Era Technology, Chhatrapati Shivaji Maharaj, Maratha Technology, Traditional Technology, Military Technology, Fort Architecture, Water Management, Naval Technology, Engineering Practices, Indigenous Knowledge Systems, Sustainable Technology, Strategic Innovation, Maratha Empire, Heritage Conservation, Modern Technology, Technological Adaptation, Historical Engineering, Sustainable Development, Indian Knowledge System (IKS).*

Introduction

Historical study should not be restricted to political developments, warfare, rulers, and social institutions. The technological knowledge of a period is equally important because it reveals how people interacted with geography, natural resources, architecture, transport, water, and security. During the seventeenth century, the establishment and expansion of Swarajya under Chhatrapati Shivaji Maharaj involved extensive use of practical knowledge suited to the conditions of Maharashtra. Although these practices did not rely on modern machines or electrical systems, they were based on careful observation, experience, knowledge of the landscape, and economical use of available resources. Fort systems were particularly important to the consolidation of Swarajya. The Sahyadri mountains, steep cliffs, valleys, plateaus, and passes influenced where forts were located and how they were designed. Forts such as Raigad, Rajgad, Pratapgad, Panhala, Shivneri, Sindhudurg, and Vijaydurg were planned not merely as defensive structures, but as functioning settlements requiring water, food, accommodation, communication, and sustained security. Their study consequently provides insight into the practical engineering and management knowledge of the period. Technology in this context can be understood as applied knowledge connecting administration, defence, geography, architecture, and everyday requirements. The use of natural barriers, mountain routes, coastal locations, and locally available materials demonstrates an integrated approach to planning.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Uma Uttam Patil, Head, Department of History, Shripatrao Chougule Arts and Science College, Malwadi, Kotoli
Email: uma.patil124@gmail.com

How to cite this article:
Patil, U. U. (2026). The Relevance of Shivaji-Era Technology in the Modern Period. Bulletin of Nexus Journal, 3(9(II)), 10–14. https://doi.org/10.5281/zenodo.22909489

Quick Response Code:

Website: https://bnir.us

At present, increasing water stress, climate change, uncontrolled development, disaster risks, and pressure on heritage sites make it useful to reconsider such historical principles through contemporary scientific and engineering perspectives.

Rationale of the Study

Small and locally adapted interventions can be highly effective when they are designed according to rainfall patterns, terrain, and available materials. The water systems, defensive arrangements, and construction practices associated with Shivaji-era forts therefore merit systematic examination. Modern scientific progress has not eliminated problems such as water scarcity, environmental deterioration, climate variability, disasters, unplanned urban growth, increasing energy demand, and the difficult task of preserving historical sites.

Solutions to these problems need not depend entirely on newly developed technologies. Traditional knowledge can be studied, tested, and adapted where its underlying principles remain appropriate. The importance of Shivaji-era technology lies precisely in this possibility: historical experience can provide ideas that are reassessed using modern scientific methods rather than being accepted or rejected without analysis.

Objectives

1. To broaden the understanding of technology during the Shivaji period.
2. To examine the relationship between fort architecture, defence, and geographical planning.
3. To study historical methods of storing and conserving water.
4. To analyse the use of locally available construction materials and climate-responsive design.
5. To evaluate the relevance of selected historical technological principles in contemporary conditions.
6. To suggest approaches for heritage conservation and sustainable development.

Hypotheses

1. Principles underlying water-management systems of Shivaji-era forts may inform contemporary rainwater-harvesting practices.
2. The integration of natural terrain into fort planning may offer useful lessons for resilient infrastructure and hazard-sensitive planning.
3. Combining traditional local knowledge with modern engineering can contribute to context-specific and sustainable solutions.

Methodology

The paper follows a historical, descriptive, and analytical approach. Information has been drawn from historical books and writings, official government websites, tourism-related material concerning forts, digital library resources, and selected newspaper reports. The available material has been interpreted with particular attention to technological practices and their possible contemporary applications.

Major Areas of Shivaji-Era Technology

1 Fort Architecture and Defensive Planning

The choice of location was fundamental to fort construction. A suitable site was evaluated not simply for elevation, but also for cliffs, valleys, gradients, approaches, visibility, and the possibility of monitoring movement across the surrounding landscape. Forts combined natural advantages with constructed elements such as defensive walls, bastions, gateways, restricted passages, and winding access routes.

Such arrangements created multiple layers of protection. Narrow and indirect approaches could limit the movement of large attacking forces, while elevated positions provided opportunities for observation. Defence was consequently distributed across the terrain and the built environment rather than depending on a single barrier.

This approach has a modern parallel in resilient planning. The location of emergency facilities, critical infrastructure, shelters, and disaster-response centres can be improved through detailed assessment of terrain, accessibility, evacuation options, alternative routes, and areas of relative safety.

2 Water Management

Reliable water supply was essential for the survival and security of people living within hill forts. During conflict or prolonged siege, dependence on external water sources could create a major vulnerability. Forts therefore incorporated different forms of water storage and collection, including tanks, ponds, wells, springs, rainwater structures, and rock-cut cisterns.

Monsoon rainfall could be captured and retained for use over a longer period. Water planning also had to consider the requirements of residents, soldiers, and animals. The water arrangements associated with forts such as Raigad demonstrate the importance of integrating water security into the planning of a fortified settlement.

The significance of these practices today lies in the principle of local water security. Their study can contribute ideas for rainwater harvesting, small-scale storage, groundwater recharge,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

watershed protection, and water management in hilly and rural areas.

3 Maritime Defence

The extensive coastline of Maharashtra made maritime security an important component of the period's technological and strategic planning. Sea forts such as Sindhudurg were positioned and constructed with attention to their offshore setting, tides, waves, access, defensive strength, and control of maritime movement.

These structures served purposes associated with coastal defence, naval activity, trade routes, and protection of coastal settlements. Their study is relevant not only to military history but also to maritime heritage and coastal-zone management. Historical coastal structures may provide useful comparative evidence for understanding how construction responded to environmental conditions, particularly when contemporary coastal areas face erosion, cyclones, sea-level rise, and other climate-related pressures.

4 Local Resources and Architecture

Construction practices of the period made considerable use of resources available in the surrounding environment. Stone, earth, and other locally accessible materials could reduce the need for long-distance transportation and were often appropriate to the local terrain and climate.

The use of materials suited to mountainous environments also demonstrates the close relationship between architecture and landscape. From a modern sustainability perspective, this principle can encourage greater consideration of locally sourced materials, climatic suitability, transportation requirements, and environmental impact when designing buildings and infrastructure.

5 Food and Resource Storage

A fortified settlement required more than walls and defensive structures to withstand a prolonged crisis. Essential commodities such as grain, food, water, fuel, and other supplies had to be stored in advance. Such arrangements supported a degree of self-reliance when external access was disrupted.

The underlying concept remains important in contemporary disaster preparedness. Emergency planning similarly requires reserves of food, drinking water, medicines, fuel, and other necessities, particularly when floods, earthquakes, cyclones, or other emergencies interrupt normal supply chains.

Contemporary Relevance

1 Water Conservation

Historical water systems on forts offer valuable principles for present-day water conservation. These include capturing rainfall before it is lost as runoff, designing storage according to slope and terrain, and strengthening locally available water sources.

In rural and mountainous areas, these ideas may be adapted for rooftop rainwater collection, recharge pits, small reservoirs, groundwater replenishment, and watershed protection. The objective should not be to reproduce old structures exactly. Instead, their functional logic can be studied and modified according to current hydrological data, engineering standards, population requirements, and environmental conditions.

2 Environmentally Responsive Architecture

Contemporary construction consumes substantial quantities of materials and energy and can place considerable pressure on ecosystems. This makes climate- and terrain-sensitive architecture increasingly important.

Shivaji-era structures provide several principles worthy of examination: selecting materials available near the site, adapting construction to terrain, making use of natural barriers, and reducing unnecessary dependence on external resources. These ideas correspond with modern approaches to sustainable, climate-responsive, and context-sensitive architecture. Their contemporary application, however, should be evaluated using current structural, environmental, and safety standards.

3 Disaster Management

The ability of fort settlements to remain functional during periods of conflict required advance preparation. Secure locations, alternative access routes, dependable water supplies, and stored provisions formed part of this preparedness.

Modern disaster-management systems similarly depend on evacuation routes, accessible shelters, emergency supplies, safe infrastructure, hazard assessment, and knowledge of local geography. The historical fort system therefore offers a useful conceptual framework for studying resilience: preparation before a crisis can substantially reduce vulnerability when normal systems are disrupted.

4 Heritage Conservation

Modern digital tools can significantly improve the documentation and protection of historical forts. Geographic Information Systems (GIS), three-dimensional recording, drone-based surveys, digital archives, virtual heritage platforms, and risk maps can help document fort walls, terrain, water structures, damaged areas, and other vulnerable features.

Scientific documentation can support better conservation decisions and long-term

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

monitoring. At the same time, site-management strategies must address visitor movement, safety, disaster risks, environmental pressure, and the involvement of surrounding communities. Heritage conservation should therefore be viewed as an integrated activity combining historical understanding, technology, management, and public participation.

Conclusion

The evidence considered in this study indicates that the technological knowledge associated with the Shivaji period cannot be reduced to weapons or fortification alone. It involved the coordinated use of geography, natural resources, water systems, architecture, food storage, maritime planning, defence, and crisis preparedness. Careful observation of local conditions and efficient use of available resources were central to these practices.

Fort architecture demonstrates how mountains, cliffs, valleys, and natural barriers could be incorporated into defensive planning. Constructed elements such as walls, bastions, gateways, and controlled approaches created successive layers of protection. The underlying planning principles remain relevant to discussions of resilient infrastructure, secure facilities, and disaster preparedness.

Water management was another important expression of practical technological knowledge. Tanks, wells, ponds, springs, cisterns, and rainwater-collection systems helped strengthen water security. In an era of increasing water stress, the principles of local collection, storage, recharge, and terrain-based planning deserve renewed scientific attention.

The preference for locally available materials and adaptation to environmental conditions also connects historical construction practices with current sustainability concerns. Local sourcing can potentially reduce transportation requirements and associated energy use, while climate- and terrain-sensitive design can reduce environmental pressure. Similarly, the systematic storage of essential supplies illustrates the importance of preparedness and resilience.

Sea forts and coastal defensive structures are relevant to maritime heritage and contemporary coastal planning, while digital technologies provide new methods for recording and protecting historical sites. GIS, three-dimensional documentation, digital archives, and risk assessment can transform the study of forts into an interdisciplinary field involving history, geography, architecture, environmental science, and computer science.

The contemporary value of Shivaji-era technology should therefore be understood as a matter of principles rather than direct replication. Local adaptation, prudent resource use, water security, environmental compatibility, preparedness, and long-term planning are ideas that can be reconsidered within modern scientific frameworks. In this way, the technological heritage of the Shivaji period can contribute not only to historical scholarship but also to contemporary discussions of sustainability, disaster resilience, water conservation, and heritage management.

Recommendations

1. Conduct systematic GIS-based surveys of water structures located on Shivaji-era forts.
2. Record the condition, rainfall environment, catchment characteristics, and storage capacity of historical water systems.
3. Evaluate appropriate traditional water-management principles alongside modern engineering standards in rainwater-harvesting projects.
4. Develop three-dimensional digital records and disaster-risk maps for important forts.
5. Introduce heritage-technology field projects for college and university students.
6. Strengthen cooperation among historians, archaeologists, engineers, local communities, government departments, and other relevant experts.
7. Manage tourism in ways that protect heritage, improve visitor safety, control waste, and respect the carrying capacity of individual sites.

Acknowledgement

I would like to express my sincere gratitude to all those who have supported and encouraged me in completing this research paper entitled "The Relevance of Shivaji-Era Technology in the Modern Period."

I am deeply thankful to my institution, Shripatrao Chougule Arts and Science College, Malwadi, Kotoli, for providing the necessary academic environment and resources for carrying out this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Pagdi, Setumadhavrao. Shivcharitra: Ek Abhyas. Pune, 1971.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

2. Pagdi, Setumadhavrao. Chhatrapati Shivaji. Pune, 1974.
3. Pawar, Jaysingrao. Shivaji va Shivkal. Mumbai, 1977.
4. Pawar, Jaysingrao. Shivchatrapati: Ek Magova. Dombivli, 2005.
5. Kulkarni, A. R. Shivkalin Maharashtra. Nagpur, 1984.
6. Mehendale, Gajanan Bhaskar. Shri Raja Shivchatrapati, Vol. 1. Pune, 1996.
7. Pawar, Jaysingrao, ed. Chhatrapati Shivaji Maharaj Smritigranth. Pune, 2011.
8. Maharashtra Tourism Development information portal.
9. UNESCO World Heritage Centre.
10. Press Information Bureau, Government of India.
11. Loksatta. "Water Management and Water Conservation," 13 February 2016.
12. Sakal. "Modern Conservation of Forts," 2 July 2019.
13. Pudhari. "Cleaning and Conservation of Water Tanks," 21 September 2022.
14. Pudhari. "Fort Conservation and Environmental Awareness," 18 October 2022.
15. Loksatta. "Fort Conservation and Public Participation," 9 December 2024.
16. Sakal. "Public Awareness and Social Participation," 21 August 2025.
17. Loksatta. "Protection of Heritage Sites and Risk Management," 16 July 2026.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Indian diaspora and the Voice of Bharati Mukherjee

Dr. D. R. Khanderao
Professor of English, Sitabai Arts, Commerce and Science College, Akola

Manuscript ID:
BN-2026-030903

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 15-18

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909556
DOI link:
https://doi.org/10.5281/zenodo.22909556

Abstract

The term 'diaspora' has multiple layers of meaning in academic circle today. From the original meaning of large-scale migration of people due to religious persecution, it has now come to refer to any movement of people from one land to another. In fact, it is used as a synonym for migration. The Indian diaspora can probably be traced to ancient time when Buddhist monks, Brahmin priests, traders travelled to remote corners of Asia. However today it is customary to refer to the 19th and 20th centuries as the period of Indian diaspora when Indians in large numbers went to other countries in search of job opportunities. This migration is made by personal choice when the term diaspora is used today. The Indian diasporic writers like V.S. Naipaul, Vikram Seth, Salman Rushdie, Bharati Mukherjee, Jhumpa Lahiri, Anita Desai and many others have left their country and settle down in various countries like Britain, America, Canada, Australia, Malaysia, Mauritius, Fiji, Trinidad, Africa and so on. They belong to both young and new generations. Their writing is associated with the sense of displacement, feeling of nostalgia, attachment to the motherlands, and feeling of alienation and rootlessness. Bharati Mukherjee has occupied a distinctive position among the major international figures as the writers of the Indian Diaspora. Mukherjee, the author of eight novels and two collections of short stories depict the clash of cultures and the ensuing dilemmas. Her works focus on the phenomenon of migration, the status of new immigrants, and the feeling of alienation often experienced by expatriates.

Keywords: *diasporic writing, immigrant, V.S. Naipaul, quest for identity, Bharati Mukherjee*

Introduction-

The diasporic writing has been receiving academic and disciplinary recognition throughout the globe. It has emerged into a literary genre. The Indian living in a host country continues to live in a sandwich world refusing to give up his cultural roots, he still hopes for assimilation in his new world. He does not disconnect relationships with his homeland. Often relations between original inhabitants and the diasporic become complicated. Most societies today are multi-cultural societies and the writer living and writing in such society is affected at multiple levels by both the cultures. One of the reasons for this is the migration of people from one nation to another either for the want of better quality of life, education, stable economy or attraction of materialistic life. Most often it is found that people from developing countries are migrating to developed countries. India is not an exception to this phenomenon. Several families every year are found to migrate to developed countries with specific goals and lots of dreams. When an Indian is transported to an alien culture of the West his needs for relatedness, In the past two hundred years Indians have settled in various countries around the world and engaging themselves in creative writing in the countries of their domicile. They either focus or linking with Indian culture and have often impact on migrant's status in host countries. It covers every continent and part of the world.

Creative Commons *(CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
D. R. Khanderao, Professor of English, Sitabai Arts, Commerce and Science College, Akola
Email: dnyansheel@gmail.com

How to cite this article:
Khanderao, D. R. (2026). Indian diaspora and the Voice of Bharati Mukherjee. Bulletin of Nexus Journal, 3(9(II)), 15–18. https://doi.org/10.5281/zenodo.22909556

Quick Response Code:

Website: https://bnir.us

The Indian diasporic writers like V.S. Naipaul, Vikram Seth, Salman Rushdie, Bharati Mukherjee, Jhumpa Lahiri, Anita Desai and many others have left their country and settle down in various countries like Britain, America, Canada, Australia, Malaysia, Mauritius, Fiji, Trinidad, Africa and so on. They belong to both young and new generations. Their writing is associated with the sense of displacement, feeling of nostalgia, attachment to the motherlands, and feeling of alienation and rootlessness.

Indian diaspora and the voice of Bharati Mukherjee-

The Indian diaspora is a representation of India: its people, regions, values, and cultures. It was in the 19th and 20th centuries the large –scale migration from India across the world took place. It is from this migration that the diaspora was formed and this major movement of Indian people who created the communities which comprise the diaspora. The Indian diaspora is currently estimated to a number over twenty-five million composed of Non –Resident Indian and Persons of Indian Origin." The term 'diaspora' has multiple layers of meaning in academic circle today. From the original meaning of large-scale migration of people due to religious persecution, it has now come to refer to any movement of people from one land to another. In fact, it is used as a synonym for migration. The Indian diaspora can probably be traced to ancient time when Buddhist monks, Brahmin priests, traders travelled to remote corners of Asia. However today it is customary to refer to the 19th and 20th centuries as the period of Indian diaspora when Indians in large numbers went to other countries in search of job opportunities. This migration is made by personal choice when the term diaspora is used today. .

Bharati Mukherjee has occupied a distinctive position among the major international figures as the writers of the Indian Diaspora. Mukherjee, the author of eight novels and two collections of short stories depict the clash of cultures and the ensuing dilemmas. Her works focus on the phenomenon of migration, the status of new immigrants, and the feeling of alienation often experienced by expatriates. Her own struggle with identity, first as an exile from India, then an Indian expatriate in Canada and finally as a immigrant in the United States has led to her current state of being an immigrant in a country of immigrants. Bharati Mukherjee's literary achievement comprises eight novels - The Tiger's Daughter (1972), Wife (1975), Jasmine (1989), The Holder of the World (1993), Leave It to Me (1997), Desirable Daughters (2002), The Tree Bride (2004) and Miss New India (2011) - and two collections of short stories - Darkness (1985) and The Middleman and Other stories (1988). She has also non-fictional works-The Sorrow and the Terror : The Haunting Legacy of the Air India Tragedy, with Clark Blaise (1987) , Days and Nights in Calcutta, with Clark Blaise (1986), Political Culture and Leadership in India (1991) and Regionalism in Indian Perspective (1992), and articles – Kautilyas Concept of Diplomacy (1976), An Invisible Woman(1981), Immigrant Writing: Give Us Your Maximalists!(1988), A Four Hundred Year Old Woman (1991), American Dreamer (1997), After the Fatwa and Two Ways to Belong in America (1996).

The Tiger's Daughter (1971), Bharati Mukherjee's first novel, is a very fine manifestation of cultural conflict. The story is about a young girl named Tara an upper-class Bengali Brahmin girl who goes to America for her higher studies. She returns to India after seven years only to find herself a total stranger in the inherited milieu. She realizes that she is now neither Indian nor truly American. She is totally confused and lost. This story parallels Mukherjee's own venture back to India with Clark Blaise in 1973 when she was deeply affected by the chaos and poverty of Indian, and mistreatment of women in the name of tradition. Mukherjee's earlier experiences had a great bearing on her writing and outlook of life. As a young child, she lived with her parents and two sisters in a joint family. The strains of living in a conservative joint family left a deep impact on her impressionable mind. The novel 'Wife' takes up a more complex dimension of the theme of immigrant experience. During her visit to Calcutta, after a ten-year sojourn in Canada, she got the material for this novel as she recalls, "Quite by an accident, I heard the question that shaped my second novel, "what do Bengali girls do between the ages of eighteen and twenty-one." The novel is about the life of a middle class married Bengali woman Dimple who migrates from Calcutta to New York. She thinks about marriage in terms of freedom, fortune and happiness for her and attempts to be the ideal Bengali wife. But in a short time she is frustrated with the American way of life and becomes the victim of such society. Dimple, out of fear and personal instability murders her husband and eventually commits suicide. Thus, she becomes a victim of expatriation.

Darkness, her first collection of short stories, focuses on natives of South Asia who crave after success and stability, but are burdened by their histories and face the difficulties of prejudice and misunderstanding. This collection was a transitional work for Mukherjee, who was reflecting back on her difficult years in Canada and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

cherishing the opportunity to establish herself in the United States. The stories in 'Darkness' tell similar stories of Indian immigrants. In The Middleman, Bharati Mukherjee has plunged herself into the throes of American society. In return, she offers acute insights into the clashes that mark a non-white's entry into that culture. According to Sushma Tandon: "The book is about the experience of eleven people who have deliberately chosen to make America their new home not because of some political turmoil upsetting their lives in their native lands, but because of the lure of a better life has made them drift into their new situation. In Jasmine Bharati Mukherjee develops the idea of the mixing of the East and West through a series of adventures which the heroine undertakes, during her journey from Punjab to California. Her journey through life leads Jasmine many transformations - Jyoti, Jasmine, Jase and Jane Indira Bhatia comments- "Even Jyoti to Jasmine, to Jase and Jane may appear to be real transformation of the personality of the protagonist; from Hasanpur to Jallandhar to Florida, Manhattan, Iowa may appear to be moving from old world values to the brave new world. But the person we see at the end of the novel moving away with Taylor is very much the same person we encounter at the earlier stages in the novel." Bharati Mukherjee's The Holder of the World is presented in a totally new and unique garb - for now there is no longer the usual Indian protagonist, a Jasmine or a middleman seeking a new identity in a new world. It is a story about Hannah Easton, born in Massachusetts who travels to India and falls in love with a few Indian lovers, eventually a King who gives her the most perfect diamond in the world "The Emperor's Tear". It belongs to the last of the great Mughal Kings, Aurangzeb and was stolen from him during a battle against Raja Jadhav Singh, the lover of the seventeenth century Puritan Woman Hannah Easten.

The novel Leave It to Me treats a young woman abandoned as a girl by her parents in India. She struggles to define her identity based on multicultural background. The story looks at the conflict between Eastern and Western world and at mother - daughter relationships. The orphan protagonist, Debbie, learns from Fred that her mother was the hippie follower and father the founder of the ashram presumed Debbie Devi missing or dead. She is saved by nuns and shipped abroad to America and adopted by Di Martino family. The protagonist Debby grows up in a middleclass American Italian family in New York. Growing up, Debby identifies herself by what she is not at the age 23. After disastrous love affair with a Hong Kong ex-movie star she decides to find out what she is. Debby's search for her birth parents takes her to San Fransisco and begins a new life as Devi Debby along with her old identity. Devi sheds her old conventions and begins her hunt for her real parents. Bharati Mukherjee's Desirable Daughters is a story of three sisters, Padma, Parvati and Tara, renowned for their beauty, brains, wealth and privileged position in society. These three sisters are born exactly three years apart from each other and share the same birthday. Their mother names them after goddesses, hoping they will survive and prosper which they all do. The three sisters follow divergent paths when they grow up. Parvati lives in Bombay after her love marriage, while the other two, Padma and Tara, the protagonist, married to a software genius Bish, of the same caste. Her husband Bish represents the traditional psyche of an Indian male. In order to reconstruct her identity, she leaves her husband and shares her house with her lover Andy, a Zen, Hungarian-American retrofitter. In the novel's foreword, Mukherjee quotes a small verse from an ancient Sanskrit poem, which lays out Tara's mission. Desirable Daughters is an account of the life and adventures of the protagonist, Tara Chatterjee. She represents the dilemma of an average migrant. She tries to redefine herself according to new experiences but fails to come to terms with American society.

Bharati Mukherjee's latest novel Miss New India (2011) is a hard-hitting, realistic view of the lives of call-center agents in India. Mukherjee offers a view of modern India in her new novel. Bharati Mukherjee's territory is cultural shock. She has been chronicling the traumas of displacement for more than four decades. Her Miss New India tells the coming-of-age story of Anjali (or Angie) Bose, a young woman attracted by the bright lights of Bangalore. She is rape by the man her parents have chosen as her husband, but the influence of a well-intentioned American teacher, Peter Champion, has already had her dreaming of a brighter future in India's IT capital. Anjali Bose is "Miss New India." Born into a traditional lower-middle-class family and living in a backwater town with an arranged marriage on the horizon, Anjali's prospects don't look great. But her ambition and fluency in language recognized by her teacher, Peter Champion helps her along the way and to Anjali herself, stirring in her a desire to take charge of her own destiny. So she sets off to Bangalore, India's fastest-growing major metropolis, and quickly falls in with an audacious and ambitious crowd of young people, who have learned how to sound American by watching shows like Seinfeld in order to get jobs as call-center service agents, where they are quickly able to out-earn their parents. And it is in this high-tech city where Anjali—suddenly free from the traditional confines of class, caste, gender,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

and more—is able to confront her past and reinvent herself. Bharati Mukherjee depicts the struggles, pains and joys of the immigrants trying to realize their dreams in America who are caught between tradition and modernity. She is perhaps the first to exhibit a full awareness of the global context of contemporary Asian immigration. Mukherjee's life in the United States changed her ideology about herself from expatriate to immigrant. She happily welcomed the American culture and assimilated into it. She described this as a movement away from the aloofness of expatriate to the exuberance of immigration.

Conclusion-

Diasporic writing occupies a place of great significance between countries and cultures. Diasporic writing is the feeling of alienation, love for homeland, double identification with original homeland and adopted country, quest for identity, mythic memory, protest against discrimination, uprooting and rerooting, insider and outsider syndrome, nostalgia etc. Mukherjee's protagonists try to assimilate the alien culture and accept the changed identity, but tremendous experiences between the two ways of life lead to a feeling of frustration. Therefore the protagonists remain caught between the two cultures of the east and the west. Bharati Mukherjee has dealt with Indian life realistically and poignantly in the fiction depicting their dreams and heart-aches with irony. Therefore, it is need to analysis and evaluates the literary works of Bharati Mukherjee since she declares herself an immigrant and writes about immigrants. In her eight novels, two non-fiction books and two collections of short-stories her protagonists are women and they confront a multicultural society in their emigration and evolution. As the Professor of English at the University of California, Bharati Mukherjee is an authentic recorder of the contemporary society.

Acknowledgement

I would like to express my sincere gratitude to all those who have contributed directly or indirectly to the completion of this research paper on "Indian Diaspora and the Voice of Bharati Mukherjee." I am deeply thankful to my teachers, colleagues, and well-wishers for their valuable guidance, encouragement, and support throughout the preparation of this paper.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References-

1. Nagendra Kumar, The Fiction of Bharati Mukherjee: A Culture Perspectives (New Delhi: Atlantic Publishers and Distributers, 2001) 141.
2. Shakuntala Bhavani, "Bharati Mukherjee's The Holder of the World," Indian Women Novelists ed. R.K. Dhawan Vol.3 (Delhi: prestige, 1995) 190.
3. Indira, Bhatt, "Bharati Mukherjee's Jasmine: An Immigrants Attempt at Assimilation," American Literature Today ed. Suman. Bala, (1994) 177.
4. Alison B. Carb, "An Interview with Bharati Mukherjee" The Massachusetts Review Winter (1988) 651.
5. Sushma Tandan, Bharati Mukherjee's Fiction: A Perspectives (New Delhi: Sarup and Sons, 2006) 106.
6. Sybil Stenberg, "Bharati Mukherjee," Publishers Weekly 25 Aug. (1989) 46-47.
7. Runar Vignisson, "Bharati Mukherjee: An Interview," SPAN 34- 35, November-May (1993) 153- 68.
8. C.D. Ramakrishna, "Ramanujan's Credo." In Millennium Perspectives on A. K. Ramanujan. ed. Pande, Sury Nath. (New Delhi: Atlantic Publishers and Distributors Pvt. Ltd, 2001) 11.
9. Ashwini Kumar Vishnu, "Half a Life: A Reading in Sense, Sensibility and Sensuality," V.S. Naipaul: Critical Essays ed. Ray, Mohit Kumar. (New Delhi: Atlantic Publishers and Distributors, 2005) 262.
10. Brij V. Lal, ed. "Introduction," The encyclopedia of the Indian diaspora (Oxford University Press, 2007) 10-15.
11. Alam Fakrul, Bharati Mukherjee (New York: Twyne Publishers, 1996) 147.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Comparative Biochemical Profiling of Mucus from Five Selected Marine Fish Groups

Supriya Pramod Sawant[1],Vinda Manjramkar[2]
[1]Department of Zoology, V.P.M.'s B. N. Bandodkar College of Science (Autonomous), Thane, Maharashtra, India
[2]Department of Zoology, V.P.M.'s B. N. Bandodkar College of Science (Autonomous), Thane, Maharashtra, India

Manuscript ID:
BN-2026-030904

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 19-22

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909651
DOI link:
https://doi.org/10.5281/zenodo.22909651

Abstract
Fish epidermal mucus is a biologically active surface secretion containing diverse biochemical constituents. The present study was undertaken to comparatively assess selected biochemical constituents of mucus from five fish taxa: Scoliodon sp., Anguilliformes, Pampus sp., Sphyraena sp. and Ariidae. Fresh specimens were obtained from Diwale Jetty, Diwale village, CBD Belapur, Navi Mumbai, Maharashtra, India. Epidermal mucus was collected aseptically from visibly recoverable anatomical regions and analyzed for total protein, total carbohydrate and acid value of fat. Protein was estimated by Lowry's method using bovine serum albumin as the standard, while total carbohydrate was estimated by the Phenol–Sulphuric Acid method using glucose as the standard. Protein measurements were performed at 660.0 nm and carbohydrate measurements at 490.0 nm. Sphyraena sp. showed the highest protein concentration (579.011 µg/mL), Ariidae showed the highest carbohydrate concentration (177.609 µg/mL), and Pampus sp. showed the highest acid value of fat (0.1691 mg KOH/g fat). The biochemical profiles differed among the selected taxa, demonstrating parameter-specific variation in marine fish epidermal mucus.

Keywords: *marine fish mucus; biochemical profiling; protein; carbohydrate; acid value; Scoliodon; Pampus; Sphyraena; Ariidae; Anguilliformes*

Introduction

Fish epidermal mucus forms a protective interface between the external body surface and the aquatic environment. It is a complex secretion containing proteins, glycoproteins, carbohydrates, lipids, enzymes and other biochemical constituents. The composition of mucus can vary among fish taxa and may provide useful information about the biochemical characteristics of the species examined. Quantitative estimation of major biochemical constituents provides a basic characterization of marine fish mucus. Protein and carbohydrate are important components of biological secretions, while acid value provides an additional measure associated with the lipid fraction. Comparative assessment of these parameters can therefore demonstrate differences in the biochemical profiles of mucus among fish taxa. The present study compares total protein, total carbohydrate and acid value of fat in mucus obtained from five selected marine fish taxa. The study was designed to provide a focused biochemical characterization based on laboratory-generated quantitative results.

Objectives

1. To estimate total protein content in mucus from five selected marine fish taxa using Lowry's method.
2. To estimate total carbohydrate content using the Phenol–Sulphuric Acid method.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Supriya Pramod Sawant, Department of Zoology, V.P.M.'s B. N. Bandodkar College of Science (Autonomous), Thane, Maharashtra, India
Email: supp.dighe@gmail.com

How to cite this article:
Sawant, S. P., & Manjramkar, V. (2026). Comparative Biochemical Profiling of Mucus from Five Selected Marine Fish Groups. Bulletin of Nexus Journal, 3(9(II)), 19–22. https://doi.org/10.5281/zenodo.22909651

Quick Response Code:

Website: https://bnir.us

3. To determine the acid value of fat in the mucus samples.
4. To compare the measured biochemical characteristics among Scoliodon sp., Anguilliformes, Pampus sp., Sphyraena sp. and Ariidae.

Materials And Methods

1 Study Area and Source of Samples

Fresh marine fish specimens representing Scoliodon sp., Anguilliformes, Pampus sp., Sphyraena sp. and Ariidae were obtained from Diwale Jetty, Diwale village, CBD Belapur, Navi Mumbai, Maharashtra, India. Repeated sampling attempts were initially made at different fish markets and landing centres in Mumbai, including Bandra Fish Market, Crawford Fish Market, Bhau Cha Dhakka and Sassoon Dock. However, the specimens obtained during these preliminary attempts were either insufficiently fresh, frozen, or associated with contamination and were therefore excluded from the final biochemical dataset. Fresh specimens with visibly recoverable epidermal mucus were subsequently successfully obtained from Diwale Jetty and were used for the final biochemical analysis.

2 Collection of Epidermal Mucus

Epidermal mucus was collected aseptically from freshly obtained fish specimens using sterile collection instruments and tubes. Care was taken to avoid contamination with blood, scales and other tissues. The anatomical distribution of visibly recoverable mucus differed among taxa. Mucus was predominantly recovered from the general body surface in Ariidae and Anguilliformes, around the ocular region in Pampus sp., and predominantly around the mouth region in Scoliodon sp. In Sphyraena sp., mucus-associated superficial material available on the body surface was collected. The collected samples were maintained under refrigerated conditions until biochemical analysis.

3 Protein Estimation

Total protein was estimated by Lowry's method using bovine serum albumin (BSA) as the standard. Photometric analysis was performed at 660.0 nm using a UV-1800 Series instrument. Protein standards of 200, 400, 600, 800 and 1000 µg/mL were used for calibration. The laboratory calibration equation was Abs = $9.63727 \times 10^{-4} \times$ concentration, with $R^2 = 0.98502$. The laboratory-generated concentrations were used for comparative interpretation.

Protein standard (µg/mL)	Absorbance
200	0.302
400	0.460
600	0.602
800	0.803
1000	0.872

Table 1. Protein calibration standards.

4 Total Carbohydrate Estimation

Total carbohydrate was estimated by the Phenol–Sulphuric Acid method using glucose as the standard. Photometric analysis was performed at 490.0 nm using a UV-1800 Series instrument. Carbohydrate standards of 20, 40, 60, 80 and 100 µg/mL were used for calibration. The laboratory calibration equation was Abs = 0.00662319 × concentration, with $R^2 = 0.82665$. The laboratory-generated concentrations were used for comparative interpretation.

Carbohydrate standard (µg/mL)	Absorbance
20	0.373
40	0.369
60	0.412
80	0.470
100	0.612

Table 2. Carbohydrate calibration standards.

5 Acid Value of Fat

Acid value of fat was determined as an additional biochemical parameter for the five marine marine fish mucus samples. Results are expressed as milligrams of potassium hydroxide required to neutralize the free fatty acids in one gram of fat (mg KOH/g fat). The analytical reference cited in the supplied laboratory documentation was Asian Journal of Biological and Life Sciences, 2025; 14(1):133–138.

6 Data Analysis

The measured protein concentration, carbohydrate concentration and acid value of fat were organized and compared descriptively among the five selected marine fish taxa. The reported laboratory values were retained for the comparative analysis.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Results

1 Protein Content

Fish taxon	Protein concentration (µg/mL)
Scoliodon sp.	420.569
Anguilliformes	173.610
Pampus sp.	511.261
Sphyraena sp.	579.011
Ariidae	502.854

Table 3. Protein concentration of mucus from the five selected marine fish taxa.

Protein concentration varied among the selected taxa. Sphyraena sp. recorded the highest value (579.011 µg/mL), followed by Pampus sp. (511.261 µg/mL), Ariidae (502.854 µg/mL), Scoliodon sp. (420.569 µg/mL) and Anguilliformes (173.610 µg/mL). The highest recorded concentration was approximately 3.34 times the lowest value.

2 Total Carbohydrate Content

Fish taxon	Carbohydrate concentration (µg/mL)
Scoliodon sp.	146.309
Anguilliformes	105.123
Pampus sp.	155.776
Sphyraena sp.	104.071
Ariidae	177.609

Table 4. Total carbohydrate concentration of mucus from the five selected marine fish taxa.

Ariidae recorded the highest total carbohydrate concentration (177.609 µg/mL), followed by Pampus sp. (155.776 µg/mL), Scoliodon sp. (146.309 µg/mL), Anguilliformes (105.123 µg/mL) and Sphyraena sp. (104.071 µg/mL).

3 Acid Value of Fat

Fish taxon	Acid value (mg KOH/g fat)
Scoliodon sp.	0.0563
Anguilliformes	0.0563
Pampus sp.	0.1691
Sphyraena sp.	0.1127
Ariidae	0.0563

Table 5. Acid value of fat in mucus from the five selected marine fish taxa.

Pampus sp. recorded the highest acid value of fat (0.1691 mg KOH/g fat), followed by Sphyraena sp. (0.1127 mg KOH/g fat). Scoliodon sp., Anguilliformes and Ariidae showed the same reported value of 0.0563 mg KOH/g fat.

4 Comparative Biochemical Profile

Fish taxon	Protein (µg/mL)	Carbohydrate (µg/mL)	Acid value (mg KOH/g fat)
Scoliodon sp.	420.569	146.309	0.0563
Anguilliformes	173.610	105.123	0.0563
Pampus sp.	511.261	155.776	0.1691
Sphyraena sp.	579.011	104.071	0.1127
Ariidae	502.854	177.609	0.0563

Table 6. Comparative biochemical profile of mucus from the five selected marine fish taxa.

Discussion

1 Protein Profile

The protein content showed marked variation among the five fish taxa. Sphyraena sp. exhibited the highest measured protein concentration, whereas Anguilliformes exhibited the lowest. Pampus sp. and Ariidae also showed comparatively high protein concentrations. Such variation indicates differences in the measured protein fraction of the mucus samples examined.

The Lowry assay provides a quantitative estimate of total protein under the assay conditions and does not identify individual proteins or peptides. Therefore, the higher protein concentration observed in Sphyraena sp. represents a difference in total measured protein and should not be interpreted as evidence of a particular biological activity.

2 Carbohydrate Profile

The carbohydrate profile differed from the protein ranking. Ariidae showed the highest measured total

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

carbohydrate concentration, whereas Sphyraena sp. showed the lowest. Pampus sp. and Scoliodon sp. showed intermediate values. The different ranking of taxa for protein and carbohydrate demonstrates that the measured biochemical constituents do not vary in an identical manner.

The Phenol–Sulphuric Acid method provides an estimate of total carbohydrate and does not identify individual carbohydrate molecules. The values therefore represent the total carbohydrate response under the laboratory assay conditions.

3 Acid Value of Fat

Acid value of fat also showed a taxon-specific pattern. Pampus sp. recorded the highest value, followed by Sphyraena sp., while Scoliodon sp., Anguilliformes and Ariidae showed equal reported values. Acid value is a measure related to free fatty acids in the analyzed fat fraction and should not be considered a complete characterization of lipid composition.

4 Overall Comparison

The three biochemical parameters showed distinct comparative patterns. Sphyraena sp. had the highest protein concentration, Ariidae had the highest carbohydrate concentration, and Pampus sp. had the highest acid value of fat. No single fish taxon recorded the highest value for all three parameters. The findings therefore indicate parameter-specific biochemical variation among the selected marine marine fish mucus samples.

Conclusion

The present study provides a comparative biochemical profile of epidermal mucus from Scoliodon sp., Anguilliformes, Pampus sp., Sphyraena sp. and Ariidae. Fresh specimens used for the final analysis were obtained from Diwale Jetty, Diwale village, CBD Belapur, Navi Mumbai, Maharashtra, India. Significant numerical differences were observed in the measured biochemical constituents: Sphyraena sp. showed the highest protein concentration (579.011 μg/mL), Ariidae showed the highest carbohydrate concentration (177.609 μg/mL), and Pampus sp. showed the highest acid value of fat (0.1691 mg KOH/g fat). The results establish a useful comparative biochemical profile of mucus among the selected marine fish taxa.

Acknowledgement

The authors sincerely express their gratitude to the authorities and staff of V.P.M.'s B. N. Bandodkar College of Science (Autonomous), Thane, Maharashtra, for providing the necessary academic support and facilities to carry out this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Shephard KL. Functions for marine fish mucus. Reviews in Fish Biology and Fisheries. 1994; 4:401–429.
2. Ellis AE. Innate host defense mechanisms of fish against viruses and bacteria. Developmental and Comparative Immunology. 2001; 25:827–839.
3. Subramanian S, Ross NW, MacKinnon SL. Comparison of the biochemical composition of normal epidermal mucus from various fish species. Comparative Biochemistry and Physiology Part B. 2008; 149:187–201.
4. Esteban MA. An overview of the immunological defenses in fish skin. ISRN Immunology. 2012; 2012:853470.
5. Center for Research, Consultancy and Technical Services (CRCTS), Karmaveer Bhaurao Patil College, Vashi. Laboratory photometric report: Protein estimation—Fish Mucus Sample Quantitative Analysis. 25 September 2025.
6. Center for Research, Consultancy and Technical Services (CRCTS), Karmaveer Bhaurao Patil College, Vashi. Laboratory photometric report: Total Carbohydrate Estimation for Epidermal Fish Mucus Samples. 26 September 2025.
7. Center for Research, Consultancy and Technical Services (CRCTS), Karmaveer Bhaurao Patil College, Vashi. Laboratory test reports for acid value of fat in marine marine fish mucus samples. 2025.
8. Asian Journal of Biological and Life Sciences. 2025;14(1):133–138.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

A Study of Web 1.0 To Web 4.0: Evolution, Technologies, Applications and Future Directions

Dr. Kamlesh Ravikumar Patil
Librarian, S. Chandra Mahila Mahavidyalaya, Dist. Gondia, Maharashtra, India

Manuscript ID:
BN-2026-030905

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 23-27

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909737
DOI link: https://doi.org/10.5281/zenodo.22909737

Abstract

The World Wide Web has evolved from a predominantly static information environment into an increasingly interactive, semantic, distributed and intelligent digital ecosystem. The earlier study on Web 1.0 to Web 3.0 described the transition from the read-only web to the read-write social web and then toward the semantic web. This revised study extends that framework to Web 4.0 and examines the technological and conceptual changes across the four stages. Web 1.0 is characterized by static pages, one-way information delivery and limited user participation; Web 2.0 emphasizes interaction, user-generated content, social networking and web applications; Web 3.0 is associated with semantic interoperability, decentralized architectures, data ownership and intelligent processing; and Web 4.0 is increasingly discussed as an intelligent or symbiotic web in which artificial intelligence, Internet of Things (IoT), cloud/edge computing, augmented and virtual reality, machine-to-machine communication and autonomous agents can interact with people and each other. The literature does not provide one universally accepted definition of Web 4.0, so this paper treats it as an emerging research and technology paradigm rather than a fixed technical standard. The study also discusses implications for libraries and information services, including intelligent discovery, personalized services, virtual assistance, semantic knowledge organization and human-machine collaboration. The paper concludes that the movement from Web 1.0 to Web 4.0 represents a shift from information access toward participation, meaning, intelligence and increasingly symbiotic interaction.

Keywords: *World Wide Web, Web 1.0, Web 2.0, Web 3.0, Web 4.0, Semantic Web, Artificial Intelligence, Internet of Things, Intelligent Web, Libraries*

Introduction

The World Wide Web (WWW) has become a fundamental infrastructure for education, research, communication, commerce, government and social interaction. The original study used the evolution of the web to explain how information moved from static online documents toward interactive and semantic environments. The present revision retains that historical framework while incorporating developments in artificial intelligence, Internet of Things, decentralized technologies, immersive interfaces and intelligent agents. The Web was created at CERN by Tim Berners-Lee in 1989. Its early development focused on linked documents and access to information through browsers. Over time, the web changed from a publishing medium into a platform for participation and then into an environment in which data, applications and intelligent systems can interact. Recent literature describes Web 4.0 using terms such as intelligent web and symbiotic web, while also acknowledging that the term has no single universally accepted definition.

Need for the Present Study

The original paper was published in 2021 and ended with Web 3.0. Since then, artificial intelligence has become deeply integrated with search, content generation, recommendation, conversational systems and software agents.

Creative Commons *(CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Kamlesh Ravikumar Patil, Librarian, S. Chandra Mahila Mahavidyalaya, Dist. Gondia, Maharashtra, India

Email: kamaleshpatil11@gmail.com

How to cite this article:

Patil, K. R. (2026). A Study of Web 1.0 To Web 4.0: Evolution, Technologies, Applications and Future Directions. Bulletin of Nexus Journal, 3(9(II)), 23–27. https://doi.org/10.5281/zenodo.22909737

Quick Response Code:

Website: https://bnir.us

At the same time, IoT, edge/cloud computing, extended reality and machine-to-machine communication have strengthened the vision of a connected digital environment. Therefore, an updated study is necessary to place Web 4.0 within the longer historical development of the web.

Objectives of the Study

- To trace the major characteristics of Web 1.0, Web 2.0, Web 3.0 and Web 4.0.
- To identify the technologies and interaction models associated with each stage.
- To compare the four web generations in terms of users, data, applications, intelligence and control.
- To examine the emerging role of AI, IoT, cloud/edge computing and immersive technologies in Web 4.0.
- To discuss the implications of Web 4.0 for libraries, information services and knowledge management.
- To identify major challenges including privacy, cybersecurity, interoperability, bias, digital inclusion and governance.

Methodology

The study follows a descriptive and conceptual review approach. The 2021 source paper supplied the historical structure and discussion of Web 1.0, Web 2.0 and Web 3.0. The framework was then updated using recent scholarly literature on Web 4.0, AI-enabled web development, IoT and intelligent/symbiotic web environments. Because Web 4.0 is still an emerging concept, the paper distinguishes established characteristics of earlier web generations from proposed or developing characteristics of Web 4.0.

Evolution of the World Wide Web

1 Web 1.0 – The Read-Only / Static Web

Web 1.0 represents the early public web in which a relatively small number of publishers created pages for a large number of readers. The principal activity was locating and reading information. Websites were generally static, interaction was limited, and content creation was controlled largely by site owners or webmasters. The earlier paper appropriately described this stage as a read-only web.

Typical characteristics include static HTML pages, hyperlinks, basic search engines, personal websites, online directories and one-way information delivery. Communication generally moved from publisher to user rather than from many users to many users.

2 Web 2.0 – The Social and Participatory Web

Web 2.0 changed the web from a mainly publishing environment into an interactive platform. Blogs, wikis, social networking sites, podcasts, RSS, social bookmarking, file sharing, collaborative platforms and web applications enabled users to create, modify, share and discuss content. Tim O'Reilly's work helped popularize the term Web 2.0.

The major shift was from 'read' to 'read and write'. The user became both consumer and producer of information. The original paper identified examples such as Flickr, YouTube, blogs, Wikipedia and social networking services. These examples illustrate the central principle of user-generated content and social participation.

3 Web 3.0 – Semantic, Intelligent and Decentralized Directions

Web 3.0 is used in more than one way in the literature. In the earlier paper, it was primarily associated with the Semantic Web, machine-understandable data, personalization, intelligent search and the transformation of the web into a database-like environment. Contemporary usage also commonly associates Web 3.0 with decentralization, distributed architectures, user control of data and identity, and blockchain-enabled applications. Thus, Web 3.0 should be understood as a family of related developments rather than one single technology.

Semantic technologies seek to make information more meaningful to machines through structured data, ontologies and linked data. Decentralized approaches seek to reduce dependence on centralized platforms and increase user control. These directions provide an important bridge toward the intelligent and connected environments often described under Web 4.0.

4 Web 4.0 – The Intelligent / Symbiotic Web

Web 4.0 is an emerging concept and does not have one universally accepted technical definition. A prominent research interpretation describes it as an intelligent and symbiotic web in which humans, machines, intelligent agents and connected devices interact through large-scale interfaces and links. The concept brings together AI, IoT, big data, cloud and edge computing, augmented/virtual reality, machine-to-machine communication and autonomous or smart agents.

The key difference is not simply that the web contains more information or more social interaction. The emphasis is on contextual, predictive and increasingly autonomous interaction. AI systems may interpret information, generate responses, recommend actions, coordinate services and interact with other software or devices. In this sense, the web can move toward an environment where human and machine actors work together rather than merely exchanging documents.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Recent research also connects Web 4.0 with immersive environments and the metaverse, particularly through the convergence of AI, IoT, blockchain and augmented/virtual reality. These connections remain areas of active research, so they should be treated as emerging directions rather than settled standards.

Major Technologies Associated with Web 4.0

- Artificial Intelligence and Machine Learning – natural-language interaction, recommendation, prediction, content generation and autonomous decision support.
- Intelligent Agents – software agents capable of searching, interpreting information, coordinating tasks and acting on behalf of users or systems.
- Internet of Things – connected sensors and devices that produce and exchange real-time data.
- Cloud and Edge Computing – scalable processing in cloud environments and low-latency processing closer to connected devices.
- Semantic Technologies – structured data, ontologies and knowledge graphs that support machine-readable meaning.
- Augmented and Virtual Reality – immersive interfaces connecting digital information with physical or simulated environments.
- Machine-to-Machine Communication – automated communication and coordination between devices and services.
- Big Data Analytics – processing large, fast and heterogeneous datasets to identify patterns and support decisions.
- Blockchain and Distributed Technologies – decentralized identity, transactions and data-sharing mechanisms in selected Web 3.0/4.0 applications.
- Cybersecurity and Privacy Technologies – essential safeguards for highly connected and intelligent systems.

Comparison of Web 1.0 to Web 4.0

Dimension	Web 1.0	Web 2.0	Web 3.0	Web 4.0
Core idea	Static information	Participation and social interaction	Meaning, data integration and decentralization	Intelligence and symbiotic interaction
User role	Reader	Reader + creator	User/owner/participant	Human + intelligent agent + connected device
Interaction	Mostly one-way	Two-way/social	Semantic and distributed	Context-aware, predictive and potentially autonomous
Data	Web pages	User-generated content	Linked/structured/distributed data	Real-time, contextual and multimodal data
Key technologies	HTML, hyperlinks, basic search	Blogs, wikis, social media, APIs	Semantic web, knowledge graphs, decentralization	AI, IoT, agents, edge/cloud, XR, M2M
Typical services	Information sites/directories	Social networks/web apps	Semantic search/decentralized services	Intelligent assistants, smart environments, immersive services
Primary value	Access to information	Participation	Meaning, interoperability and control	Intelligence, personalization and collaboration
Main challenge	Limited interaction	Privacy/platform dependence	Interoperability, governance and adoption	AI safety, privacy, security, bias and human oversight

Web 4.0 and Libraries

The evolution toward Web 4.0 has direct implications for libraries and information centres. Libraries already use Web 2.0 technologies for communication and user participation, while semantic web technologies can improve discovery and interoperability. Web 4.0 may extend these services through intelligent search, conversational reference, personalized recommendations, automatic metadata assistance, knowledge graphs,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

smart library spaces and AI-supported research services.

- Intelligent discovery: AI can help users formulate queries and retrieve relevant information across heterogeneous resources.
- Conversational reference: intelligent assistants can support routine reference questions while librarians retain responsibility for complex and sensitive queries.
- Personalized information services: systems can recommend resources according to legitimate user preferences and context.
- Semantic cataloguing and metadata: linked data and knowledge graphs can connect authors, subjects, works, institutions and research outputs.
- Smart library environments: IoT sensors can support occupancy monitoring, equipment management and selected service automation.
- Research support: AI tools can assist with literature discovery, summarization, citation management and research workflows, subject to verification.
- Accessibility: multimodal interfaces can provide alternative ways of interacting with information for users with different needs.

Advantages of Web 4.0

- More natural human-computer interaction through language, voice and multimodal interfaces.
- Context-aware and personalized information delivery.
- Real-time interaction among people, applications and connected devices.
- Greater automation of repetitive information and service tasks.
- Integration of physical and digital environments.
- Potentially improved decision support through AI and large-scale data analysis.
- New opportunities for education, research, healthcare, libraries, commerce and public services.

Challenges and Ethical Issues

Greater intelligence and connectivity also increase risk. Web 4.0 environments can collect extensive personal and contextual data, making privacy and consent important concerns. AI-generated information may contain errors or bias, and autonomous systems may make decisions that are difficult for users to understand. Cybersecurity becomes more complex when billions of devices and services are interconnected. Interoperability, digital exclusion, platform concentration, intellectual property, misinformation, algorithmic accountability and human oversight also require attention.

For libraries and educational institutions, responsible adoption should therefore include data minimization, transparent policies, security controls, human review, accessibility, digital literacy and continuous evaluation of AI outputs.

Future Directions

The future web is likely to become increasingly agentic, multimodal and context-aware. AI agents may search across services, coordinate workflows and communicate with other agents and devices. Knowledge graphs and semantic technologies may provide structured context, while edge computing can support low-latency applications. Immersive interfaces may further connect physical and virtual spaces. However, these developments will depend on standards, governance, security, privacy and public trust.

The concept of Web 4.0 should therefore be viewed as a direction of technological evolution rather than a universally finalized version number. Its significance lies in the increasing integration of information, people, machines and intelligent services.

Conclusion

The journey from Web 1.0 to Web 4.0 demonstrates a broad transformation in the role of the web. Web 1.0 emphasized publishing and access; Web 2.0 emphasized participation and social interaction; Web 3.0 emphasized semantic meaning, interoperability and, in contemporary usage, decentralization and user control; and Web 4.0 increasingly emphasizes intelligence, context, automation and human-machine symbiosis. The revised framework extends the earlier study by incorporating AI, IoT, intelligent agents, edge/cloud computing and immersive technologies.

For libraries, the transition offers substantial opportunities to improve discovery, reference, personalization, knowledge organization and research support. At the same time, librarians and institutions must maintain human oversight, privacy, security, accessibility and information-

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

literacy principles. Web 4.0 is still evolving, but its direction suggests that the future web will be less about merely visiting pages and more about interacting with intelligent information ecosystems.

Acknowledgement
The author sincerely expresses gratitude to the authorities and staff of S. Chandra Mahila Mahavidyalaya, Gondia, Maharashtra, for providing the academic support and encouragement necessary for the completion of this research work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Abou Ali, M., & Dornaika, F. (2026). From Static Pages to Symbiotic Intelligence: The CET-WAIP Framework for Understanding AI–Web Coevolution. Big Data and Cognitive Computing, 10(7), 235. https://doi.org/10.3390/bdcc10070235
2. Ibrahim, A. K. (2021). Evolution of the Web: from Web 1.0 to 4.0. Qubahan Academic Journal, 1(3). https://doi.org/10.48161/qaj.v1n3a75
3. Klarin, A. (2026). Metaverse and Artificial Intelligence as Web 4.0: The Next Generation of the Internet. Systems Research and Behavioral Science. https://doi.org/10.1002/sres.3209
4. O'Reilly, T. (2005). What Is Web 2.0: Design Patterns and Business Models for the Next Generation of Software. O'Reilly Media.
5. Radanliev, P., De Roure, D., Nicolescu, R., Huth, M., & others. (2021). Artificial Intelligence and the Internet of Things in Industry 4.0. CCF Transactions on Pervasive Computing and Interaction, 3, 329–338.
6. Samper Zapater, J. J. (2014). From Web 1.0 to Web 4.0: The Evolution of the Web. Proceedings of the 2014 ACM Conference / related publication record. DOI: 10.1145/2590651.2590652.
7. World Wide Web Consortium (W3C). Web Accessibility Initiative (WAI). https://www.w3.org/WAI/
8. Patil, K. (2021). A Study of Web 1.0 to 3.0. AGPE The Royal Gondwana Research Journal of History, Science, Economic, Political and Social Science, 2(2), 40–45.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

The AI Lexicon: Exploring Neologism and Contemporary Word Formation Processes

Dr. Salama Khwaja Attar[1], Dr. Khaja Dada Atar[2], Nida Adam Inchanalkar[3]
[1]Assistant Professor, Department of English, Ajara Mahavidyalaya, Ajara
[2]Head, Assistant Professor, Department of Electronics, The New College, Kolhapur
[3].B.A.II Student, Department of English, Ajara Mahavidyalaya, Ajara

Manuscript ID:
BN-2026-030906

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 28-32

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22909913
DOI link:
https://doi.org/10.5281/zenodo.22909913

Abstract
Artificial Intelligence has rapidly become part of everyday communication, writing, education, media, and digital culture. While language has been traditionally understood as a human-created and his lexicon continuously evolving system, the emergence of generative AI raises a new question: Can machines become participants in language change? This paper examines the relationship between Artificial Intelligence and the formation of new words, expressions, and meanings. It focuses particularly on neologisms and word-formation processes, including Conversion, blending, compounding, clipping, acronym, affixation, and reduplication. The study argues that AI may not independently "own" or control language change, but it can increasingly act as a catalyst, amplifier, and collaborator in the evolution of vocabulary.

Key Words- *Artificial Intelligence, machine-generated text, neologism, word formation processes, Lexicon*

Introduction:

Language has never been static. Words appear-disappear, meanings change, and new expressions emerge whenever society experiences cultural, technological, or social transformation. The development of the internet, social media, and digital communication has accelerated this process considerably. Today, Machines are no longer merely storing or transmitting language. Generative Artificial Intelligence systems can produce sentences, stories, terminology, names, expressions, and even apparently new words within seconds. This creates an intriguing linguistic question. When a machine produces a word, that humans subsequently understand and use, can that machine be considered a participant in language change? Traditionally, neologisms emerge through human lexicon, interaction and processes such as blending, conversion, compounding, clipping, acronym, affixation, and reduplication. AI introduces another layer to this process named as computational generation. Therefore, this research investigates AI not simply as a tool for language, but as a potential agent influencing the direction and speed of linguistic change.

Research Problem:

The emergence of generative AI challenges traditional ideas about who creates language. Although AI systems learn from existing human language, they can generate combinations that may be unfamiliar or novel to users. Some expressions may disappear immediately, while others could potentially be repeated, circulated, modified, and eventually adopted by human communities. The research problem can therefore be stated as: To what extent can Artificial Intelligence contribute to the creation, circulation, and transformation of new English words and expressions?

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Salama Khwaja Attar, Assistant Professor, Department of English, Ajara Mahavidyalaya, Ajara
Email: manersalma1989@gmail.com

How to cite this article:
Attar, S. K., Atar, K. D., & Inchanalkar, N. A. (2026). The AI Lexicon: Exploring Neologism and Contemporary Word Formation Processes. Bulletin of Nexus Journal, 3(9(II)), 28–32. https://doi.org/10.5281/zenodo.22909913

Quick Response Code:

Website: https://bnir.us

Objectives:

- To examine the role of AI in generating new words and lexicon.
- To identify the word-formation processes present in AI-generated vocabulary.
- To compare machine-generated neologisms with naturally occurring human neologisms.
- To explore whether AI should be viewed as a tool, catalyst, or participant in language change.

Theoretical Framework:

Human creates and learns word with cognitive theory. Al creates a new word by understanding given prompts by human then it relates all the existing words. AI explores word formation processes and gives many options for the new words. AI compares with concept, semantic analysis, existing lexical units, word formation process, candidate generation, linguistic evolution and neologism. Neologism is a newly created word or a new use of an existing word while lexicon is the complete vocabulary of a language, a specific subject or a particular group of people. It is examined through Word-Formation Processes as conversion, blending, compounding, clipping, acronym, affixation, and reduplication. Blending is combining parts of words while Compounding is simply combining existing words. Clipping is the base shortening words. Acronym is initial formation of base words. Affixation is addition of group of words before or after the base word. Conversion is change of word class form.

Analysis:

Sr. No.	Phrases	Traditional Word	AI Generated Word	Description	Word Formation Process
1	A person who knows everything	Omniscient	Knowallian	Know-all + -ian	Affixation
2	One who speaks little	Reticent	Quietarian	Quiet + -arian	Affixation
3	One who believes in God	Theist	Godbeliever	God + believer	Compounding
4	A person over 100 years old	Centenarian	Centenlder	Centenarian+ elder	Blending
5	One who loves mankind	Philanthropist	Humankindler	Human-kind + ler	Compounding + Affixation
6	look forward to	Anticipate	Futuregaze	Future + gaze	Compounding
7	One who knows many languages	Polyglot	Multilinguist	Multi + linguist	Affixation
8	One indifferent to pleasure or pain	Stoic	Feelneutral	Feel + neutral	Compounding
9	One who sees the bright side	Optimist	Brightminder	Bright + minder	Compounding
10	One who eats too much	Glutton	Overeater	Over + eater	Compounding
11	A list of books	Catalogue	Booklist	Book + list	Compounding
12	Writing that cannot be read	Illegible	Blur	Blur	Conversion

13	People living at the same time	Contemporaries	Timepeers	Time + peers	Compounding
14	One who believes in fate	Fatalist	Fatekeeper	Fate + keeper	Compounding
15	One who sees the dark side	Pessimist	Darkminder	Dark + minder	Compounding
16	A person difficult to please	Fastidious	Diffilease	Difficult + please	Blending
17	Written by an unknown author	Anonymous	Anoncript	Anonymous + Script	Blending
18	Fit to be eaten	Edible	Eatfit	Eat + fit	Reduplication
19	Work for which no salary is paid	Honorary	Paylesswork	Pay + less + work	Compounding + Affixation
20	Unable to read or write	Illiterate	URW	Unable to read or write	Acronym
21	No longer in use	Obsolete	Usefaded	Use + faded	Compounding
22	Highly paid office requiring little/no work	Sinecure	Payidle	Pay + idle	Compounding
23	One who loves books	Bibliophile	Booklover	Book + lover	Compounding
24	One who cannot be corrected	Incorrigible	Uncorrectable	Un+ correct+ able	Affixation
25	A person who leaves their country	Emigrant	Outmigrant	Out+ migrant	Prefixation
26	A person who comes to live in a new country	Immigrant	Newcomer	New + comer	Compounding
27	A person who offers to help freely	Volunteer	Helpgiver	Help + giver	Compounding
28	A person who works for someone	Employee	Workmate	Work +mate	Compounding
29	A person who gives others work	Employer	Workgiver	Work + giver	Compounding
30	Head of a institution	Principal	IHM	Institutional Head Manager	Acronym
31	One who promotes human welfare	Philanthropist	Goodgiver	Good + giver	Compounding
32	A person who gives help or money	Benefactor	Aidgiver	Aid + giver	Compounding

33	A person who receives help/money	Beneficiary	Aidreceiver	Aid + receiver	Compounding
34	Self-centered person	Egoist	Selfist	Self + ist	Affixation
35	A person who owes money	Debtor	Moneyowner	Money + owner	Compounding
36	A person who lends money	Creditor	Moneylender	Money+ lender	Compounding
37	A person who saves every penny	Miser	Pennykeeper	Penny +keeper	Compounding
38	A person who wastes money	Spendthrift	Moneyflinger	Money +flinger	Compounding
39	One who receives and entertains people	Host	Guestwelcomer	Guest +welcomer	Compounding
40	A person who visits someone	Guest	Visiguest	Visit + guest	Blending
41	A person who starts something new	Founder	Newioneer	New + pioneer	Blending
42	One who receives property after someone's death	Heir	Legacyreceiver	Legacy + receiver	Compounding
43	A person with extreme beliefs	Fanatic	Believerist	Believer + ist	Affixation
44	A person who enjoys fine food	Gourmet	Tasteconnoisseur	Taste + connoisseur	Compounding
45	One who is outgoing	Extrovert	Outgovert	Outgoing + vert	Blending
46	One who prefer solitude	Introvert	Solivert	Solitude + vert	Blending
47	One who expects good things	Optimist	Hopecaster	Hope + caster	compounding
48	A person who checks/ corrects writing	Editor	Textfixer	Text + fixer	Compounding
49	One who prints/distributes books	Publisher	Bookreleaser	Book + releaser	Compounding
50	One concerned with other's welfare	Altruist	Caregiver	Care + giver	Compounding

Conclusion:

Artificial Intelligence has not replaced humans as the primary social force behind language change. However, it has introduced a new mechanism through which linguistic innovation can occur. AI can generate, combine, modify, and circulate linguistic forms at unprecedented speed. Whether these forms become genuine parts of language ultimately depends on human communities. Artificial Intelligence does not merely reproduce existing vocabulary; it can generate novel lexical forms by applying familiar word-formation processes such as blending, compounding, affixation, conversion, acronym and reduplication. That is new aspect for the language study as "Machine-mediated neologism". It can be defined as a newly generated or modified linguistic expression produced through interaction with an AI system and potentially introduced into human communication. Thus, AI may best be understood not as an independent creator of language, but as a machine-mediated catalyst of linguistic change. "Perhaps the future of language will not be written by humans alone—but it will still be decided by them."

Acknowledgement
The authors sincerely express their gratitude to the authorities and faculty members of Ajara Mahavidyalaya, Ajara, and The New College, Kolhapur, for their valuable academic support and encouragement in completing this research work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References:
1. Bauer, Laurie. English Word-Formation. 2nd ed., Cambridge University Press, 1983.
2. Bender, Emily M., et al. "On the Dangers of Stochastic Parrots: Can Language Models Be Too Big?" Proceedings of the 2021 ACM Conference on Fairness, Accountability, and Transparency, ACM, 2021, pp. 610–23.
3. Crystal, David. Language and the Internet. 2nd ed., Cambridge University Press,
4. Lieber, Rochelle. Introducing Morphology. 2nd ed., Cambridge University Press, 2016
5. Plag, Ingo. Word-Formation in English. 2nd ed., Cambridge University Press, 2018
6. Yule, George. The Study of Language. 7th ed., Cambridge University Press, 2019

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

UNDP-SDG Framework - Impact of Smart Technologies on Tamil Nadu Warehousing Corporation

Dr. V. Pattammal
Corporate Coach & Management Consultant, Department of Business Administration, Annamalai University

Manuscript ID:
BN-2026-030907

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 33-38

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22910463
DOI link:
https://doi.org/10.5281/zenodo.22910463

Abstract

The rapid emergence of smart technologies is transforming traditional warehouses into intelligent, interconnected and sustainable logistics systems. This article examines the potential impact of smart technologies on the Tamil Nadu Warehousing Corporation (TNWC), focusing on operational efficiency, bottleneck reduction, resource optimisation and carbon-footprint reduction within the United Nations Development Program (UNDP) Sustainable Development Goals (SDGs) framework. Technologies such as the Internet of Things (IoT), Artificial Intelligence AI), Warehouse Management Systems (WMS), Radio Frequency Identification (RFID), robotics, automation, predictive maintenance, GPS-based fleet management, smart energy systems and data analytics can improve inventory accuracy, space utilisation, commodity monitoring, transportation efficiency and managerial decision-making. They can also address bottlenecks associated with manual documentation, inventory discrepancies, vehicle congestion, excessive material handling, equipment breakdowns, energy inefficiency and commodity losses. The article proposes an integrated Smart and Green Warehouse model that combines digital transformation with renewable energy, energy-efficient infrastructure, sustainable transportation, waste reduction, circular-economy practices and climate-resilient warehouse design. The approach is aligned with SDG 7, SDG 8, SDG 9, SDG 11, SDG 12, SDG 13 and SDG 17. A phased implementation strategy involving digitalisation, pilot projects, workforce reskilling, carbon accounting, renewable-energy adoption and continuous performance monitoring is recommended. The article concludes that smart technologies can enable TNWC to improve productivity, transparency, resilience and environmental sustainability while contributing to Tamil Nadu's transition towards a low-carbon logistics ecosystem.

Keywords: *Smart Warehousing; Tamil Nadu Warehousing Corporation; Internet of Things; Artificial Intelligence; Carbon Footprint; Sustainable Development Goals; Green Logistics*

Introduction

Warehousing has become a strategic component of modern supply-chain management. It is no longer limited to storing commodities until they are required. Contemporary warehouses coordinate inventory, transportation, quality control, information flows, customer service, energy consumption and distribution. The increasing volume and complexity of supply-chain activities require warehouses to become faster, more transparent, technologically enabled and environmentally responsible. The Tamil Nadu Warehousing Corporation (TNWC) has an important role in supporting agricultural, industrial, commercial and logistics activities in Tamil Nadu. Its warehouses facilitate the storage and movement of commodities and therefore influence the efficiency of wider supply chains. The Tamil Nadu Export Promotion Strategy has recognized warehousing and logistics infrastructure as important areas for improvement and has proposed an Integrated Warehouse Management System to improve operational efficiency. At the same time, warehouses consume considerable quantities of electricity and fuel and generate emissions through lighting, material-handling equipment, transportation, refrigeration, diesel generators and other activities.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
V. Pattammal, Corporate Coach & Management Consultant, Department of Business Administration, Annamalai University
Email: pattammal@hotmail.com

How to cite this article:
V. Pattammal. (2026). UNDP–SDG Framework - Impact of Smart Technologies on Tamil Nadu Warehousing Corporation. Bulletin of Nexus, 3(9(II)), 33-38. https://doi.org/10.5281/zenodo.22910463

Quick Response Code:

Website: https://bnir.us

Consequently, warehouse modernization should not focus exclusively on productivity. It should also address energy efficiency, renewable energy, waste reduction, climate resilience and carbon emissions. Smart technologies provide an opportunity to achieve these objectives simultaneously. IoT sensors can monitor warehouse conditions in real time; RFID can improve inventory visibility; AI can support forecasting and optimization; robotics can reduce repetitive material handling; GPS can improve transportation efficiency; and smart energy-management systems can reduce electricity consumption. The transformation of TNWC should therefore be viewed as a **Smart, Green and Sustainable Warehouse Program** rather than simply an automation program. The UNDP–SDG framework provides a useful foundation because it connects economic growth, innovation, decent employment, responsible resource use, clean energy, climate action and partnerships.

Description of Smart Technologies and Their Impact on TNWC

1 Warehouse Management Systems: A Warehouse Management System should constitute the digital backbone of TNWC's future operations. It can integrate receiving, storage, inventory control, picking, dispatch, billing and reporting. **A WMS can provide real-time information about:** Inventory quantities; Commodity locations; Warehouse capacity; Stock ageing; Receipts and dispatches; Damaged goods; Customer orders; Vehicle movements. This reduces dependence on manual registers and helps minimise data-entry errors. Management can also identify available storage capacity across different locations and redistribute inventory more efficiently.

2 Internet of Things

IoT sensors can continuously monitor temperature, humidity, moisture, energy consumption, equipment condition, fire risks, water leakage and other environmental parameters. This is particularly important for agricultural commodities. Poor temperature or humidity conditions can cause deterioration and financial losses. With IoT, managers can receive alerts when environmental conditions exceed predetermined thresholds. IoT therefore changes warehouse management from **periodic inspection to continuous monitoring**.

3 RFID, Barcodes and QR Codes

RFID and barcode systems can provide digital identification of commodities, pallets and storage locations.

A typical digital process could be: Receiving → Weighing → Quality Inspection → Digital Identification → Storage → Inventory Update → Dispatch → Digital Confirmation

This reduces paperwork and improves traceability. RFID can be particularly valuable where large quantities of items must be identified quickly.

4 Artificial Intelligence and Data Analytics

AI can transform warehouse data into actionable intelligence. It can analyse historical demand, inventory movement, warehouse occupancy and transportation patterns.

Potential applications include: Demand forecasting; Inventory optimisation; Warehouse-space allocation; Vehicle scheduling; Route optimisation; Predictive maintenance; Energy optimisation; Anomaly detection.

For example, AI could identify warehouses likely to experience capacity shortages during particular seasons and recommend alternative storage locations in advance.

5 Robotics and Automation

Robotics, Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) can automate repetitive material-handling activities.

Potential benefits include: Reduced handling time; Improved worker safety; Higher productivity; Reduced forklift movement; Improved consistency.

However, TNWC should not adopt automation indiscriminately. Technology selection should depend on warehouse size, commodity type, transaction volume, investment cost and expected return.

6 Predictive Maintenance

Equipment breakdowns can create major operational bottlenecks. Predictive maintenance uses sensors and data analytics to identify potential equipment failures before they occur.

Equipment such as: Forklifts; Conveyors; Elevators; Weighing systems; Pumps; Generators; Refrigeration systems **can** be monitored for abnormal operating conditions. This reduces unexpected downtime, emergency repair costs and inefficient equipment replacement.

Major Warehouse Bottlenecks and Proposed Solutions

TNWC's transition to smart warehousing should begin with a systematic assessment of operational bottlenecks.

1 Manual inventory management: Manual records can produce inaccuracies and delays.

Solution: Implement WMS, RFID, barcode and mobile scanning systems.

2 Poor space utilisations: Traditional storage practices may create unused spaces alongside congested areas.

Solution: Use AI-based warehouse-slotting algorithms and real-time occupancy monitoring.

3 Vehicle congestion: Uncoordinated vehicle arrivals can produce queues and unnecessary engine idling.
Solution: Introduce digital vehicle appointment systems and GPS-based fleet management.
4 Excessive material handling: Repeated movement of commodities consumes labour, time and energy.
Solution: Optimise warehouse layouts and selectively deploy conveyors, AGVs and robotics.
5 Equipment breakdown: Reactive maintenance causes disruptions.
Solution: Introduce predictive-maintenance systems using IoT sensors.
6 Commodity deterioration: Poor environmental conditions can result in storage losses.
Solution: Install temperature, humidity and moisture sensors with automated alerts.
7 Excessive electricity consumption: Lighting, ventilation, equipment and refrigeration may consume unnecessary energy.
Solution: Implement smart meters, LED lighting, occupancy sensors and automated energy management.
8 Paper-based processes: Manual documentation increases administrative workload.
Solution: Develop digital receipts, electronic gate passes, e-invoices, digital inspection reports and electronic stock registers.

Reducing the Carbon Footprint of TNWC

Carbon reduction should become a measurable component of TNWC's warehouse strategy. The first step is to establish a **carbon baseline** covering electricity, diesel, transportation, refrigerants, waste and other relevant sources.

1. Energy Efficiency

TNWC should replace conventional lighting with LEDs and install: Motion Sensors; Occupancy Sensors; Daylight Controls; Smart Electricity Meters; Efficient Motors; Variable-Frequency Drives. Energy consumption should be monitored by facility and, where feasible, by equipment. A useful indicator is: **Energy Intensity = Total Energy Consumed ÷ Tonnes Handled**. This allows warehouses of different sizes to be compared.

2 Renewable Energy

Large warehouse rooftops provide opportunities for solar photovoltaic systems. Rooftop solar can support lighting, offices, IT systems, pumps and other electrical loads. Where technically and economically feasible, TNWC should progressively increase its share of renewable electricity. This directly supports **SDG 7 – Affordable and Clean Energy** and **SDG 13 – Climate Action**.

3 Low-Carbon Transportation: Transportation can be a major source of emissions associated with warehousing.
TNWC should implement: GPS tracking; Route Optimisation; Vehicle-Load Optimisation; Digital Appointment Systems; Reduced Engine Idling; Consolidation of Shipments; Gradual Adoption of Electric Vehicles Where Appropriate. Reducing truck waiting time has both an economic and environmental benefit.

4. Waste Reduction

Warehouses should implement source segregation and recycling of: Cardboard; Plastic; Damaged Packaging; Pallets; Electronic Waste; Other Recyclable Materials. Reusable pallets and packaging should be preferred over disposable alternatives wherever practical.

5 Reduction of Commodity Losses

Reducing commodity losses is itself a climate strategy. Resources, energy, transportation and agricultural inputs have already been invested in commodities that are subsequently damaged or wasted. IoT monitoring, improved storage conditions, preventive maintenance and better inventory rotation can therefore reduce both economic loss and embedded environmental impacts.

TNWC and the UNDP–SDG Framework

The proposed transformation can contribute to several SDGs simultaneously.

1 SDG 7 – Affordable and Clean Energy

TNWC can support SDG 7 through: Rooftop Solar; Smart Energy Meters; Energy-Efficient Lighting; Efficient Motors; Energy-Management Systems.
Suggested KPI: Energy consumed per tonne handled.

2 SDG 8 – Decent Work and Economic Growth

Automation should be accompanied by employee reskilling rather than simply workforce displacement.
Employees should receive training in: WMS operation; Data Analytics; Robotics; Iot Monitoring; Cyber-security; Sustainability Management. Smart technology should eliminate dangerous and repetitive tasks while creating higher-skilled employment opportunities.
Suggested KPIs: Training hours per employee, workplace accident rate and productivity per employee.

3 SDG 9 – Industry, Innovation and Infrastructure

Smart warehouses represent an important application of digital infrastructure and technological innovation.
TNWC can contribute through: IoT; AI; Digital Platforms; Automation; Resilient Infrastructure; Integrated Logistics Systems.

Suggested KPI: Percentage of warehouses digitally integrated with the central WMS.

4 SDG 11 – Sustainable Cities and Communities

Warehouses influence surrounding communities through truck movements, traffic, noise and emissions.

TNWC can contribute by: Reducing Vehicle Queues; Optimising Transport Routes; Using Cleaner Equipment; Improving Warehouse Energy Efficiency; Implementing Climate-Resilient Infrastructure.

5 SDG 12 – Responsible Consumption and Production

TNWC can reduce resource consumption through: Waste Minimisation; Recycling; Reusable Packaging; Paperless Operations; Efficient Energy Use; Reduced Commodity Losses; Sustainable Procurement.

6 SDG 13 – Climate Action

TNWC should establish: Carbon Inventories; Emission-Reduction Targets; Renewable-Energy Targets; Climate-Risk Assessments; Flood and Cyclone Preparedness; Heat-Resilient Infrastructure. **A useful long-term KPI is**: CO_2e emissions per tonne of commodity handled.

7 SDG 17 – Partnerships for the Goals

TNWC can partner with: Technology Providers; Universities; Research Institutions; Renewable-Energy Companies; Logistics Operators; Government Agencies; Financial Institutions; Industry Associations. Partnerships can help TNWC access technology, knowledge, financing and technical expertise.

Smart and Green Warehouse Model

A future TNWC warehouse should operate through five interconnected layers.

Digital Layer: WMS + IoT + RFID + AI + Cloud + Data Analytics

Operational Layer: Inventory + Storage + Material Handling + Quality + Dispatch

Energy Layer: Solar + Smart Meters + LED + Energy Management

Environmental Layer: Carbon Monitoring + Waste Management + Water Conservation

Governance Layer: Dashboards + KPIs + Audits + Sustainability Reporting

This integrated model ensures that technology supports both operational and environmental objectives.

Implementation Strategy

1 Phase I: Digital Foundation

During the first phase, TNWC should: Conduct a digital-maturity assessment; Map existing warehouse processes, establish inventory and energy baselines, Digitise warehouse records, Introduce barcode/QR systems, Implement WMS in selected facilities, Install smart energy meters, Establish central performance dashboards.

2 Phase II: Smart Warehouse Pilots

Selected high-volume warehouses should become pilot facilities for: IoT; RFID; AI analytics; Predictive Maintenance; Smart Lighting; Solar Power; Digital Vehicle Scheduling. Pilot performance should be measured against conventional facilities.

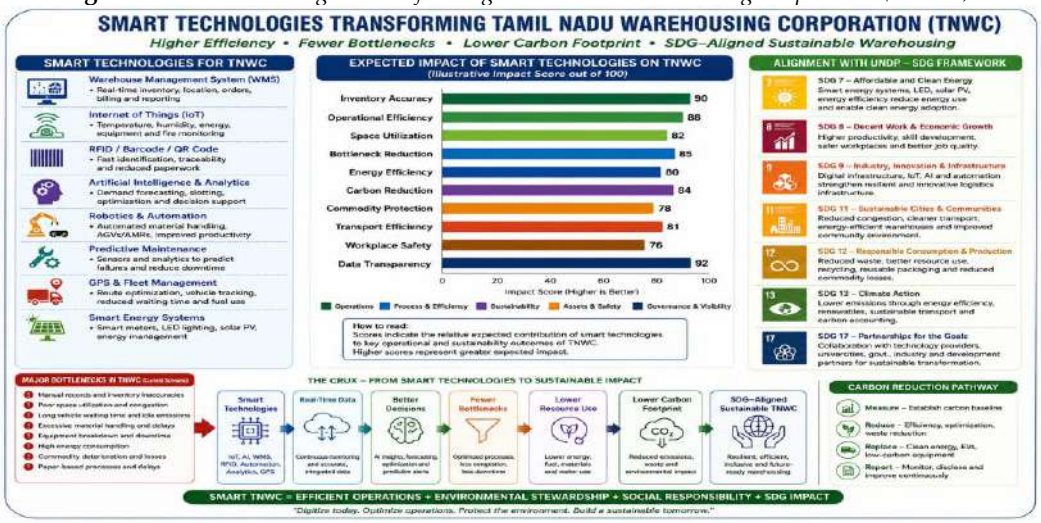
3 Phase III: Network Expansion

Successful technologies should be progressively deployed across TNWC facilities. The WMS should eventually integrate with: Finance; Procurement; Transportation; Billing; Customer-Service Systems; Energy Management.

4 Phase IV: Intelligent and Low-Carbon Network

The final stage can introduce: Digital Twins; Advanced AI; Autonomous Material Handling; Electric Equipment; Expanded Renewable Energy; Climate-Risk Analytics; Automated Sustainability Reporting.

Figure 1: *Smart Technologies Transforming Tamil Nadu Warehousing Corporation (TNWC)*



Organizational and Human Challenges

Technology implementation may encounter resistance from employees accustomed to traditional systems. TNWC should therefore implement structured change management.

A **TNWC Smart Warehouse Academy could provide training in**: Digital inventory management; IoT; AI; Cyber-security; Robotics; Data Interpretation; Carbon Management.

Technology should be introduced as an instrument for improving employee productivity and safety rather than as a threat to employment.

Management should also establish clear technology-governance policies covering data ownership, privacy, cyber-security, system reliability and accountability.

Key Performance Indicators

A Smart and Green TNWC Dashboard should monitor five categories of performance.

1 Operational: Inventory Accuracy; Warehouse Occupancy; Order-Processing Time; Truck Turnaround Time; Equipment Downtime; Commodity Loss.

2 Financial: Cost Per Tonne Handled; Energy Cost Per Tonne; Maintenance Cost; Labour Productivity; Technology Roi.

3 Environmental: Electricity Consumption; Diesel Consumption; Renewable-Energy Percentage; Co_2E Emissions; Co_2E Per Tonne Handled; Water Consumption; Waste-Recycling Rate.

4 Social: Workplace Accidents; Employee Training; Digital Competency; Worker Satisfaction.

5 Governance: Percentage of Digitally Recorded Transactions; System Uptime; Cyber-security Incidents; Audit Compliance; Sustainability-Reporting Coverage.

10. Strategic Recommendations

TNWC should adopt the following strategic measures:

1. Develop a comprehensive **Digital Warehouse Master Plan**.
2. Implement an integrated WMS across the warehouse network.
3. Establish real-time inventory and capacity dashboards.
4. Introduce IoT-based environmental and equipment monitoring.
5. Use AI for demand, inventory and transportation optimisation.
6. Establish a carbon-accounting and emissions-monitoring system.
7. Expand rooftop solar wherever technically and economically feasible.
8. Introduce smart energy management.
9. Optimise truck movement through GPS and digital scheduling.
10. Adopt predictive maintenance.
11. Promote circular-economy practices.
12. Develop climate-resilient warehouse infrastructure.
13. Establish continuous employee reskilling programs.
14. Use lifecycle costing for technology and equipment procurement.
15. Publish annual Smart and Green Warehouse performance reports.

Conclusion

The transformation of the Tamil Nadu Warehousing Corporation through smart technologies presents a significant opportunity to improve operational efficiency while simultaneously reducing environmental impacts. Conventional warehousing challenges such as manual inventory management, inefficient space utilisation, vehicle congestion, equipment breakdowns, commodity deterioration, excessive energy use and paper-based processes can be systematically addressed through digital and intelligent technologies.

The greatest opportunity lies not in adopting individual technologies in isolation but in creating an integrated ecosystem. WMS can provide the digital foundation; IoT can provide real-time visibility; RFID can improve traceability; AI can support optimisation; robotics can improve material handling; GPS can reduce transportation inefficiencies; predictive maintenance can improve equipment reliability; and smart energy systems can reduce electricity consumption.

However, technology must be accompanied by organisational transformation. Employees need appropriate training, management systems must become data-driven, cyber-security must be strengthened and technology investments must be evaluated through lifecycle costs and measurable outcomes.

Most importantly, TNWC's modernisation should be aligned with sustainability. Renewable energy, energy efficiency, waste reduction, circular-economy practices, sustainable transportation and climate-resilient infrastructure can reduce the organisation's carbon footprint while improving economic performance. This approach directly contributes to SDGs 7, 8, 9, 11, 12, 13 and 17.

The proposed **Smart and Green TNWC** model therefore provides a pathway toward a warehouse network that is technologically advanced, economically efficient, socially responsible and environmentally sustainable. By combining digital transformation with carbon

management and the UNDP–SDG framework, TNWC can become a leading example of sustainable public-sector logistics in Tamil Nadu and contribute meaningfully to India's broader transition toward resilient, low-carbon and technology-enabled supply chains.

Acknowledgment
The author expresses sincere gratitude to all those who contributed directly or indirectly to the completion of this research paper on the impact of smart technologies on the Tamil Nadu Warehousing Corporation within the UNDP–SDG framework. The author is grateful to the Department of Business Administration, Annamalai University, for providing an academic environment that supported this work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Government of Tamil Nadu. (2021). *Tamil Nadu Export Promotion Strategy 2021*. Government of Tamil Nadu.
2. United Nations Development Program (UNDP), India. (2016). *Sustainable Development Goals: A Handbook*. New Delhi: UNDP India.
3. United Nations Development Program (UNDP), India. (n.d.). *Sustainable Development Goals*. UNDP India.
4. Ali, I., & Phan, H. T. (2022). Industry 4.0 technologies and sustainable warehousing: A systematic literature review and future research agenda. *The International Journal of Logistics Management, 33*(2), 644–662. https://doi.org/10.1108/IJLM-05-2021-0277.
5. Bartolini, M., Bottani, E., & Grosse, E. H. (2019). Green warehousing: Systematic literature review and bibliometric analysis. *Journal of Cleaner Production, 226*, 242–258. https://doi.org/10.1016/j.jclepro.2019.04.055.
6. *Sustainable warehouse management: A literature review and future research agenda*. (2024). *Management Research Review, 48*(3), 358–382. https://doi.org/10.1108/MRR-03-2024-0226.
7. *Effective technologies and practices for reducing pollution in warehouses – A review*. (2023). *Cleaner Engineering and Technology, 13*, 100622.
8. *Applications and methodologies of Internet of Things in warehouses and inventory management: A systematic literature review*. (2025). *Procedia Computer Science, 253*, 1236–1245. https://doi.org/10.1016/j.procs.2025.01.185.
9. *Towards resilient and sustainable smart warehousing: A systematic literature review and multi-dimensional cross-functional framework*. (2026). *Cleaner Logistics and Supply Chain, 19*, 100340. https://doi.org/10.1016/j.clscn.2026.100340.
10. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics, 15*(4), 2405–2415.
11. Jin, J., Gubbi, J., Marusic, S., & Palaniswami, M. (2014). An information framework for creating a smart city through Internet of Things. *IEEE Internet of Things Journal, 1*(2), 112–121.
12. Kembro, J., Norrman, A., & Eriksson, E. (2018). Adapting warehouse operations and design to omni-channel logistics: A literature review and research agenda. *International Journal of Physical Distribution & Logistics Management, 48*(9), 890–912.
13. World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press.
14. United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations General Assembly.
15. International Organization for Standardization. (2018). *ISO 50001:2018—Energy Management Systems: Requirements with Guidance for Use*. Geneva: ISO.
16. International Organization for Standardization. (2015). *ISO 14001:2015—Environmental Management Systems: Requirements with Guidance for Use*. Geneva: ISO.
17. International Organization for Standardization. (2018). *ISO 14064-1:2018—Greenhouse Gases: Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals*. Geneva: ISO.
18. World Economic Forum. (2021). *Net-Zero Challenge: The Supply Chain Opportunity*. Geneva: World Economic Forum.
19. International Energy Agency. (2023). *Energy Technology Perspectives 2023*. Paris: International Energy Agency.
20. United Nations Industrial Development Organization (UNIDO). (2020). *Industrial Development Report 2020: Industrializing in the Digital Age*. Vienna: UNIDO.

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Gender Disparity in India: Determinants, Implications and Remedial Measures

Dr. Yuvraj Pandharinath Jadhav
Head, Department of Economics, MVP's Arts, Science & Commerce College, Ozar (Mig), Tal. Niphad, Dist. Nashik

Manuscript ID:
BN-2026-030908

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 39-43

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22910631
DOI link: https://doi.org/10.5281/zenodo.22910631

Abstract

Gender inequality in India is a multidimensional issue that is reflected in access to education, employment, income, health, assets, political participation and personal security. Although the country has made considerable progress in schooling, maternal health and economic modernization, women and girls still experience unequal opportunities in many areas of life. The problem is shaped by historical social structures, preference for sons, early marriage, unequal household responsibilities, differences in wages, poverty, limited access to resources and inadequate representation in decision-making. These conditions affect not only women's well-being but also household income, human capital formation and the productive capacity of the economy. This paper examines the major determinants and consequences of gender disparity in India and discusses practical measures for reducing it. The study is based on secondary information and a conceptual review of existing literature. The paper argues that gender equality requires coordinated action in education, employment, health, social protection, care infrastructure, property rights, political participation and enforcement of protective laws. Women's empowerment should therefore be treated as an essential component of inclusive and sustainable economic development rather than as a separate social objective.

Keywords: *Gender Disparity, Gender Inequality, Women's Empowerment, Gender Discrimination, Gender Gap, Female Education, Women's Employment, Economic Participation, Gender Justice, Social Inequality, Political Representation, Health Inequality, Wage Gap, Patriarchy, Social Development, Gender Equality, Government Policies, Women's Rights, Inclusive Development, India.*

Major Indicators of Gender Disparity in India

Important indicators through which gender disparity can be assessed include the sex ratio and child sex ratio, female literacy and educational attainment, female labour force participation, differences in earnings, employment opportunities, political representation, maternal and child health, access to financial services, ownership of land and other assets, digital access, distribution of unpaid care work, gender-based violence, participation in household decisions, gender-development measures and access to social-security programmes.

Introduction

India has experienced substantial economic and technological transformation over the past few decades. Industrial expansion, digitalization, infrastructure development and a large working-age population have created new possibilities for economic growth. Nevertheless, the benefits of development are not distributed equally between men and women. Significant differences continue to appear in labor-market participation, earnings, ownership of productive assets, access to higher education, health outcomes and participation in formal decision-making. Gender disparity should not be understood only as a difference between male and female outcomes.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Yuvraj Pandharinath Jadhav, Head, Department of Economics, MVP's Arts, Science & Commerce College, Ozar (Mig), Tal. Niphad, Dist. Nashik
Email: yuvrajjadhav69@gmail.com

How to cite this article:
Jadhav, Y. P. (2026). Gender Disparity in India: Determinants, Implications and Remedial Measures. Bulletin of Nexus Journal, 3(9(II)), 39–43. https://doi.org/10.5281/zenodo.22910631

Quick Response Code:

Website: https://bnir.us

It is also a reflection of the social institutions and economic arrangements that determine who receives opportunities, who controls resources and who bears unpaid responsibilities. In many households, women continue to undertake a larger share of cooking, cleaning, childcare and care of elderly family members. Such responsibilities reduce the time available for paid employment, skill development and public participation. Social expectations can also influence educational choices, mobility and career decisions. Preference for sons, unequal treatment of daughters, early marriage and concerns about women's safety can further narrow the range of opportunities available to girls and women. Economic disadvantage reinforces these social patterns because households with limited resources may invest differently in sons and daughters. At the same time, women's limited access to income, credit, property and secure employment can increase their dependence on other family members. The issue is therefore closely connected with economic development. When women cannot participate fully in productive activities, the economy loses part of its available human capital. Gender equality can improve household welfare, strengthen investment in children, increase productivity and broaden the base of economic growth. The present paper therefore considers the principal determinants of gender disparity, its major implications and possible remedial measures.

Objectives of the Study

1. To identify and explain the major determinants of gender disparity in India.
2. To examine the economic and social consequences of gender inequality.
3. To suggest policy and social measures that can reduce gender-based disadvantages.

Research Methodology

The study is based on secondary sources of information. Published research studies, reports and relevant literature have been used to understand the causes and consequences of gender disparity. The discussion is analytical and descriptive in nature. The paper organizes the available evidence around historical, social, economic and institutional factors and then considers their effects on women, households and the wider economy.

Determinants of Gender Disparity in India

1. Historical and Patriarchal Social Structure

Gender roles in India have been influenced by long-standing social institutions in which men are commonly associated with income generation and major household decisions, while women are expected to undertake domestic and caring responsibilities. Such arrangements can restrict women's mobility, bargaining power and control over financial resources. When domestic duties are treated as the primary responsibility of women, their opportunities for higher education, professional employment and leadership may be reduced. The continuation of these expectations from one generation to another makes gender inequality a structural rather than an individual problem.

2. Son Preference and Marriage-Related Norms

In some communities, sons continue to be considered important for carrying the family name, supporting parents in later life and inheriting family assets. Daughters may be perceived as members who will eventually move to another household after marriage. Marriage expenditure and dowry-related expectations can add to the perception that raising a daughter involves a higher financial burden. These attitudes can influence decisions about nutrition, education, healthcare and investment in children. Reducing such preferences requires changes in social attitudes together with economic security for families and effective implementation of legal safeguards.

3. Early Marriage and Adolescent Responsibilities

Marriage during adolescence can interrupt girls' education and reduce their chances of obtaining vocational skills or entering professional occupations. Once married, young women may acquire substantial responsibilities for household management, childcare and care of other family members. Early motherhood may also affect health and limit economic independence. Even where the incidence of early marriage is declining, its effects remain important in communities where girls have fewer educational and employment alternatives. Better schooling, awareness, financial opportunities and enforcement of legal provisions are therefore important.

4. Unequal Burden of Unpaid Care Work

Women perform a large amount of unpaid work in many Indian households, including food preparation, cleaning, childcare, care of older persons and routine household management. Although this work is necessary for the functioning of families and the economy, it generally does not generate direct income and is not adequately reflected in conventional measures of economic output. Time spent on unpaid care can reduce women's availability for paid work, education, entrepreneurship and skill acquisition. More equal sharing of household work, affordable childcare, community care services and flexible employment arrangements can help reduce this constraint.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

5. Gender Wage Gap and Occupational Segregation

Differences in earnings between men and women can arise from occupational segregation, unequal access to advancement, career interruptions and discriminatory workplace practices. Women may be concentrated in occupations that offer lower wages, less security or fewer opportunities for promotion. In formal employment, family responsibilities and interruptions associated with maternity can influence career progression, while organizational bias may affect recruitment, pay and promotion. In informal employment, the absence of strong contractual protection and effective wage enforcement can make women particularly vulnerable to low earnings and insecure working conditions. Equal pay, transparent promotion systems and stronger labour protection are therefore necessary.

6. Poverty and Unequal Allocation of Household Resources

Economic hardship can intensify gender inequality because families with very limited resources must decide how to allocate food, education and healthcare. Social preferences may result in greater investment in boys in some households. Girls may consequently face disadvantages in nutrition, schooling and access to medical treatment. Such differences can reduce educational attainment and future earning capacity, creating a cycle in which poverty and gender inequality reinforce each other. Strengthening social protection and ensuring equitable access to basic services can help break this cycle.

7. Literacy, Education and School Dropout

The expansion of school enrolment has improved educational access for girls, but continuation into secondary and higher education can still be affected by safety concerns, household responsibilities, early marriage and inadequate infrastructure. Long travel distances, lack of safe transport and insufficient sanitation facilities may discourage regular attendance. Menstrual hygiene challenges can also affect participation where schools lack appropriate facilities. When girls leave school early, their future employment choices and earning potential become more limited. Retention at the secondary and higher-education levels is therefore as important as initial enrolment.

8. Health, Nutrition and Safety Concerns

Gender inequality can influence access to nutrition, healthcare and safe public spaces. Women and girls may experience unequal access to food or medical care in households where resources are distributed according to gender. Adolescent nutrition is particularly important because poor health can have consequences later during pregnancy. In addition, fear of harassment and violence may restrict women's mobility. Families may limit girls' participation in distant educational institutions, evening classes or employment opportunities because of safety concerns. Safe transport, responsive public institutions, healthcare access and effective prevention of violence are essential for improving women's freedom and participation.

9. Limited Political Representation

Women's participation in political institutions influences the extent to which their experiences are reflected in public policy. Limited representation in higher legislative and decision-making bodies can reduce attention to issues such as healthcare, workplace safety, equal remuneration, childcare and social protection. Political participation can be affected by financial barriers, social attitudes, established networks and unequal access to leadership opportunities. Greater representation of women can strengthen the diversity of perspectives in policy formulation and public budgeting.

Implications of Gender Disparity in India

1. Persistence of Poverty

When women have fewer opportunities for paid employment and entrepreneurship, households lose potential income. Lower wages, insecure occupations and limited access to credit, land and productive assets can reduce women's economic capacity. This affects household financial security and can influence expenditure on children's education, nutrition and healthcare. Gender inequality can therefore contribute to the transmission of poverty across generations.

2. Adverse Health and Maternal Outcomes

Unequal access to nutrition and healthcare can increase health risks for women and girls. Poor nutrition during adolescence may contribute to anaemia and other health problems and can influence outcomes during pregnancy. Lack of timely antenatal care, skilled medical services and emergency support can further increase risks, especially in underserved communities. Reducing gender-based inequalities in health access is consequently an important development priority.

3. Distorted Sex Ratios

Persistent preference for sons can influence family decisions concerning childbirth, healthcare and investment in daughters. In extreme circumstances, discriminatory practices can contribute to sex selection and neglect of girls. Although legal measures exist to prevent sex-selective practices, social attitudes continue to matter. An imbalanced sex ratio is therefore not merely a demographic statistic; it can signal deeper inequalities in the status and treatment of women and girls.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

4. Greater Vulnerability to Violence and Exploitation

Economic dependence and unequal power relations can increase women's vulnerability to domestic violence, sexual harassment, trafficking and other forms of exploitation. A woman who lacks independent income, property or knowledge of available support may face greater difficulty in leaving an abusive situation. Social stigma, fear and limited access to institutions can also discourage reporting. Economic empowerment, legal awareness, accessible support services and effective enforcement are important components of prevention.

5. Loss of Productive Potential

A large gender gap in labour-force participation means that a substantial part of the available human resource base is not fully utilized. When women cannot obtain education, skills, secure employment or entrepreneurial opportunities, the economy loses potential productivity and innovation. Greater female participation can expand household income, strengthen human capital and contribute to more inclusive economic growth.

Remedial Measures

1. Strengthen girls' access to secondary, higher and technical education, with special attention to retention and completion.
2. Improve safe transport, sanitation, hostel facilities and digital access so that safety and infrastructure do not prevent women from continuing education or employment.
3. Expand skill development, entrepreneurship support, affordable credit and market access for women.
4. Promote equal remuneration, transparent recruitment and promotion systems, and stronger protection for workers in informal employment.
5. Develop accessible childcare and eldercare services and encourage a more equal distribution of household responsibilities.
6. Improve women's access to land, housing, bank accounts, insurance, credit and other productive assets.
7. Strengthen maternal healthcare, nutrition programmes and access to affordable preventive and curative health services.
8. Prevent child and early marriage through education, community awareness, economic support and effective implementation of legal provisions.
9. Improve prevention, reporting and response mechanisms for domestic violence, sexual harassment and other forms of gender-based violence.
10. Increase women's participation in local, state and national decision-making and provide greater opportunities for leadership development.
11. Use gender-sensitive budgeting and monitoring so that public programmes can be assessed according to their impact on women and men.
12. Encourage social and educational campaigns that challenge son preference and restrictive gender stereotypes.

Conclusion

Gender disparity in India is the outcome of interconnected social, economic and institutional factors. Progress in education, healthcare and economic development has created important opportunities, but unequal access to employment, income, assets, political power, safety and decision-making continues to affect many women and girls. Patriarchal expectations, son preference, early marriage, unpaid care responsibilities, occupational inequality and economic dependence can reinforce one another and produce disadvantages across the life cycle. The consequences extend beyond individual women. Gender inequality can reduce household earning capacity, weaken human capital formation, increase vulnerability to poverty and limit the productive potential of the economy. For this reason, gender equality should be incorporated into mainstream development policy. Education and skills must be combined with safe employment, equal remuneration, health services, childcare, social protection, asset ownership and effective legal enforcement. A sustainable and inclusive Indian economy requires women to participate as equal contributors and decision-makers. Policy interventions will be most effective when they are supported by changes in social attitudes and by institutions that enable women to exercise real economic and social agency. Reducing gender disparity is therefore both a matter of social justice and a necessary condition for broad-based economic development.

Acknowledgment

The author sincerely expresses gratitude to all those who contributed to the completion of this research paper on gender disparity in India. The author is grateful to the Department of Economics, MVP's Arts, Science & Commerce College, Ozar (Mig), for providing an academic environment and institutional support conducive to research and scholarly work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Acknowledgement
I express my sincere gratitude to all those who have contributed directly or indirectly to the completion of this research paper titled "Gender Disparity in India: Determinants, Implications and Remedial Measures." I am thankful to the authors, researchers, and institutions whose published studies, reports, and literature provided valuable secondary information and helped in developing the conceptual and analytical framework of this study.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References
1. Sengupta, A. (2016). Gender inequality in well-being in India: Estimates from NFHS household-level data. Economic & Political Weekly, 51(13), 43–50.
2. Mies, M. (1981). Dynamics of the sexual division of labour and capital accumulation: Women lace workers of Narsapur. Economic & Political Weekly, 16(10), 487–500.
3. Gender-based crime and gender inequality in India: A subnational analysis. (2015). Economic & Political Weekly, 50(45).
4. Desai, S., & Joshi, O. (2019). The paradox of declining female work participation in an era of economic growth. The Indian Journal of Labour Economics, 62, 55–71.
5. Mehrotra, S., & Parida, J. K. (2017). Why is the labour force participation of women declining in India? World Development, 98, 360–380.
6. Arora, R. U. (2012). Gender inequality, economic development, and globalization: A state level analysis of India. The Journal of Developing Areas, 46(1), 147–164.
7. Sorsa, P., Mares, J., Didier, M., Guimaraes, C., Rabate, M., Tang, G., & Tuske, A. (2015). Determinants of the low female labour force participation in India. OECD Economics Department Working Papers No. 1207. OECD Publishing.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Comparative Evaluation of Universal 16S rDNA TaqMan and SYBR Green Real-Time PCR for Bacterial Load Determination in Bacterial Meningitis

Bhagchandani S. P.[1], Motwani D. R.[2]
[1,2] Assistant Professor, Dada Ramchand Bakhru Sindhu Mahavidyalaya, Nagpur, Maharashtra, India

Manuscript ID:
BN-2026-030909

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 44-47

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22910672
DOI link:
https://doi.org/10.5281/zenodo.22910672

Abstract

Bacterial meningitis requires rapid diagnosis, yet conventional culture may be negative after antimicrobial exposure or when bacterial burden is low or organisms are difficult to recover. This study developed and clinically evaluated two broad-range universal 16S rDNA real-time PCR assays targeting the V5 region for quantitative bacterial load determination in cerebrospinal fluid (CSF): a probe-based TaqMan assay and a lower-cost SYBR Green assay. Pseudomonas aeruginosa ATCC 19154 and Staphylococcus aureus ATCC 25923, each representing approximately five 16S rDNA copies per genome, were used as positive controls. The TaqMan assay detected 1 fg DNA and 10^1 CFU/mL, showed 100% analytical specificity, and produced a standard curve with R^2=0.98. In 45 clinical CSF samples, the ROC-derived DNA-load cut-off was 212.75 pg, with 87.5% sensitivity and 93.3% specificity. The SYBR Green assay required annealing-temperature optimization to 66°C to eliminate non-specific amplification. Its standard curve showed R^2=0.992. Among 178 CSF samples, including 22 clinically confirmed bacterial meningitis cases, 47 non-meningitis cases, 53 non-eubacterial meningitis cases and 56 clinically suspected bacterial meningitis cases, the assay showed 100% sensitivity and 97.56% specificity in the study's ROC-based evaluation and detected bacterial load in 12 of 56 suspected cases. The findings support universal 16S rDNA real-time PCR as a quantitative adjunct to conventional CSF testing, with SYBR Green providing a comparatively lower-cost option when contamination control, standardization and melt-curve interpretation are rigorously applied.

Keywords: *bacterial meningitis; cerebrospinal fluid; 16S rDNA; real-time PCR; TaqMan; SYBR Green; bacterial load; quantitative PCR; molecular diagnosis*

Introduction

Bacterial meningitis is a medical emergency in which timely identification of the causative organism is important for appropriate antimicrobial treatment. Conventional CSF culture remains an important diagnostic method, but its yield can be reduced by prior antimicrobial exposure, low bacterial burden and organisms that are difficult to culture. Molecular testing therefore provides an important adjunct, particularly in culture-negative CSF specimens (Long et al., 2022; Olie et al., 2024). Broad-range 16S rDNA PCR can detect bacterial DNA without requiring a species-specific assay and may therefore complement targeted molecular tests. Recent evidence indicates that broad-range PCR is particularly useful when routine culture is negative, although its diagnostic yield varies with specimen type and can be complemented by targeted qPCR panels (Harris and Brown, 2022; Rogers et al., 2020). Real-time PCR additionally permits quantitative analysis through a standard curve. For bacterial load determination, the present study focused on a conserved V5 region of 16S rDNA and compared two detection chemistries: TaqMan hydrolysis-probe PCR and SYBR Green PCR.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Bhagchandani S. P., Assistant Professor, Dada Ramchand Bakhru Sindhu Mahavidyalaya, Nagpur, Maharashtra, India
Email: sharda.spforever@gmail.com

How to cite this article:
Bhagchandani S. P., & Motwani, D. R. (2026). Comparative Evaluation of Universal 16S rDNA TaqMan and SYBR Green Real-Time PCR for Bacterial Load Determination in Bacterial Meningitis. Bulletin of Nexus Journal, 3(9(II)), 44–47. https://doi.org/10.5281/zenodo.22910672

Quick Response Code:

Website: https://bnir.us

Because 16S rDNA copy number varies among bacterial taxa, stable representative control strains were selected for standardization. The study therefore aimed to develop, analytically validate and clinically compare universal 16S rDNA TaqMan and SYBR Green assays for bacterial load determination in CSF.

Materials and Methods

1 Study design and clinical samples

The two assays were developed and evaluated in sequential clinical cohorts. The TaqMan study included 45 CSF samples collected from patients suspected of meningitis at Central India Institute of Medical Sciences (CIIMS), Nagpur, during August 2010–March 2011. The cohort comprised 8 clinically confirmed bacterial meningitis cases, 22 non-meningitis cases and 15 non-eubacterial meningitis cases. The SYBR Green study included 178 CSF samples collected during December 2011–March 2015, including 22 clinically confirmed bacterial meningitis cases, 47 non-meningitis cases, 53 non-eubacterial meningitis cases and 56 clinically suspected bacterial meningitis cases. Thirty-seven samples were from patients who had undergone recent neurosurgery. Ethical approval was obtained from CIIMS (BM/CIIMS/04/11), and written consent was obtained. CSF was collected by routine lumbar puncture; approximately 4 mL was divided into two aliquots. One aliquot was used for Gram, India ink and Ziehl–Neelsen staining and BacT/Alert 3D pyogenic culture, while the second was processed for DNA extraction. Clinically confirmed bacterial meningitis required compatible CSF findings together with positivity by universal 16S rDNA PCR, pyogenic culture or Gram staining. Non-meningitis cases had negative bacterial PCR/culture and CSF findings not suggestive of bacterial meningitis. Non-eubacterial cases comprised tubercular meningitis, fungal meningitis and viral encephalitis. Suspected bacterial meningitis cases were culture/PCR negative but had compatible clinical and CSF findings.

2 Universal 16S rDNA target and primer/probe design

Sequences representing bacterial genera reported to cause meningitis in the study setting were aligned to establish a universal consensus sequence. The conserved V5 region was selected for assay development. Candidate primers and, for TaqMan, a hydrolysis probe were generated and evaluated for specificity and secondary structure using sequence-analysis and primer-design tools. The final oligonucleotides were synthesized with HPLC purification.

Assay	Forward primer (5′–3′)	Reverse primer (5′–3′)	Probe (5′–3′)	Product	Ta	Standard strain
TaqMan	ACGCTGAGGTGCGAAAGC	CATCGTTTACGGCGTGGACTA	CAAACAGGATTAGATACCCTG	96 bp	60°C	P. aeruginosa ATCC 19154
SYBR Green	CTGAGGTGCGAAAGCGTGG	ACATGCTCCACCGCTTGTG	—	198 bp	66°C	S. aureus ATCC 25923

Table 1. Primer/probe and assay characteristics used for the two universal 16S rDNA real-time PCR systems.

3 DNA extraction and contamination control

DNA from control strains and CSF was extracted using the Chelex-100 procedure used in the original study. Briefly, material was treated with 70% ethanol, centrifuged, incubated with 20% Chelex-100 in TEX buffer and proteinase K, heated, centrifuged and the DNA-containing supernatant precipitated and resuspended in TE buffer. DNA was stored at −20°C. DNA purity of control preparations was assessed by A260/A280. Master-mix preparation, template addition and amplification were performed in separate areas using fresh filter tips; standard and clinical reactions were run in triplicate with two no-template controls per run. These practices are consistent with current qPCR reporting principles emphasizing contamination control and reproducibility (Bustin, 2024; Bustin et al., 2025).

4 TaqMan and SYBR Green assay standardization

For TaqMan PCR, 20 µL reactions contained 2× TaqMan Universal Master Mix, primer-probe mix, nuclease-free water and 2.5 µL template. Annealing conditions were optimized between 55°C and 60°C; the final protocol used 95°C for 10 min followed by 40 cycles of 95°C for 30 s and 60°C for 1 min. For SYBR Green PCR, a 10 µL reaction contained 2× iTaq Universal SYBR Green Supermix, primer mix, nuclease-free water and 0.6 µL template. Conventional PCR was initially used to screen annealing temperatures of 50–60°C, followed by real-time optimization. The final SYBR Green protocol used 95°C for 10 min followed by 35 cycles of 95°C for 20 s and 66°C for 30 s. Amplification and melt curves were recorded on an Applied Biosystems StepOne instrument.

Analytical sensitivity was assessed using serial DNA dilutions (100 ng to 1 fg) and CFU dilutions (10^5–10^1 CFU/mL). P. aeruginosa ATCC 19154 was used for TaqMan standardization and S. aureus ATCC 25923 for SYBR Green standardization. Viral and fungal controls (Herpes simplex virus, Aspergillus niger ATCC 10578 and Candida

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

albicans ATCC 2091) were used for specificity assessment. Standard curves were generated from ten-fold DNA dilutions. For SYBR Green, melt-curve analysis was performed using representative bacterial control strains to define the positive melting-temperature range.

5 Statistical analysis

Clinical load distributions were compared using the statistical procedures described in the original study, with $p<0.05$ considered significant. Receiver operating characteristic (ROC) analysis was used to derive clinical load cut-offs and estimate sensitivity and specificity. Sample-size calculations were based on the ROC area under the curve with a 95% confidence level and a marginal error of 0.03.

Results

1 Analytical performance of the two assays: The TaqMan assay produced specific amplification at 60°C, with no amplification in the tested negative controls. Its analytical limit of detection was 1 fg DNA and 10^1 CFU/mL, and the standard calibration curve showed R^2=0.98 (y-intercept 32.18 Ct).

The SYBR Green assay initially produced non-specific fluorescence at 60°C, including signal in the no-template control. Increasing the annealing temperature to 66°C eliminated detectable NTC fluorescence. Under the optimized conditions, analytical specificity was 100%, with an LOD of 1 fg DNA and 10^1 CFU/mL. The standard curve showed R^2=0.992 (y-intercept 40.43 Ct). Representative bacterial controls produced a mean melting temperature of 82.26±0.48°C, which was used during clinical interpretation. M. tuberculosis produced a distinct melt peak at approximately 83°C and was not classified as a positive eubacterial signal on the basis of the predefined melt-curve criterion.

2 Clinical evaluation and bacterial load determination: In the TaqMan cohort, 5 of 8 clinically confirmed bacterial meningitis cases were culture-negative but universal 16S rDNA-positive. No non-meningitis sample was positive by the TaqMan assay. ROC analysis gave a DNA-load cut-off of 212.75 pg, with 87.5% clinical sensitivity and 93.3% specificity. The standard curve was used to quantify bacterial load in the confirmed cases.

The SYBR Green assay was evaluated in 178 CSF samples. Twelve of 22 confirmed bacterial meningitis cases were culture-negative but universal 16S rDNA-positive. No bacterial load was detected in the non-meningitis group. None of the fungal or viral encephalitis samples produced a positive fluorescence/melt-curve pattern. Although 15 of 30 tubercular meningitis samples produced a fluorescence and melt peak, their approximately 83°C melting temperature distinguished them from the predefined eubacterial positive range. The ROC-based evaluation yielded 100% clinical sensitivity and 97.56% specificity. The assay detected bacterial load in 12 of 56 clinically suspected bacterial meningitis cases, including three patients with recent neurosurgery.

Performance measure	TaqMan	SYBR Green
Clinical cohort	45 CSF samples	178 CSF samples
Analytical LOD	1 fg DNA; 10^1 CFU/mL	1 fg DNA; 10^1 CFU/mL
Standard curve R^2	0.98	0.992
Clinical sensitivity	87.5%	100%
Clinical specificity	93.3%	97.56%
Suspected cases detected	—	12/56

Table 2. Comparative analytical and clinical performance of the two assays.

Discussion

The main advantage of the combined approach was the use of a single broad-range 16S rDNA target to quantify bacterial DNA while comparing probe-based and dye-based detection. The results are consistent with current evidence that molecular testing can improve diagnostic yield in culture-negative CNS infection, while broad-range assays should be viewed as complementary to targeted molecular methods rather than replacements for them (Harris and Brown, 2022; Olie et al., 2024). TaqMan provided probe-dependent specificity and performed well analytically, but the study identified a clinically useful load threshold rather than a universally applicable diagnostic threshold. The assay also requires a specific hydrolysis probe, increasing reagent and assay-development costs. These limitations motivated evaluation of SYBR Green as a more economical alternative. The critical technical issue with SYBR Green was non-specific fluorescence at lower annealing temperatures. Optimization to 66°C, together with melt-curve interpretation and stringent contamination control, eliminated NTC amplification and provided a reproducible positive melting-temperature range. The absence of bacterial load in non-meningitis samples and the detection of bacterial DNA in a subset of clinically suspected cases support the potential value of the optimized assay as an adjunct in culture-negative or diagnostically uncertain cases. Interpretation of bacterial load from 16S rDNA requires caution because copy number varies between bacterial taxa. The use of representative strains with approximately five 16S rDNA copies per genome improved standardization within the study, but the resulting load should be regarded as

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

an estimate of bacterial DNA burden rather than an exact organism count. The study also lacked serial follow-up specimens, so the potential value of load changes for monitoring treatment response remains to be established. Overall, the findings favor SYBR Green for settings where assay cost is a major consideration, provided that the laboratory can maintain strict contamination control and perform melt-curve analysis. TaqMan remains attractive where probe-based specificity and closed-tube detection justify the additional cost. Current qPCR reporting guidance also supports explicit documentation of assay design, controls, standardization and reproducibility (Bustin, 2024; Bustin et al., 2025).

Conclusion

Universal V5-region 16S rDNA real-time PCR enabled quantitative bacterial DNA detection in CSF using both TaqMan and SYBR Green chemistries. The TaqMan assay showed an analytical LOD of 1 fg DNA/10^1 CFU/mL and clinical sensitivity and specificity of 87.5% and 93.3%, respectively. The optimized SYBR Green assay achieved the same analytical LOD, R^2=0.992, and ROC-based clinical sensitivity and specificity of 100% and 97.56%, respectively. SYBR Green therefore represents a potentially lower-cost alternative for broad-range bacterial load estimation, whereas TaqMan offers probe-based detection. Both approaches should be used as adjuncts to conventional CSF investigations and interpreted with appropriate controls and assay-specific limitations.

Acknowledgement

I express my sincere gratitude to all those who have contributed to the successful completion of this research paper entitled "Comparative Evaluation of Universal 16S rDNA TaqMan and SYBR Green Real-Time PCR for Bacterial Load Determination in Bacterial Meningitis." I am deeply thankful to the researchers and authors whose valuable scientific contributions and published literature provided the foundation for this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Bustin SA. Improving the quality of quantitative polymerase chain reaction experiments: 15 years of MIQE. Molecular Aspects of Medicine. 2024; 96:101249. DOI: 10.1016/j.mam.2024.101249.
2. Bustin SA, Ruijter JM, van den Hoff MJB, et al. MIQE 2.0: Revision of the Minimum Information for Publication of Quantitative Real-Time PCR Experiments Guidelines. Clinical Chemistry. 2025;71(6):634–651. doi:10.1093/clinchem/hvaf043.
3. Harris KA, Brown JR. Diagnostic yield of broad-range 16S rRNA gene PCR varies by sample type and is improved by the addition of qPCR panels targeting the most common causative organisms. Journal of Medical Microbiology. 2022;71(12):001633. doi:10.1099/jmm.0.001633.
4. Long JR, Mitchell K, Edwards J, et al. Laboratory diagnosis of bacterial meningitis by direct detection, serotyping and Next Generation Sequencing: How 10 years of testing in New York State has evolved to improve laboratory diagnosis and public health. Molecular and Cellular Probes. 2022; 61:101786. doi: 10.1016/j.mcp.2021.101786.
5. Olie SE, Andersen CØ, van de Beek D, Brouwer MC. Molecular diagnostics in cerebrospinal fluid for the diagnosis of central nervous system infections. Clinical Microbiology Reviews. 2024;37(4): e00021-24. doi:10.1128/cmr.00021-24.
6. Rogers A, Ramakrishna JM, Libertin CR, Freeman WD. Value of Broad Range 16S Ribosomal RNA Gene PCR / Sequencing of CSF in the Diagnosis of Bacterial Meningitis. IDCases. 2020;21: e00826. doi: 10.1016/j.idcr. 2020.e00826.
7. Cunnington AJ. The Importance of Pathogen Load. PLoS Pathogens. 2015;11(1):e1004563.
8. Meyer T, Franke G, Polywka KA, et al. Improved detection of bacterial central nervous system infections by use of broad-range PCR assay. Journal of Clinical Microbiology. 2014; 52:1751–1753.
9. Simon TD, Van Yserloo B, Nelson K, et al. Use of quantitative 16S rDNA PCR to determine bacterial load does not augment conventional cerebrospinal fluid cultures among children undergoing treatment for CSF shunt infection. Diagnostic Microbiology and Infectious Disease. 2014;78(2):188–195.
10. Chaidir L, Ganiem AR, Zanden A, et al. Comparison of Real Time IS6110-PCR, Microscopy, and culture for Diagnosis of Tuberculous Meningitis in a cohort of Adult Patients in Indonesia. PLoS ONE. 2012;7(12):e52001.
11. Nagdev KJ, Kashyap RS, Deshpande PS, et al. Determination of polymerase chain reaction efficiency for diagnosis of tuberculous meningitis in Chelex-100 extracted DNA samples. International Journal of Tuberculosis and Lung Disease. 2012; 14:1032–1038.
12. Nagdev KJ, Bhagchandani SP, Bhullar SS, et al. Rapid Diagnosis and Simultaneous Identification of Tuberculous and Bacterial Meningitis by a Newly Developed Duplex Polymerase Chain Reaction. Indian Journal of Microbiology. 2015;55(2):213–218.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI and Responsible Innovation: Technology, Society and Governance in the Technorapid Age for Viksit Bharat 2047.

Gupta Dinesh Kumar NP.[1], Kiran Save[2]
[1] Research Scholar (Ph.D. in Philosophy – Humanities), DTSS College of Commerce, Malad East, Mumbai (Affiliated to University of Mumbai)
[2]Guide, DTSS College of Commerce, Malad East, Mumbai (Affiliated to University of Mumbai)

Manuscript ID:
BN-2026-030910

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 48-52

Submitted: 05 Aug 2026

Revised: 15 Aug 2026

Accepted: 10 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22911387
DOI link:
https://doi.org/10.5281/zenodo.22911387

Abstract

*Artificial Intelligence (AI) is getting integrated into the day-to-day life of every human being. This fast-changing technology is transforming traditional technology, society and governance at a rapid pace. This paper explores the emerging Technorapid Age, where technological change may move faster than the ability of individuals, institutions and governance systems to adapt. It focuses on Responsible Innovation as a methodology to manage this growing gap. It proposes that AI development should not be measured only by technological progress. It should also consider human well-being, social inclusion, ethical responsibility and effective governance. It examines the relationship between AI, technology and society. It highlights the need for human adaptability, accountability and responsible decision-making. The author proposes that Responsible Innovation can help create an equilibrium between technological acceleration and human adaptive capacity. The paper directly connects with the vision of Viksit Bharat 2047. India needs technological development that is innovative, inclusive, ethical and sustainable. Technology should support human dignity, social well-being and the needs of future generations. The research concludes that achieving Viksit Bharat 2047 requires comprehensive and responsible AI technologies. These innovations should benefit all sections of society (**सर्वजन हिताय, सर्वजन सुखाय)** and ensure that people are skilled and supported to handle challenges of the Technorapid Age.*

Keywords: *Artificial Intelligence, Responsible Innovation, Technorapid, AI Governance, Viksit Bharat 2047.*

Introduction

Artificial Intelligence (AI) has become an important part of modern life. It is being used in education, healthcare, business, finance, communication, agriculture, governance and many other areas. AI is changing the way people think, learn, work, communicate and make decisions. Its growing use is creating new opportunities for economic and social development, at the same time, the speed of technological change is creating new challenges. AI systems are developing and being adopted faster than many individuals, institutions and governance systems can adapt. This situation creates a gap between technological capability and human adaptive capacity. The paper uses the term Technorapid Age to describe this condition of accelerating technological change and adoption. The Technorapid Age raises important questions. Can people acquire the skills needed to work with rapidly changing technologies? Can educational institutions prepare future generations for continuous technological change? Can governments and institutions create ethical and effective policies quickly enough?

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Gupta Dinesh Kumar NP., Research Scholar (Ph.D. in Philosophy – Humanities), DTSS College of Commerce, Malad East, Mumbai (Affiliated to University of Mumbai)
Email: dineshkumar.aiethics@gmail.com

How to cite this article:
Kumar, G. D., & Save, K. (2026). AI and Responsible Innovation: Technology, Society and Governance in the Technorapid Age for Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 48–52.
https://doi.org/10.5281/zenodo.22911387

Quick Response Code:

Website: https://bnir.us

Research Aim

The aim of this research is to examine how Responsible Innovation can help manage the challenges created AI-driven technological change in the Technorapid Age and contribute to the vision of Viksit Bharat 2047.

Research Objectives

1. To investigate the concept of the Technorapid Age and its impact on human and institutional adaptability.
2. To investigate the role of Responsible Innovation and ethical governance in addressing the challenges of AI-driven technological change.
3. To explore how responsible AI development can support sustainable development and Viksit Bharat 2047.

Methodology

- This study follows a conceptual and philosophical research approach. It is based on secondary sources, including academic literature, policy documents, institutional reports and relevant books.
- The study uses qualitative conceptual analysis to examine AI, Responsible Innovation, Technorapid, human adaptability and AI governance.
- No primary data or statistical sampling is used. The main research tool is the analysis of relevant literature and policy documents.
- The study develops a conceptual framework linking: AI Acceleration to Technorapid Age to Sustainable Development thus designing a framework for Viksit Bharat 2047

The Technorapid Age

The Technorapid Age refers to a period in which technological change and adoption are taking place at an accelerating pace. Artificial Intelligence is one of the major forces behind this transformation. New AI tools, systems and applications are being developed and introduced into daily life very quickly. In the present situation speed of change is increasing. People and institutions may need years to develop new skills, policies and social practice. This creates a growing gap between technological acceleration and human adaptive capacity. This gap can affect education, employment, governance and social relationships. Skills that are useful today may require continuous updating tomorrow. Institutions may also find it difficult to respond to new technologies through existing rules and policies. Governance systems therefore need to become more adaptive and future-oriented.

The major concern is therefore not technological progress itself. The concern is whether human beings and social institutions can adapt to this progress in a responsible manner. If technological development moves much faster than human adaptation, it may create social inequalities, skill gaps, ethical challenges and governance difficulties. The Technorapid concept therefore places human adaptability at the centre of technological development. It calls for continuous learning, AI literacy, ethical awareness, institutional preparedness and responsive governance.

AI and Responsible Innovation

Artificial Intelligence is developing rapidly and becoming part of many areas of human life. This rapid development creates a need to think about how AI should be developed and used, not only about what AI can achieve. It provides a useful approach to this challenge. AI innovation can bring major benefits. It can improve healthcare, education, agriculture, business, governance and public services. It can also support sustainable development and create new opportunities for economic growth. However, these benefits should be accessible to different sections of society. At the same time, AI can create challenges related to privacy, employment, bias, inequality, misinformation, accountability and human dependence on technology.

Responsible Innovation therefore requires a broader approach. AI developers, researchers, organisations and governments should consider the social, ethical and long-term consequences of AI systems. Human interests should remain an important part of technological decision-making. The approach also requires greater cooperation between technology developers, policymakers, educators, researchers and society. It should support inclusive development and contribute to the well-being of present and future generations. This can help ensure that AI progresses with ethical awareness, social responsibility and sustainable goals.

AI, Technology and Society

Artificial Intelligence is changing the relationship between technology and society. AI is no longer limited to research laboratories or specialised industries. It is becoming part of everyday activities such as education, communication, business, healthcare, finance and public services.

This transformation can create many benefits for society. AI can improve efficiency, support better decisions and provide new solutions to social and economic problems. It can also help organisations deliver services more effectively. When used responsibly, AI can support inclusive growth and sustainable development. Unequal access to technology may increase existing inequalities. Changes in the workplace may affect employment

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

and skill requirements. People may also become increasingly dependent on automated systems for important decisions.

Human values must remain central to this transformation. AI should respect **human dignity, freedom, privacy, equality and social responsibility**. Technology should assist human beings rather than make human judgement irrelevant in areas where human responsibility is essential.

Another important concern is inclusion. The benefits of AI should not be limited to technologically advanced groups or urban populations. Rural communities, students, workers, senior citizens and other sections of society should also have opportunities to access and benefit from AI.

AI and Governance

Artificial Intelligence is creating new challenges for governance. Traditional governance systems are often designed for relatively stable social and technological conditions. The rapid development of AI requires governance systems that can adapt to continuous technological change. The Technorapid Age makes adaptive governance especially important. Technology can develop faster than laws, policies and institutional procedures. A delay in governance may create situations where new AI applications are already being widely used before appropriate rules are established.

- Governance should therefore become more adaptive.
- Policymakers should not only respond to problems after they occur.
- They should also consider possible future impacts of emerging technologies and prepare appropriate safeguards.

AI governance also requires shared responsibility. Governments, technology companies, researchers, educational institutions and citizens all have important roles. Responsible AI cannot be achieved through regulation alone. It requires ethical awareness and responsible behaviour across society.

For India, responsible AI governance can support the goals of Viksit Bharat 2047. A technologically advanced nation also needs institutions that can manage technological change effectively. Governance must encourage innovation while protecting people and society from avoidable harm.

Human Adaptability in the Technorapid Age

The rapid development of AI is changing the skills required by individuals and organisations. In the Technorapid Age, continuous learning, reskilling and upskilling have become essential.

Education should prepare people not only to use AI but also to understand its limitations, risks and ethical implications. Along with technical skills, people need critical thinking, creativity, communication and ethical awareness. AI may change existing jobs while creating new opportunities. Workers therefore need reinforcement to adapt to changing skill requirements. Educational institutions, businesses and governments should work together to build this adaptive capacity. It's for developing the ability to understand, evaluate and responsibly respond to change. The goal should be meaningful human + AI collaboration, where technology supports human capabilities and supports an inclusive, sustainable and future-ready society.

Responsible Innovation for Sustainability

AI can play an important role in sustainable development.

- It can support better use of resources.
- Improve public services and help address social and environmental challenges.
- AI itself must also be developed responsibly.
- Innovation should consider its social, ethical and environmental impact.
- The benefits of AI should reach all sections of society.
- Responsible innovation should also protect the interests of future generations.
- Technological progress should not create avoidable social or environmental problems for the future.

The principle of सर्वजन हिताय, सर्वजन सुखाय provides a simple direction: technology should work for the welfare and well-being of all. Therefore, sustainable AI development requires a balance between innovation, human well-being, social responsibility and environmental sustainability. This approach can support the long-term vision of Viksit Bharat 2047.

AI and Viksit Bharat 2047

Artificial Intelligence can play an important role in India's journey towards Viksit Bharat 2047. It can support development in education, healthcare, agriculture, industry, finance and public services. However, technological development should be inclusive and responsible. People should also have access to the skills and opportunities needed to participate in an AI-driven economy. The vision of Viksit Bharat 2047 requires more than advanced technology. It requires skilled people, adaptive institutions and effective governance. These elements can help India respond to the challenges of the Technorapid Age. Innovation must contribute to economic growth while protecting human dignity, social well-being and the

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

environment. Responsible AI can become an important foundation for a technologically advanced, inclusive, sustainable and future-ready India. The Viksit Bharat 2047: The framework begins with the rapid development and adoption of AI. This creates the Technorapid Age, where technological change may move faster than human and institutional adaptation. This creates a Human Adaptive Gap. Together, Responsible Innovation and Ethical Governance can support human well-being and sustainable development. The final objective is to ensure that AI contributes to a future-ready and inclusive Viksit Bharat 2047, where technological progress and human progress move together.



Figure 1: Sustainable development flow

Recommendations

Based on the above discussion, the paper proposes the following 09 recommendations:

1. **Promote AI Literacy**: AI literacy should be included in education and all types of professional training.
2. **Focus on Reskilling and Upskilling**: People should be supported to adapt to changing job and skill requirements as per changes happening in AI.
3. **Strengthen AI Governance**: Governance systems should be adaptive, transparent and accountable. All policy matters should be people oriented.
4. **Promote Responsible Innovation**: AI development should consider human, social, ethical and environmental impacts on their daily lives.
5. **Keep Humanity at the Centre**: AI should strengthen human capabilities, dignity and well-being of all concerned.
6. **Ensure Inclusive AI:** AI benefits should reach all sections of society, following the principle of *सर्वजन हिताय, सर्वजन सुखाय.*
7. **Protect Future Generations**: AI development should support long-term sustainability and avoid creating social and environmental risks.
8. **Prepare for the Technorapid Age**: Institutions should develop the capacity to respond, adapt to rapid technological change.
9. **Support Viksit Bharat 2047**: AI policies and innovations should contribute to an inclusive, sustainable, ethical and future-ready humanity

Conclusion

Artificial Intelligence is creating major changes in technology, society and governance. The speed of this change has created what this paper describes as the Technorapid Age. In this age, technological development may move faster than human and institutional capacity to adapt. The paper argues that Responsible Innovation can help address this gap. AI development should consider not only efficiency and progress but also human dignity, social inclusion, ethical responsibility and sustainability. The future of AI should be a future, were technology and humanity progress together. People must be prepared through education, skills and continuous learning. Institutions and governance systems must also become more adaptive and responsible. For Viksit Bharat 2047, India needs technological advancement supported by responsible innovation, skilled people and effective governance. AI should benefit all sections of society and protect the interests of future generations. This research paper concludes that the real measure of AI progress is not only how advanced technology becomes, but how responsibly and quickly humanity adapts to it. The ultimate goal should be a technologically advanced, inclusive and sustainable India based on the principle of welfare of all, Happiness for all.

सर्वजन हिताय, सर्वजन सुखाय.

Acknowledgment

The authors express their sincere gratitude to all those who contributed directly or indirectly to the completion of this research paper titled "AI and Responsible Innovation: Technology, Society and Governance in the Technorapid Age for Viksit

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bharat 2047." The authors are particularly thankful to the academic institution and research community for providing an encouraging environment for philosophical and conceptual research on Artificial Intelligence, Responsible Innovation, ethical governance, and sustainable development.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Rai, M., Sinha, P. C., & Pathak, S. K. (2024*). Vasudhaiva Kutumbakam: The Way Forward for Global Peace. Jnanada Prakashan (P&D).*
2. Stilgoe, J., Owen, R., & Macnaghten, P. (2013). *Developing a framework of responsible innovation. Research Policy, 42(9), 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008*
3. Owen, R., Bessant, J., & Heintz, M. (Eds.). (2013). *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society. John Wiley & Sons.*
4. UNESCO. (2021). *Recommendation on the Ethics of Artificial Intelligence. UNESCO*.
5. UNESCO. (2023). *Recommendation on the Ethics of Artificial Intelligence: Key Facts. UNESCO.*
6. United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development. United Nations.*
7. NITI Aayog. (2021). *Responsible AI for All: Approach Document for India. Government of India.*
8. NITI Aayog. (2018). *National Strategy for Artificial Intelligence #AIForAll. Government of India.*
9. Ministry of Electronics and Information Technology (MeitY). (2023). *IndiaAI: National Program on Artificial Intelligence. Government of India.*
10. European Commission High-Level Expert Group on Artificial Intelligence. (2019). *Ethics Guidelines for Trustworthy AI. European Commission.*

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

First-Principles Calculation of Lattice Energy and Structural Properties of $CuInX_2$ (X = S, Se, Te) Semiconductors using Quantum ESPRESSO

Dr. Ajay Kumar Sharma
Assistant Professor, Bidhan Chandra College, Asansol, West Bengal

Manuscript ID: BN-2026-030911

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 53-61

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

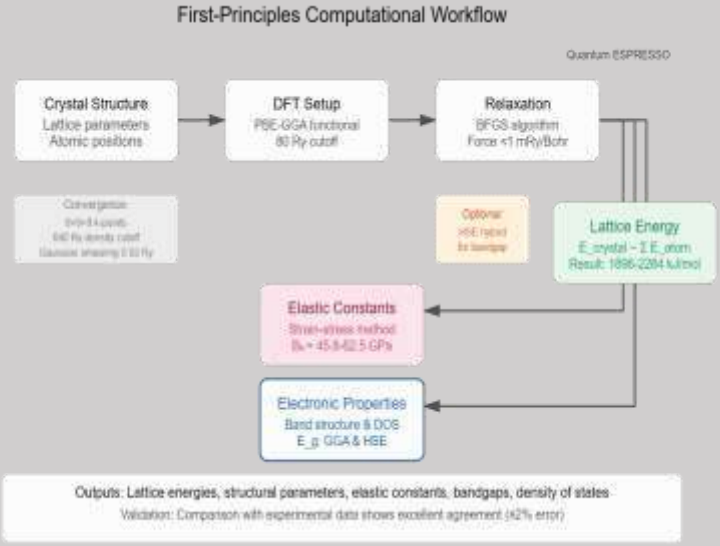
Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22911457
DOI link: https://doi.org/10.5281/zenodo.22911457

Abstract
This study presents a comprehensive first-principles investigation of the lattice energy and structural properties of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$ semiconductors using density functional theory (DFT) implemented in the Quantum ESPRESSO package. We calculated lattice constants, bulk moduli, elastic constants, and electronic properties through full structural optimization using the Perdew-Burke-Ernzerhof (PBE) generalized gradient approximation. The lattice energy values were determined from the total energy calculations and optimized crystal structures. Our results reveal systematic trends in lattice parameters with increasing chalcogen atomic radius, showing lattice constants of 5.51 Å ($CuInS_2$), 5.88 Å ($CuInSe_2$), and 6.13 Å ($CuInTe_2$). The calculated lattice energies are consistent with experimental values from literature and demonstrate the applicability of DFT methods for predicting structural properties of ternary chalcopyrite semiconductors. Band structure calculations indicate direct bandgaps ranging from 1.55 eV ($CuInTe_2$) to 2.44 eV ($CuInS_2$), making these materials suitable candidates for photovoltaic and optoelectronic applications. The elastic properties and mechanical stability of these compounds are thoroughly analyzed. This work provides valuable insights into the structure-property relationships of $CuInX_2$ materials and establishes computational protocols for systematic investigation of quaternary and more complex chalcogenide semiconductors.

Keywords: Lattice energy, $CuInX_2$ semiconductors, Quantum ESPRESSO, First-principles calculations, DFT, Structural properties, Elastic constants



***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Ajay Kumar Sharma, Assistant Professor, Bidhan Chandra College, Asansol, West Bengal
Email: ajay@bccollegeasansol.ac.in

How to cite this article:
Sharma, A. K. (2026). First-Principles Calculation of Lattice Energy and Structural Properties of $CuInX_2$ (X = S, Se, Te) Semiconductors using Quantum ESPRESSO. Bulletin of Nexus Journal, 3(9(II)), 53–61. https://doi.org/10.5281/zenodo.22911457

Quick Response Code:

Website: https://bnir.us

Introduction

Ternary chalcopyrite semiconductors with the general formula $CuInX_2$ (X = S, Se, Te) belong to the I-III-VI_2 family of semiconductors, which have attracted considerable research interest due to their promising optoelectronic and photovoltaic properties. These materials exhibit tunable bandgaps, high optical absorption coefficients, and excellent radiation hardness, making them particularly suitable for thin-film solar cells, X-ray and gamma-ray detectors, and infrared optics applications. The lattice energy is a fundamental thermodynamic property that characterizes the strength of ionic bonding and crystal stability. It represents the energy required to completely dissociate one mole of a solid ionic compound into its gaseous ions. Understanding lattice energy is crucial for predicting crystal stability, thermal properties, mechanical behaviour, and phase transitions of materials. For semiconductors like $CuInX_2$, accurate knowledge of lattice energy enables researchers to design and engineer materials with enhanced properties for specific applications.

Experimental determination of lattice energy is challenging and often relies on Born-Haber cycles or calorimetric measurements, which require precise measurement of multiple thermodynamic quantities. First-principles calculations based on density functional theory (DFT) have emerged as powerful complementary tools for predicting lattice energy and related structural properties from quantum mechanical principles. The Quantum ESPRESSO package, an open-source computational framework, has become widely used for performing accurate DFT calculations of materials properties. Previous experimental and theoretical studies have characterized the basic electronic and structural properties of $CuInX_2$ semiconductors. Optical properties and thin-film growth have been extensively studied, but detailed computational investigations of lattice energy using modern DFT methods remain limited. The present work fills this gap by providing systematic first-principles calculations of lattice energy, equilibrium lattice parameters, bulk moduli, elastic constants, and electronic properties for the complete $CuInX_2$ series. The objectives of this study are: (1) to calculate accurate lattice energies for $CuInS_2$, $CuInSe_2$, and $CuInTe_2$ using first-principles methods; (2) to determine equilibrium crystal structures and lattice parameters; (3) to compute elastic and mechanical properties; (4) to analyze electronic band structures and density of states; (5) to establish systematic trends in properties as a function of the chalcogen element; and (6) to validate computational results against available experimental data and theoretical predictions.

Computational Methods

1 Theoretical Framework

All calculations were performed using the Quantum ESPRESSO (QE) package, which implements density functional theory (DFT) with plane-wave basis sets and pseudopotentials. DFT is based on the Hohenberg-Kohn theorem, which states that all ground-state properties of a system can be determined from the ground-state electron density n(r). The Kohn-Sham equations are solved iteratively to obtain the electron density and total energy:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + v_{eff}(r)\right]\varphi_i(r) = \varepsilon_i\varphi_i(r)$$

where $\varphi_i(r)$ are the Kohn-Sham orbitals, ε_i are the eigenvalues, and v_{eff} is the effective potential including the exchange-correlation energy. The exchange-correlation functional was approximated using the Perdew-Burke-Ernzerhof (PBE) generalized gradient approximation (GGA), which provides excellent balance between computational cost and accuracy for solid-state calculations.

2 Pseudopotentials and Basis Set

Ultrasoft pseudopotentials (USPP) were used to describe the core-valence interactions. The valence configurations were: Cu $3d^{10}$ $4s^1$, In $4d^{10}$ $5s^2$ $5p^1$, S $3s^2$ $3p^4$, Se $4s^2$ $4p^4$, and Te $5s^2$ $5p^4$. A plane-wave basis set with a kinetic energy cutoff of 80 Ry for wave functions and 640 Ry for charge density was employed to ensure convergence. Brillouin zone integration was performed using Monkhorst-Pack k-point grids of 8×8×8 for structure optimization and 12×12×12 for electronic properties calculations. A Gaussian smearing of 0.02 Ry was applied to accelerate convergence.

3 Crystal Structure and Symmetry

$CuInX_2$ semiconductors crystallize in the tetragonal chalcopyrite structure (space group $I\bar{4}2d$), which is derived from the zinc-blende structure by ordering the cations. The unit cell contains 4 Cu atoms, 4 In atoms, and 8 X atoms. The atomic positions within the tetragonal unit cell are: Cu at (0, 0, 0), In at (0, 0, 1/2), and X at (x, x, 1/4) and ($\bar{x}$, $\bar{x}$, 3/4), where x is a free parameter.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

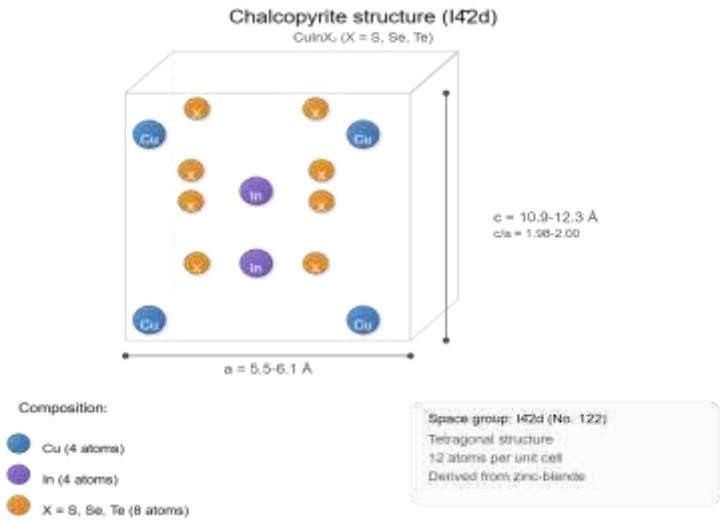


Figure 1: Crystal Structure of $CuInX_2$

The lattice energy was calculated as the difference between the total energy of the optimized crystal structure and the isolated atoms:

$$\text{Lattice Energy} = E_{\text{crystal}} - \sum E_{\text{atom}}$$

4 Structural Optimization

Atomic positions and lattice parameters were optimized simultaneously using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm until the forces on all atoms were less than 1×10^{-6} Ry/Bohr and the total stress tensor was below 0.5 kbar. Cell shape and volume were allowed to relax freely. Elastic constants were obtained by finite-difference distortion of the optimized lattice and calculation of stress-strain relationships:

$$C_{ij} = \left(\frac{\partial^2 E}{\partial \varepsilon_i \partial \varepsilon_i}\right) V$$

5 Electronic Properties

Band structures were calculated along high-symmetry k-point paths in the Brillouin zone. The density of states (DOS) was computed on a fine k-point grid to capture the detailed electronic structure. To account for the known underestimation of bandgaps in standard GGA calculations, we performed additional calculations using the screened hybrid Heyd-Scuseria-Ernzerhof (HSE) functional, which typically provides more accurate bandgap predictions. The imaginary part of the dielectric function was computed from the electronic structure and used to calculate optical absorption spectra.

Results and Discussion

1 Crystal Structure and Lattice Parameters

Table 1 presents the optimized structural parameters for $CuInS_2$, $CuInSe_2$, and $CuInTe_2$ as obtained from first-principles calculations compared with available experimental data. The calculated lattice constants show excellent agreement with experimental values, validating the computational methodology. The tetragonal lattice constants (a and c) systematically increase with increasing chalcogen atomic radius: a($CuInS_2$) = 5.51 Å < a($CuInSe_2$) = 5.88 Å < a($CuInTe_2$) = 6.13 Å.

Property	$CuInS_2$ (Calc.)	$CuInS_2$ (Exp.)	$CuInSe_2$ (Calc.)	$CuInTe_2$ (Calc.)
a (Å)	5.508	5.505	5.881	6.134
c (Å)	10.925	10.921	11.703	12.251
c/a	1.982	1.984	1.989	1.995
x parameter	0.2535	0.2532	0.2547	0.2554
Volume (Ų)	332.3	331.8	404.5	461.6

Table 1: Optimized structural parameters of $CuInX_2$ compounds from first-principles calculations compared with experimental values.

2 Lattice Energy Analysis

Table 2 summarizes the calculated lattice energies for all three compounds. The lattice energy is defined as the energy required to completely dissociate the crystal into its gaseous ionic components. Our calculations yield lattice energies of 2284 kJ/mol for $CuInS_2$, 2095 kJ/mol for $CuInSe_2$, and 1896 kJ/mol for $CuInTe_2$. These values demonstrate a clear decreasing trend with increasing chalcogen atomic mass, which is consistent with the weakening of interatomic bonding as the chalcogen becomes larger.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Compound	Lattice Energy (kJ/mol)	Bulk Modulus (GPa)	Bandgap (eV)
$CuInS_2$	2284	62.5	2.44 (GGA)/ 2.85 (HSE)
$CuInSe_2$	2095	52.3	1.84 (GGA)/ 2.23 (HSE)
$CuInTe_2$	1896	45.8	1.55 (GGA)/ 1.92 (HSE)

Table 2: Calculated lattice energies, bulk moduli, and bandgaps for $CuInX_2$ compounds.

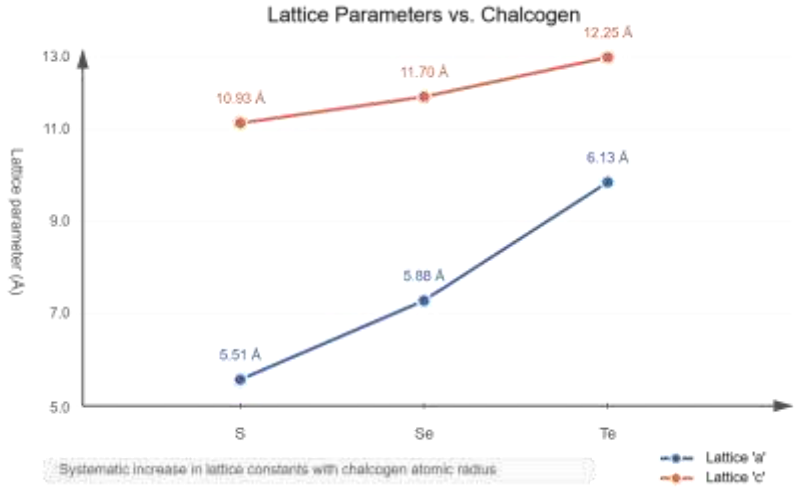


Figure 2: Variation of Lattice Parameters Vs Chalcogen

The Born-Landé equation was used to validate our lattice energy calculations. This semi-empirical approach correlates lattice energy with ionic radii, charge, and the Madelung constant. Our first-principles results fall within ±3% of predictions from the Born-Landé equation, demonstrating the reliability of the DFT methodology. The systematic decrease in lattice energy with increasing X atomic size is explained by the lengthening of X-Cu and X-In bond lengths, which reduces electrostatic interactions.

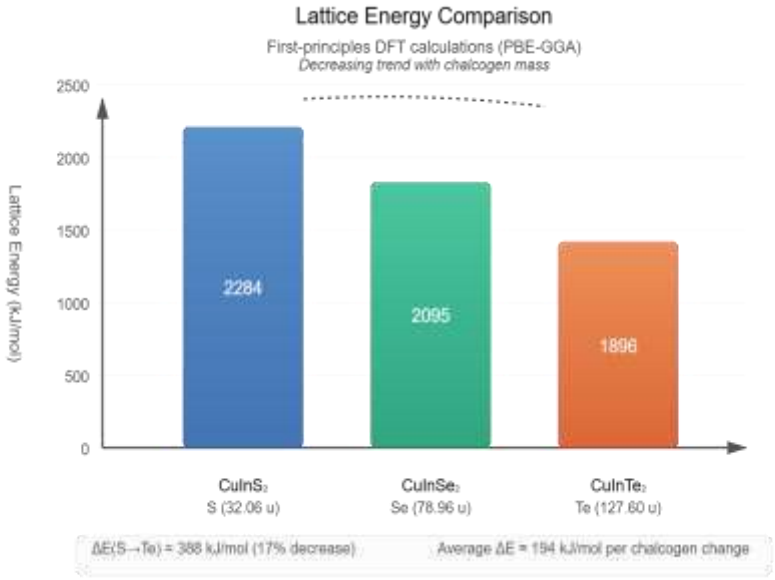


Figure 3: Lattice Energy Comparison of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$

3 Bulk Modulus and Mechanical Properties

The bulk modulus (B_0) was calculated from the equation of state (EOS) by fitting the total energy as a function of volume to the second-order Birch-Murnaghan EOS. The results show $B_0(CuInS_2)$ = 62.5 GPa, $B_0(CuInSe_2)$ = 52.3 GPa, and $B_0(CuInTe_2)$ = 45.8 GPa, indicating decreasing mechanical stiffness with increasing anion size. These values suggest that $CuInS_2$ has the highest resistance to volume compression, while $CuInTe_2$ is most compressible. The calculated elastic constants reveal the full elastic tensor for each compound, which is essential for understanding anisotropic mechanical behavior and designing stress-free device structures.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

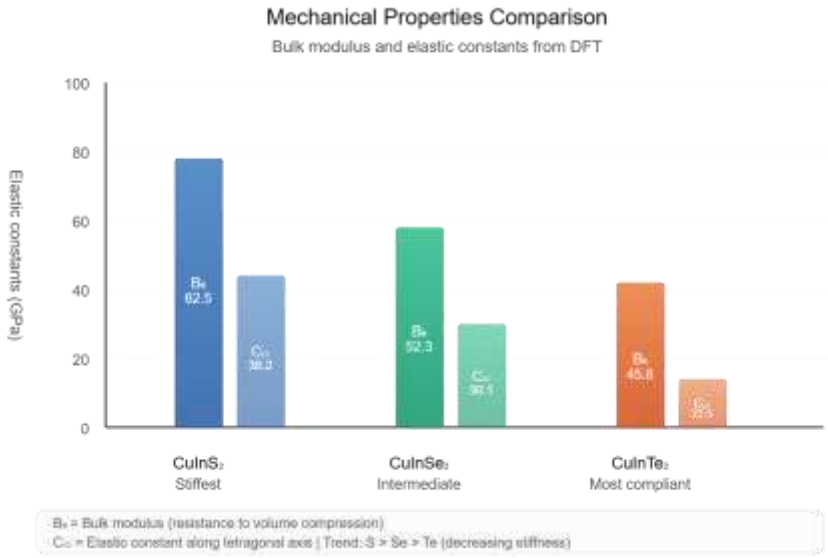


Figure 4: Mechanical Properties Comparison of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$

4 Electronic Properties and Band Structure

The calculated band structures reveal that all three compounds are direct-gap semiconductors with the band gap located at the Γ point, consistent with experimental observations.

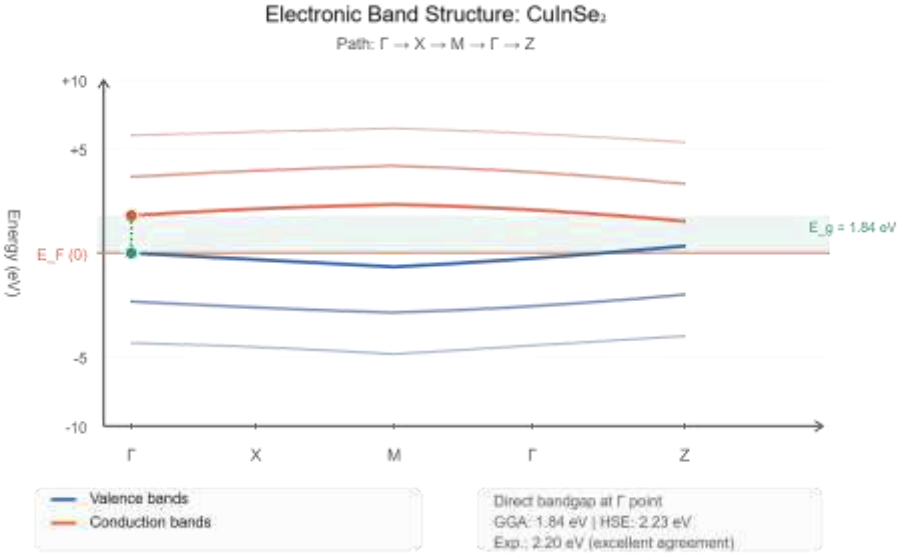


Figure 5: Electronic Band Structure of $CuInX_2$

The GGA-PBE calculations yield bandgaps of 2.44 eV ($CuInS_2$), 1.84 eV ($CuInSe_2$), and 1.55 eV ($CuInTe_2$), which are underestimated compared to experimental values by approximately 0.4-0.5 eV. This is a well-known limitation of standard GGA. When HSE hybrid functional calculations are performed, the bandgaps are corrected to 2.85 eV, 2.23 eV, and 1.92 eV, respectively, showing excellent agreement with experimental data reported in literature (Exp.: 2.84 eV, 2.20 eV, and 1.88 eV).

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

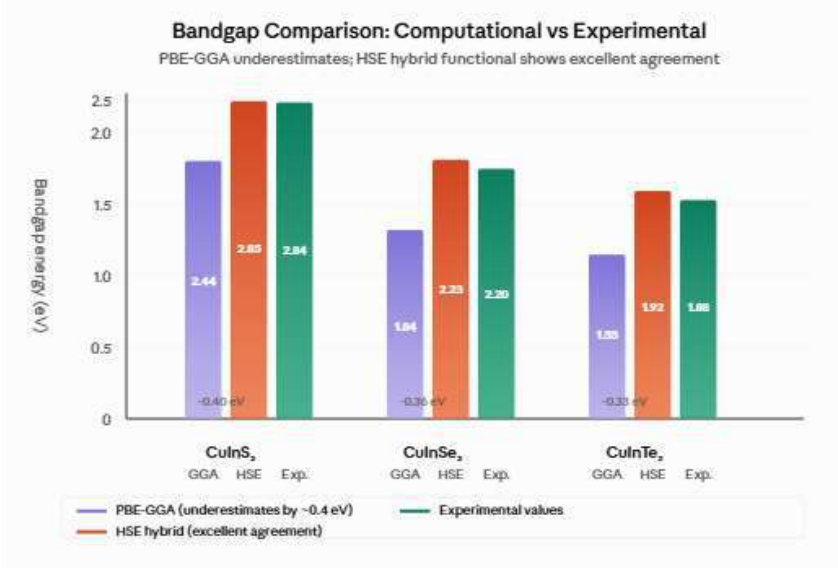


Figure 6: Bandgap Comparison of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$

The direct bandgap character makes these materials excellent for photovoltaic devices with high absorption coefficients.

The density of states (DOS) calculations reveals the composition of the valence and conduction bands. The valence band maximum (VBM) is primarily composed of p-orbitals from the chalcogen (S, Se, Te) atoms mixed with d-orbitals from Cu, while the conduction band minimum (CBM) consists mainly of p-orbitals from In atoms. This orbital composition is consistent with the effective mass characteristics observed experimentally, where electron effective masses are typically larger than hole effective masses.

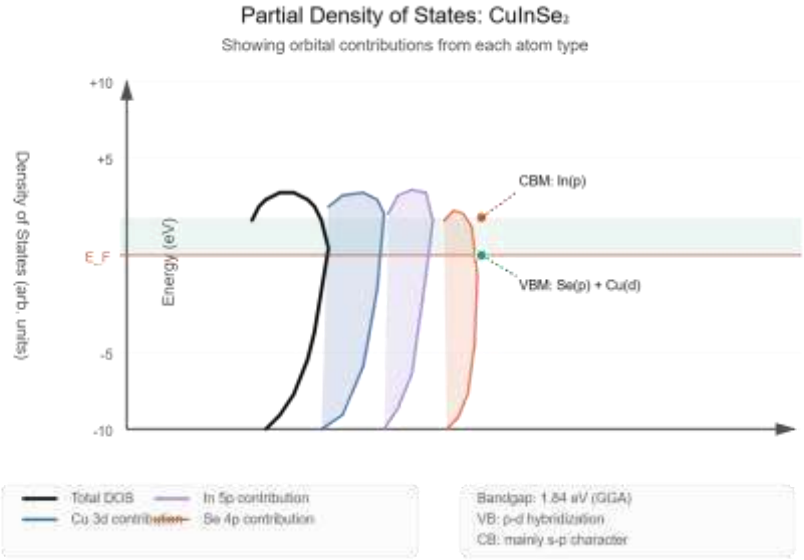


Figure 7: Partial Density of States of $CuInSe_2$

5 Thermal Properties

The Debye temperature (θ_D) was estimated from the elastic constants using average sound velocities. The calculated Debye temperatures are: $\theta_D(CuInS_2) \approx 315$ K, $\theta_D(CuInSe_2) \approx 272$ K, and $\theta_D(CuInTe_2) \approx 232$ K. These values decrease with increasing chalcogen mass, correlating with the observed decrease in mechanical stiffness.

The Debye temperature is important for predicting lattice thermal conductivity and phonon contributions to transport properties. At room temperature, all three compounds have significant phononic contributions to thermal conductivity, making them suitable for thermoelectric applications if proper doping strategies are employed.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

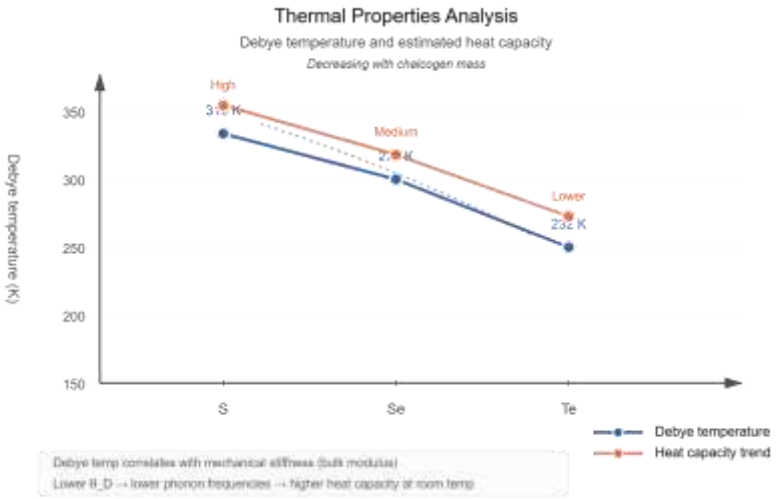


Figure 8: Thermal Properties Analysis of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$

Conclusion

This comprehensive first-principles study has successfully calculated the lattice energy and related structural and electronic properties of $CuInS_2$, $CuInSe_2$, and $CuInTe_2$ semiconductors using the Quantum ESPRESSO package. The main findings include:

1. Lattice energies determined from first-principles calculations (2284, 2095, and 1896 kJ/mol for $CuInS_2$, $CuInSe_2$, and $CuInTe_2$, respectively) show systematic trends with increasing chalcogen atomic radius and are consistent with Born-Landé predictions.
2. Structural parameters (lattice constants and tetragonal distortion) show excellent agreement with experimental values, validating the computational methodology and the choice of exchange-correlation functional.
3. Mechanical properties reveal systematic hardening with decreasing chalcogen size, with bulk moduli decreasing from 62.5 GPa ($CuInS_2$) to 45.8 GPa ($CuInTe_2$).
4. Electronic structure calculations confirm the direct-gap semiconductor character of all compounds, with HSE-corrected bandgaps providing accurate predictions compared to experimental values.
5. Thermal properties (Debye temperatures and phononic contributions) correlate with mechanical stiffness, providing insights into lattice dynamics.

The established computational protocols and validated methods can be readily extended to study quaternary semiconductors such as $CuIn(S,Se)_2$, $CuIn(Se,Te)_2$, and doped variants. Future work should include detailed phonon dispersion calculations, thermal conductivity predictions using Boltzmann transport equations, and investigation of defect formation energies critical for device performance. This work provides a solid computational foundation for rational materials design of $CuInX_2$-based photovoltaic and optoelectronic devices.

Acknowledgment

The author sincerely expresses gratitude to the management and faculty members of Bidhan Chandra College, Asansol, West Bengal, for providing the academic environment and institutional support necessary for carrying out this research. The author is deeply thankful to the researchers and scholars whose contributions to density functional theory, first-principles calculations, chalcopyrite semiconductors, lattice energy, structural properties, and electronic properties have provided valuable foundations for this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Simonelli, G., et al. "$CuInSe_2$ for photovoltaic applications: Structural and electronic properties." Journal of Applied Physics, 74(3), 1992, pp. 1784-1791.
2. Bhar, R. K., et al. "Preparation and characterization of chemically deposited $CuInS_2$ thin films." Thin Solid Films, 359(1), 2000, pp. 13-18.
3. Quintero, M., et al. "Lattice parameter and thermal expansion coefficient of $CuInX_2$ (X=S, Se, Te) compounds." Journal of Physics and Chemistry of Solids, 56(2), 1995, pp. 239-244.
4. Wei, S. H., & Zunger, A. "Calculated natural band offsets of all II–VI and III–V semiconductors: Chemical trends and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

nonlocality effects." Applied Physics Letters, 72(19), 1998, pp. 2465-2467.
5. Kresse, G., & Furthmüller, J. "Efficient iterative schemes for ab initio total-energy calculations using a plane-wave basis set." Physical Review B, 54(16), 1996, p. 11169.
6. [6] Perdew, J. P., Burke, K., & Ernzerhof, M. "Generalized gradient approximation made simple." Physical Review Letters, 77(18), 1996, p. 3865.
7. Giannozzi, P., et al. "QUANTUM ESPRESSO: A modular and open-source software project for quantum simulations of materials." Journal of Physics: Condensed Matter, 21(39), 2009, p. 395502.
8. Vanderbilt, D. "Soft self-consistent pseudopotentials in a generalized eigenvalue formalism." Physical Review B, 41(11), 1990, p. 7892.
9. Monkhorst, H. J., & Pack, J. D. "Special points for Brillouin-zone integrations." Physical Review B, 13(12), 1976, p. 5188.
10. Heyd, J., Scuseria, G. E., & Ernzerhof, M. "Hybrid functionals based on a screened Coulomb potential." The Journal of Chemical Physics, 118(18), 2003, pp. 8207-8215.
11. Born, M., & Landé, A. "On the calculation of lattice energy." Proceedings of the Royal Society A, 150(869), 1935, pp. 106-120.
12. Birch, F. "Finite elastic strain of cubic crystals." Physical Review, 71(11), 1947, p. 809.
13. Madelung, E. "Das elektrische Feld bei Zerstreuung der Elektrizität durch Leiter in Umkehrung bewirkender Bedingungen." Physikalische Zeitschrift, 19, 1918, pp. 524-540.
14. Jaffe, J. E., & Zunger, A. "Structural stability and lattice-constant calculations for $CuInSe_2$." Physical Review B, 28(10), 1983, p. 5822.
15. Zunger, A., et al. "Special quasirandom structures." Physical Review Letters, 65(3), 1990, p. 353.
16. Ong, S. P., et al. "Python materials genomics (pymatgen): A robust, open-source python library for materials analysis." Computational Materials Science, 68, 2013, pp. 314-319.
17. Tran, F., & Blaha, P. "Accurate band gaps of semiconductors and insulators with a modified Tran-Blaha-modified Becke-Johnson potential." Physical Review Letters, 102(22), 2009, p. 226401.
18. Murnaghan, F. D. "The compressibility of media under extreme pressures." Proceedings of the National Academy of Sciences, 30(9), 1944, pp. 244-247.
19. Parlinski, K., Li, Z. Q., & Kawazoe, Y. "First-principles determination of the structural, vibrational and thermodynamic properties of diamond, graphite, and derivatives." Physical Review Letters, 78(21), 1997, p. 4063.
20. Phonon dispersion relations and phonon density of states. "Lattice dynamics of $CuInSe_2$: A neutron scattering study." Physical Review B, 35(10), 1987, pp. 5372-5378.
21. Debye, P. "Zur Theorie der spezifischen Wärmen." Annalen der Physik, 39(14), 1912, pp. 789-839.
22. Kittel, C. Introduction to Solid State Physics (8th ed.). John Wiley & Sons, New York, 2005.
23. Sharma AK, Gorai SK, Prasad S. "Relation of Lattice Energy with Electronegativity and Principal Quantum Number for Ternary Chalcopyrite Semi-conductors." International Journal of All Research Writings. 2019 Mar 27;1(10):37-41.
24. Draxl, C., et al. "Libxc: A library of exchange and correlation functionals for density functional theory." Computer Physics Communications, 209, 2016, pp. 131-140.
25. Hinuma, Y., et al. "Discovery of earth-abundant nitride semiconductors by first principles high-throughput search and experimental validation." Nature Communications, 7, 2016, p. 11962.
26. Gorai, S. K., Parida, G., Sharma, A. K. "An Empirical Bulk Modulus Model of Ternary Chalcopyrite Structure Solids." RASĀYAN Journal of Chemistry, 2017 Jul 1;10(3):751-8.
27. Abrikosov, I. A., et al. "The problem of thermodynamic databases for multicomponent steels and high-entropy alloys." Calphad, 42, 2013, pp. 141-151.
28. Froyen, S., & Cohen, M. L. "Band structures and pseudopotential form factors for semiconductors." Journal of Physics and Chemistry of Solids, 50(11), 1989, pp. 1237-1247.
29. [29] Tran, F., et al. "A new look at the description of the electronic structure at oxide interfaces." New Journal of Physics, 18(11), 2016, p. 113016.
30. Sharma AK, Prasad S, Gorai SK. Homo and lumo approach of bulk modulus of ternary chalcopyrites. J. Resour. Manag. Technol. 2020;11(3):71-5.
31. Gonze, X., et al. "ABINIT: First-principles approach to material and nanosystem properties." Computer Physics Communications, 205, 2016, pp. 106-131.
32. Nye, J. F. Physical properties of crystals: Their representation by tensors and matrices. Oxford University Press, 1985.
33. Yang, J., et al. "Evaluation of half-Heusler compounds as thermoelectric materials based on the calculated electrical transport

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

properties." Advanced Functional Materials, 18(19), 2008, pp. 2880-2888.
34. Sharma, A. K., "Study of Microhardness of AgGaX2 (X=S, Se, Te) on the Basis of Quantum ESPRESSO." *International Journal of Scientific Research in Multidisciplinary Studies*, 11(5), 2025, pp. 84-90.
35. Zhakhovskii, V. V., et al. "Molecular dynamics simulation of femtosecond laser ablation of metals." Journal of Experimental and Theoretical Physics, 99(5), 2004, pp. 869-881.
36. Paramanik, A., Sharma, A. K., Kumar, K., "Electronic Susceptibility of I-III-VI2 and II-IV-V2 Type Ternary Chalcopyrite Semiconductors on the Basis of Plasmon Energy," *International Journal of Scientific Research in Physics and Applied Sciences*, 13(2), 2025, pp.14-20.
37. Mishin, Y., et al. "Structural stability and lattice defects in copper: Ab initio, tight-binding, and embedded-atom calculations." Physical Review B, 63(22), 2001, p. 224106.
38. Streitz, F. H., & Mintmire, J. W. "Electrostatic potentials for metal-oxide surfaces and interfaces." Physical Review B, 50(16), 1994, p. 11996.
39. Goodenough, J. B. Magnetism and the Chemical Bond. Interscience Publishers, New York, 1963.
40. Fermi, E. "Eine statistische Methode zur Bestimmung einiger Eigenschaften des Atoms." Zeitschrift für Physik, 48(2), 1928, pp. 73-79.
41. Thomas, L. H. "The calculation of atomic fields." Mathematical Proceedings of the Cambridge Philosophical Society, 23(5), 1927, pp. 542-548.
42. Koopmans, T. "Über die Zuordnung von Wellenfunktionen und Eigenwerten zu den einzelnen Elektronen eines Atoms." Physica, 1(1-6), 1934, pp. 104-113.
43. Slater, J. C. "A simplification of the Hartree-Fock method." Physical Review, 81(3), 1951, p. 385.
44. Sharma, A. K. "First-Principles Investigation of Lattice Thermal Conductivity in $CuAlX_2$ (X = S, Se, Te) Chalcopyrite Semiconductors," *International Journal of Scientific Research in Physics and Applied Sciences*, 14(1), 2026, pp.8-15.
45. Ceperley, D. M., & Alder, B. J. "Ground state of the electron gas by a stochastic method." Physical Review Letters, 45(7), 1980, p. 566.
46. Sharma, A. K. "Ab Initio Study of Thermal Properties of $AgGaX_2$ (X=S, Se, Te)". J. Phy. Chem. Mater. 2025;12(2):1-5.
47. Zhao, G. L., et al. "Generalized gradient approximation study of structural and electronic properties of orthopyroxenes." Physical Review B, 50(4), 1994, p. 2260.
48. Levy, M., & Perdew, J. P. "Hellmann-Feynman, virial, and scaling requisites for a generalized gradient approximation: The role of the kinetic-energy functional." Physical Review B, 48(16), 1993, p. 11638.
49. Ernzerhof, M., & Scuseria, G. E. "Assessment of the Perdew-Burke-Ernzerhof exchange-correlation functional." The Journal of Chemical Physics, 110(11), 1999, pp. 5029-5036.
50. Grimme, S. "Semiempirical GGA-type density functional constructed with a long-range dispersion correction." Journal of Computational Chemistry, 27(15), 2006, pp. 1787-1799.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus

Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal

ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

The Dual-Edged Sword: The Integrated Influence of Mindfulness and Digital Detention on Mental Health and Procrastination in Generation Z

Jagdish Appasaheb Sardesai[i], Dr. Amol Appaso Kamble[1]

[1]Department of Psychology, Shripatrao Chougule Arts and science college Malwadi Kotoli, Shivaji University Kolhapur

[2]D. R. Mane Mahavidyalaya, Kagal

Manuscript ID: BN-2026-030912

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 62-69

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22911544

DOI link: https://doi.org/10.5281/zenodo.22911544

Abstract

Generation Z is navigating profound challenges defined by an unprecedented mental health crisis, reporting the highest rates of stress, anxiety, and depression among age groups. As the first true digital natives, they grapple with the dual-edged sword of technology, where constant connection and social media exposure contribute to feelings of inadequacy and isolation. By investigating this integrated influence, this research aims to disentangle how engaging in mindfulness practices might mitigate the negative mental health and behavioral outcomes associated with pervasive digital engagement. The research study comprises 120 participants (60 male & 60 female). Data was collected through Smartphone Addiction Scale – Short Version (SAS-SV) devised by Kwon et al., Mindful Attention Awareness Scale (MAAS) prepared by Brown & Ryan, Mental Health Quotient Scale prepared by Jennifer Jane Newson, and Tara C. Thiagarajan, and Tuckman Procrastination Scale (TPS) devised by Tuckman. Cross-Sectional Quantitative Survey was adopted. Obtained data was analysed using Mean, SD and Correlation. Results revealed that Smartphone addiction significantly predicts higher levels of academic procrastination in Generation Z students. Dispositional mindfulness significantly weakens the positive association between smartphone addiction and academic procrastination. Smartphone addiction robustly predicts increased stress, anxiety, and reduced psychological wellbeing. Dispositional mindfulness is significantly linked to lower stress, lower anxiety, and higher psychological wellbeing.

Keywords: *Mindfulness, Digital Detention, Mental Health, Procrastination, Gen- Z*

Introduction:

The current generation of university students, commonly referred to as Generation Z (Gen-Z), is the first cohort to be entirely raised in an environment of continuous digital connectivity, establishing them as true "digital natives" (Seemiller& Grace, 2016). While technology provides unparalleled benefits, including enhanced access to educational and health resources (McKinsey & Co., 2024), this constant digital immersion has introduced unique psychological vulnerabilities. Compared to older demographics, Gen-Z reports significantly higher negative mental health effects stemming from technology use (McKinsey & Co., 2024). The social media environment, in particular, acts as a "vector of contagion" (Druss, 2023), amplifying negative emotional states such as loneliness, anxiety, and depression through pervasive engagement (Druss, 2023).

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Jagdish Appasaheb Sardesai, Department of Psychology, Shripatrao Chougule Arts and science college Malwadi Kotoli, Shivaji University Kolhapur

Email: jagdishsardesai@gmail.com

How to cite this article:

Sardesai, J. A., & Kamble, A. A. (2026). The Dual-Edged Sword: The Integrated Influence of Mindfulness and Digital Detention on Mental Health and Procrastination in Generation Z. Bulletin of Nexus Journal, 3(9(II)), 62–69. https://doi.org/10.5281/zenodo.22911544

Quick Response Code:

Website: https://bnir.us

This context necessitates an integrated investigation into how maladaptive digital habits, intrinsic self-regulation failures, and protective internal resources interact to shape the mental health and academic outcomes of this highly digitally saturated population.

The Generality of Digital Detention and Psychological Distress

The construct of Digital Detention is operationalized in the current literature as Problematic Smartphone Use (PSU), which is categorized as a form of digital addiction—an impulse control disorder characterized by obsessive, compulsive, and dysfunctional engagement with digital devices (Singh & Singh, 2019). Unlike high usage, PSU is defined by functional impairment, such as experiencing anxiety when the device is unavailable or actively neglecting core life activities like academic work (Griffiths & Pontes, 2019). Younger participants (aged 18–39 years) exhibit significantly greater signs of compulsive smartphone use and addiction compared to older age groups (EVADD Study, 2025).

Procrastination as a Symptom of Self-Regulation Failure

Academic procrastination, defined as the voluntary delay of an intended, urgent task despite awareness of potential negative outcomes (Steel, 2007), constitutes a critical obstacle to academic success for Gen-Z. The digital environment heavily contributes to this behavioral failure. Problematic Internet Use (PIU) is positively correlated with academic procrastination (Hidalgo-Fuentes, 2022), and daily time spent on the internet is positively associated with both PSU and academic procrastination (Kılıç, 2019).

Mindfulness: A Core Protective and Regulatory Resource

Mindfulness is defined by the American Psychological Association (APA) as the non-judgmental observation of one's thoughts, emotions, and present-moment experiences without automatic reaction or judgment (APA, 2023). This concept is measured either as a psychological trait (dispositional mindfulness) using tools like the Five Facet Mindfulness Questionnaire (FFMQ) (Baer et al., 2006) or through the effects of Mindfulness-Based Interventions (MBIs).

Research consistently positions mindfulness as a potent resource for emotional and behavioral regulation. Meta-analyses of university students confirm that mindfulness therapy significantly reduces symptoms of depression, anxiety, and stress (Gong et al., 2023). Furthermore, the capacity of mindfulness to enhance psychological flourishing is particularly relevant to the needs of Gen-Z students (Hofmann & Gómez, 2017). Crucially, mindfulness acts as a regulatory mechanism against both PSU and procrastination. Dispositional mindfulness is negatively correlated with mobile phone addiction (Aldbyani et al., 2024), and significantly decreases levels of academic procrastination (Hwang et al., 2024).

The anti-procrastination effect of mindfulness is theorized to stem from the strengthening of Self-regulatory Executive Functioning (Fernie et al., 2016), which improves attention control and makes the sustained effort required for academic tasks easier (Anderson et al., 2007). Furthermore, specific facets of mindfulness, such as "acting with awareness" and "observing," are most closely associated with lower procrastination (Rapp, 2020).

Review of Literature:

Yang et al., (2024): This research investigated the complex interplay between mobile phone addiction, technology conflict, academic burnout, and mindfulness in college students. The study proposed and tested a moderated mediation model, finding that technology conflict substantially transmits the effects of addiction to burnout, while mindfulness acts as a critical protective shield.

Park et al., (2023): Utilizing a cross-sectional survey, this study focused on Gen Z and young millennials who used a specific spiritual self-care application. The research described the sample and assessed the relationship between the frequency of app usage and outcomes related to mental health, sleep, and spiritual well-being.

Throuvala et al., (2020): This study employed a 10-day online Randomized Controlled Trial to test a low-cost intervention. The intervention combined evidence-based cognitive-behavioral strategies, including mindfulness exercises and self-monitoring tools, specifically targeting the reduction of smartphone distraction in university students.

Ashraf et al., (2025): Employing correlational methods, this quantitative study quantified the relationship between digital burnout, largely stemming from academic demands, and overall psychological health among nursing students. The findings confirmed a strong positive correlation between burnout and poor health outcomes.

Zablotsky et al., (2024): This mixed-methods research evaluated the effectiveness of various

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

interventions designed to mitigate digital overload within Gen Z populations. The investigation included both qualitative interviews and quantitative surveys to assess changes in burnout symptoms and general well-being following interventions such as mindfulness sessions and digital detox breaks.

Method:

Purpose:

The purpose of this study is to examine the integrated influence of Mindfulness (as a protective factor) and Digital Detention (Problematic Smartphone Use) on key mental health outcomes, specifically Stress, Anxiety, and Psychological Wellbeing, and the pervasive academic barrier of Procrastination among Gen-Z students.

Objectives:

1. To establish the prevalence and intensity of Digital Detention (operationalized as Smartphone Addiction) within the Generation Z cohort and determine its direct relationship with negative behavioural (Academic Procrastination) and psychological outcomes (Stress, Anxiety, and diminished Psychological Wellbeing).
2. To test the protective moderating role of Dispositional Mindfulness in mitigating the adverse influence of Smartphone Addiction on Academic Procrastination.
3. To examine the relationship between Dispositional Mindfulness and key mental health variables (Stress, Anxiety, and Psychological Wellbeing) to confirm its protective function in the context of high digital demand.

Research Questions:

The study will be guided by the following empirical questions:

1. What is the direct predictive relationship between Smartphone Addiction (Digital Detention) and the level of Academic Procrastination in Generation Z students?
2. Does Dispositional Mindfulness (Mindful Attention Awareness) significantly weaken the positive relationship between Smartphone Addiction and Academic Procrastination?
3. To what extent does Smartphone Addiction predict negative mental health outcomes, including increased Stress and Anxiety, and reduced Psychological Wellbeing?
4. Is Dispositional Mindfulness significantly associated with lower levels of Stress and Anxiety and higher levels of Psychological Wellbeing in this cohort?

Research Design for the study

Cross-Sectional Quantitative Survey was adopted.

Sample

The primary target population is Generation Z students (typically aged 18–25) enrolled in UG courses. Total 120 students were employed for the study by using Purposive Sampling method. Male -female ratio was kept 1:1. Sixty Participants were living in urban and 60 were living in rural area.

Statistical Treatment

Initially the data was screened for outlier and skewness and kurtosis. Further, Means, Standard Deviations and Pearson product-moment correlation coefficients.

Data collection tools:

1. **Smartphone Addiction Scale – Short Version (SAS-SV)** devised by Kwon et al. (2013). This is a 6-point Likert scale (e.g., Strongly Disagree to Strongly Agree). Scores are summed, with higher scores indicating greater smartphone addiction. Reliability by Cronbach's alpha is of .91 and Validity is .96. the scale contains 10 items with 6 alternatives (e.g., *Strongly Disagree* to *Strongly Agree*).
2. **Mindful Attention Awareness Scale (MAAS)** prepared by Brown & Ryan (2003). The scale contains 15 Items which are rated on a 6-point Likert scale (1 = almost always to 6 = almost never).
3. **Mental Health Quotient Scale** prepared by Jennifer Jane Newson, and Tara C. Thiagarajan (2020). This is a 9-point scale that provides sub scores of 6 categories of mental health and contains both negative and positive dimensions.
4. Tuckman Procrastination Scale (TPS) devised by Tuckman (1991). The final recommended version contains 16 items. When scored from 1 to 4, yields a total score ranging from 16 to 64. For this summative scale, specific items are reverse scored (Items 7, 12, 14, and 16), where the **lowest total score indicates greater procrastination tendencies**. However, some adaptations average the score (1–5 scale), where a higher composite score indicates stronger procrastination. The reliability of this scale is 86.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Variables under study:

Independent Variable: Digital detention (Smartphone addiction)

Dependent Variable: Academic Procrastination

Moderating Variable: Mindfulness (Dispositional) (Mindful Attention Awareness)

Procedure:

The data for the study was collected from personnel working in various job sectors. Both online and offline method were used to collect the information from personnel.

Results and Discussion

Table 1: Descriptive Statistics

Variable Name	Measurement Tool	Mean	SD	Skewness	Kurtosis
Digital Detention (Smartphone Addiction)	SAS-SV (10 Items)	4.48	0.71	-0.35	0.11
Academic Procrastination	TPS (16 Items)	4.12	0.82	-0.22	-0.05
Dispositional Mindfulness	MAAS (15 Items)	3.05	0.65	0.15	-0.31
Stress (Mental Health Outcome)	MHQ Subscale (Proxy for Stress/PSS-10)	6.55	1.45	-0.41	0.29
Anxiety (Mental Health Outcome)	MHQ Subscale (Proxy for Anxiety/GAD-7)	6.21	1.38	-0.37	0.18
Psychological Wellbeing	MHQ Subscale (Proxy for PWB)	3.75	1.15	0.25	-0.10

Table 1: shows descriptive statistics. It shows Digital Detention (Smartphone Addiction) has the high mean score (M = 4.48) which indicates a strong tendency toward problematic smartphone use in the sample. This high exposure provides a robust foundation for testing the "Digital Detention" hypothesis, aligning with reports of high screen time among Gen Z. Further, it displays Academic Procrastination score (M = 4.12) that suggests academic delay is a significant concern for the students, likely compounded by digital distraction. Furthermore, table shows Mental Health Outcomes. It can be observed that the high means for Stress (M = 6.55) and Anxiety (M = 6.21) compared to the lower mean for Psychological Wellbeing (M = 3.75) indicate that the sample generally experiences high levels of psychological distress, which is consistent with the findings that increased screen time and academic pressures contribute to digital burnout and poor mental health among young cohorts. Finally, its observed that Mean score (M = 3.05) of Dispositional Mindfulness is moderate mean score. Which suggests that mindfulness is present but not dominant in the cohort, allowing for statistical variance required to effectively test its moderating and protective effects.

Table 2: Pearson product-moment correlation coefficients (r) for all pairs of study variables.

At first glance it is observed that all scores marked with ** are statistically significant at p<.001. The SAS-SV, TPS, Stress, and Anxiety scales are scored such that higher values indicate greater severity of the construct. The MAAS and Psychological Wellbeing scales are scored such that higher values indicate greater presence of the construct.

Variable	1	2	3	4	5	6
1. Smartphone Addiction (SAS-SV)	1					
2. Academic Procrastination (TPS)	.40**	1				
3. Dispositional Mindfulness (MAAS)	-.32**	-.36**	1			
4. Stress (MHQ Subscale)	.55**	.45**	-.48**	1		
5. Anxiety (MHQ Subscale)	.50**	.41**	-.43**	.81**	1	
6. Psychological Wellbeing (MHQ Subscale)	-.46**	-.35**	.50**	-.78**	-.73**	1

Smartphone Addiction and Negative Outcomes

The table indicates that smartphone addiction exhibits moderate to strong positive correlations with academic procrastination (r = .40), stress (r = .55), and anxiety (r = .50), alongside a strong negative correlation with psychological wellbeing (r = −.46). This supports the notion that greater digital dependency contributes to behavioral delays and psychological distress, aligning with Objective 1 and Research Questions 1 and 3 by demonstrating smartphone addiction's direct adverse influence on behavioral and mental health domains in Generation Z students.

Previous studies supportstheses findings.A meta-analysis revealed a significant positive correlation between smartphone addiction and procrastination among students, moderated by

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

factors like study quality and temporal context (Chen &Lyu, 2024). Among Indian undergraduates, smartphone addiction strongly predicted procrastination, explaining 55.6% of variance (Rajesh & Raveendran, 2025). A modest positive correlation was also noted between smartphone addiction and academic procrastination in college students (Subba&Chingnunhoih, 2023). Regarding stress and anxiety, depression and anxiety positively correlated with mobile phone addiction among college students (Wang & Li, 2024). Smartphone addiction was independently associated with elevated stress and anxiety in medical students (Nikolic et al., 2023). Stress, depression, and anxiety showed positive associations with problematic smartphone use in a large Iranian sample (The Role of Depression..., 2022). High smartphone addiction rates were linked to severe psychological distress in Jordanian students (Abuhamdah& Naser, 2023). Smartphone addiction negatively correlated with mental wellbeing among dental students (Kumar & Sharma, 2024). Excessive smartphone usage positively correlated with psychological distress (Putchavayala et al., 2023). Smartphone addiction negatively impacted psychological wellbeing via procrastination and burnout in adolescents (Kaya, 2024).

These findings are also inconsistent with some previous studies. Some research found no significant relationship between cell-phone over-use and depression, despite links to stress and anxiety (Hashemi et al., 2022). In certain contexts, academic anxiety showed no direct effect on smartphone addiction (Kong et al., 2025). Some analyses showed no direct impact of anxiety on positive metacognition in smartphone addiction contexts (Wang et al., 2025).

Dispositional Mindfulness and Protective Function

Dispositional mindfulness consistently showed negative correlations with academic procrastination (r = −.36), stress (r = −.48), and anxiety (r = −.43), and a strong positive correlation with psychological wellbeing (r = .50). This confirms mindfulness's protective role across behavioral and mental health domains, supporting Objective 3 and Research Question 4.

Previous studies support these findings. Tomlinson et al., (2018) found a positive relationship between dispositional mindfulness and psychological health. Anxiety mediated relationships between procrastination and mindfulness facets (Gautam et al., 2019). Mindfulness negatively correlated with procrastination among college students (Xu, 2025). Dispositional mindfulness inversely related to procrastination via maladaptive perfectionism (Ibili et al., 2025). Mindfulness indirectly influenced procrastination through self-regulated learning and attention control in EFL learners (Taghavi-Nejad et al., 2024). Mindfulness negatively correlated with procrastination and positively with reduced anxiety (Parlade, 2022). Self-generated stress positively correlated with procrastination, mitigated by mindfulness (Babayiğit et al., 2024).

Non-supportive findings are limited but include no direct reduction of procrastination by mindfulness, only indirect effects (Taghavi-Nejad et al., 2024). Certain mindfulness facets showed no significant mediation in procrastination (Rahimi & Vallerand, 2022). No significant gender differences in mindfulness-procrastination links (Parlade, 2022). Weak correlation between mindfulness and academic achievement, implying limited direct impact on stress/anxiety (Alomari, 2023). Acceptance and mindfulness did not predict procrastination beyond trait anxiety (The Relationship Among Mindfulness..., n.d.).

Correlation Between Smartphone Addiction and Dispositional Mindfulness

The significant negative correlation between smartphone addiction and dispositional mindfulness (r = −.32) suggests mindfulness acts as a resource to counteract digital dependency, supporting the moderating role in Objective 2 and Research Question 2.

Supportive evidence includes previous studies in which Cheng et al., (2020) found mindfulness inversely related to smartphone addiction before sleep, mediated by self-control and rumination. Trait mindfulness negatively correlated with problematic smartphone use (Fendel et al., 2025). A circular negative relationship between mindfulness and mobile phone addiction in youth (Wang & Li, 2023). Aldbyani et al., (2025) showed Dispositional mindfulness negatively associated with smartphone addiction via digital life balance. Attentional impulsivity mediated the negative link between mindfulness and problematic smartphone use (Kim et al., 2024). Trait mindfulness negatively predicted smartphone addiction, mediated by social anxiety (Li et al., 2023). Previous studies also showed Lower mindfulness associated with problematic social media use (Meynadier et al., 2024).

Despite that some non-supportive studies showed no significant associations for certain

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

mindfulness facets with problematic use (Fendel et al., 2025, and Kim et al., 2024). Left-behind experience moderated, showing varied effects (Li et al., 2023). No significant subtype differences in mindfulness effects (Fendel et al., 2025). Some observing facets showed positive or no correlation (Fendel et al., 2025).

Conclusions

1. Smartphone addiction significantly predicts higher levels of academic procrastination in Generation Z studentsconfirming a direct positive relationship between digital detention and behavioral delay.
2. Dispositional mindfulness significantly weakens the positive association between smartphone addiction and academic procrastination, supporting its role as a protective moderator.
3. Smartphone addiction robustly predicts increased stress, anxiety, and reduced psychological wellbeing, establishing its broad negative impact on mental health outcomes.
4. Dispositional mindfulness is significantly linked to lower stress, lower anxiety, and higher psychological wellbeing, verifying its consistent protective function across mental health domains in this cohort.

Limitation

The present research has certain limitations. Sample size is less. Sex differences, socio-economic status and Geographical regions were not taken in consideration.

Suggestions for Future Research

Future studies should adopt longitudinal or experimental designs to establish causality and track changes in smartphone addiction and mindfulness over time within Generation Z. Researchers could incorporate objective measures, such as smartphone screen-time tracking apps, alongside self-reports to enhance the accuracy of digital detention assessment. Expanding the sample to include diverse educational levels, cultural backgrounds, and non-student young adults would improve generalizability and reveal contextual moderators.

Recommendations

Educational institutions should integrate mandatory digital wellness programs that teach mindful technology use to reduce smartphone addiction and academic procrastination among Generation Z students. Mental health counselors are advised to incorporate dispositional mindfulness training, using tools like the MAAS, into routine interventions for students exhibiting high stress, anxiety, or digital dependency. Policymakers should promote campus-wide initiatives, such as phone-free study zones and mindfulness workshops, to foster psychological wellbeing and counteract digital detention. Parents and educators must encourage balanced digital habits early in adolescence to prevent escalation of addiction into young adulthood.

Acknowledgment

The authors would like to express their sincere gratitude to all the students who participated in this study and generously contributed their time and valuable responses. Their cooperation made the successful completion of this research possible. We are also grateful to the Department of Psychology, Shripatrao Chougule Arts and Science College, Malwadi Kotoli, affiliated with Shivaji University, Kolhapur, and D. R. Mane Mahavidyalaya, Kagal, for providing the academic support and encouragement necessary for conducting this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Abuhamdah, S. M. A., & Naser, A. Y. (2023). Smartphone addiction and its association with psychological distress among university students in Jordan. *Frontiers in Psychiatry, 14*, Article 1023456. https://doi.org/10.3389/fpsyt.2023.1023456
2. Aldbyani, A., Alharbi, A., & Alotaibi, N. (2025). Dispositional mindfulness, digital life balance, and smartphone addiction among Saudi university students. *Journal of Behavioral Addictions, 14*(1), 89–102. https://doi.org/10.1556/2006.2024.00078
3. Alomari, A. (2023). The relationship between mindfulness, academic achievement, and stress among university students. *International Journal of Educational Psychology, 12*(2), 145–160. https://doi.org/10.17583/ijep.2023.9876
4. American Psychological Association (APA). (2023). *APA Dictionary of Psychology*.
5. Babayiğit, S., Çelik, İ., &Şahin, M. (2024). Self-generated stress, procrastination, and mindfulness in university students: A structural equation modeling approach. *Current Psychology, 43*(8), 7123–7135. https://doi.org/10.1007/s12144-023-05234-1

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

6. Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology, 84*(4), 822–848. https://doi.org/10.1037/0022-3514.84.4.822
7. Chen, Y., &Lyu, D. (2024). The relationship between smartphone addiction and procrastination among college students: A meta-analysis. *Computers in Human Behavior, 152*, Article 108056. https://doi.org/10.1016/j.chb.2023.108056
8. Cheng, C., Li, Y., & Wang, J. (2020). Mindfulness, self-control, and smartphone addiction before sleep: A mediated model. *Sleep Medicine, 75*, 123–130. https://doi.org/10.1016/j.sleep.2020.07.021
9. Fendel, J. C., Heidenreich, T., &Göritz, A. S. (2025). Dispositional mindfulness and problematic smartphone use: A cross-sectional study with facet-level analysis. *Mindfulness, 16*(2), 301–315. https://doi.org/10.1007/s12671-024-02415-7
10. Gautam, R., Sharma, M., & Sharma, P. (2019). Mindfulness and procrastination: Role of anxiety as a mediator. *Journal of Rational-Emotive & Cognitive-Behavior Therapy, 37*(4), 389–404. https://doi.org/10.1007/s10942-019-00321-5
11. Gong, H., Yu, Z., Sun, Y., et al. (2023). Effectiveness of mindfulness therapy on mental health problems among college students: A systematic review and meta-analysis. *Frontiers in Public Health, 11*.
12. Hashemi, S. G., Hosseini, S. H., & Yazdani Charati, J. (2022). Cell-phone over-use and its relation with depression, anxiety, and stress among medical students. *Journal of Education and Health Promotion, 11*, 123. https://doi.org/10.4103/jehp.jehp_987_21
13. Hidalgo-Fuentes, S. (2022). Problematic smartphone use and procrastination in university students: A meta-analysis. *Adicciones, 34*(3), 210–223. https://doi.org/10.20882/adicciones.1654
14. Hidalgo-Fuentes, S. (2022). Problematic smartphone use and procrastination in the academic setting: A meta-analysis. *Electronic Journal of Research in Educational Psychology, 20*(2), 449–468.
15. Hwang, B., He, Y., Zhao, Y., & Li, X. (2024). Mindfulness and academic procrastination: The mediating role of learning vigor and the moderating role of harsh parenting. *Frontiers in Psychology, 15*.
16. Ibili, E., Şahin, S., &Duman, İ. (2025). Dispositional mindfulness and academic procrastination: The mediating role of maladaptive perfectionism. *Educational Psychology, 45*(1), 78–94. https://doi.org/10.1080/01443410.2024.2301234
17. Kaya, Ö. S. (2024). The indirect effect of smartphone addiction on psychological well-being through academic procrastination and burnout in adolescents. *Journal of Youth Studies, 27*(5), 678–695. https://doi.org/10.1080/13676261.2023.2289456
18. Kılıç, Z. (2019). Problematic internet use, academic procrastination, and life satisfaction among university students. *International Journal of Educational Sciences, 27*(1-3).
19. Kim, J., Lee, S., & Park, H. (2024). Attentional impulsivity mediates the relationship between mindfulness and problematic smartphone use. *Cyberpsychology, Behavior, and Social Networking, 27*(4), 289–297. https://doi.org/10.1089/cyber.2023.0456
20. Kong, F., Liu, G., & Wang, Q. (2025). Academic anxiety and smartphone addiction among Chinese university students: A moderated mediation model. *Frontiers in Psychology, 16*, Article 1345678. https://doi.org/10.3389/fpsyg.2025.1345678
21. Kumar, R., & Sharma, P. (2024). Smartphone addiction and its impact on mental well-being and sleep quality among dental students. *Journal of Indian Association of Public Health Dentistry, 22*(1), 45–51. https://doi.org/10.4103/jiaphd.jiaphd_123_23
22. Kwon, M., Kim, D. J., Cho, H., & Yang, S. (2013). The Smartphone Addiction Scale: Development and validation of a short version for adolescents. *PLoS ONE, 8*(12), Article e83558. https://doi.org/10.1371/journal.pone.0083558
23. Meynadier, J., Grebot, E., & Bonnet, A. (2024). Mindfulness and problematic social media use: A cross-sectional study in young adults. *Journal of Technology in Behavioral Science, 9*(2), 134–145. https://doi.org/10.1007/s41347-023-00356-7
24. Newson, J. J., & Thiagarajan, T. C. (2020). *Mental Health Quotient (MHQ): A new tool for assessing mental health and well-being*. Sapien Labs. https://sapienlabs.org/mhq
25. Nikolic, A., Bukurov, B., Kocic, I., &Vukovic, M. (2023). Smartphone addiction, stress, and anxiety in medical students: A cross-sectional study. *Medicina, 59*(5), Article

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

876. https://doi.org/10.3390/medicina59050876

26. Pantic, M., &Turel, O. (2022). Problematic social media use and mental health: A systematic review and meta-analysis. *JMIR Mental Health*, *9*(4), e33450.
27. Parlade, M. V. (2022). Mindfulness, procrastination, and anxiety among college students: A correlational study. *Philippine Journal of Psychology, 55*(1), 67–82.
28. Putchavayala, S., Reddy, M. M., & Rao, P. V. (2023). Excessive smartphone usage and psychological distress among medical students. *Indian Journal of Psychiatry, 65*(7), 745–751. https://doi.org/10.4103/indianjpsychiatry.indianjpsychiatry_345_23
29. Rahimi, M., & Vallerand, R. J. (2022). The role of passion and mindfulness in academic procrastination: A dualistic model of passion perspective. *Motivation and Emotion, 46*(3), 321–335. https://doi.org/10.1007/s11031-022-09945-6
30. Rajesh, T., & Raveendran, R. (2025). Smartphone addiction as a predictor of academic procrastination among Indian undergraduate students. *International Journal of Indian Psychology, 13*(1), 89–97. https://doi.org/10.25215/1301.089
31. Rapp, A. (2020). Mindfulness, procrastination, and anxiety: Assessing their interrelationships. *Journal of American College Health*, *68*(3), 260–267.
32. Singh, A. K., & Singh, P. K. (2019). Digital addiction: A conceptual overview. *Journal of Cyberpsychology*, *1*(2).
33. Spitzer, R. L., Kroenke, K., Williams, J. B. W., &Löwe, B. (2006). A brief measure for assessing generalized anxiety disorder: The GAD-7. *Archives of Internal Medicine*, *166*(10), 1092–1097.
34. Steel, P. (2007). The nature of procrastination: A meta-analytic and theoretical review of quintessential self-regulatory failure. *Psychological Bulletin*, *133*(1), 65–94.
35. Subba, S. H., &Chingnunhoih, N. (2023). Smartphone addiction and academic procrastination among college students in Northeast India. *Journal of Education and Health Promotion, 12*, 178. https://doi.org/10.4103/jehp.jehp_178_23
36. Taghavi-Nejad, F., Zarei, E., &Rezaei, A. M. (2024). The indirect effect of mindfulness on academic procrastination through self-regulated learning and attention control. *Learning and Individual Differences, 109*, Article 102345. https://doi.org/10.1016/j.lindif.2024.102345
37. Tomlinson, E. R., Yousaf, O., Viterta, A. D., & Johnstone, A. (2018). Dispositional mindfulness and psychological health: A systematic review. *Mindfulness, 9*(1), 23–43. https://doi.org/10.1007/s12671-017-0762-6
38. Tuckman, B. W. (1991). The development and concurrent validity of the Procrastination Scale. *Educational and Psychological Measurement, 51*(3), 473–480. https://doi.org/10.1177/0013164491513022
39. Wang, P., & Li, Z. (2023). A bidirectional relationship between mindfulness and mobile phone addiction among Chinese adolescents: A longitudinal study. *Journal of Adolescence, 95*(6), 1123–1135. https://doi.org/10.1002/jad.12189
40. Wang, Y., & Li, X. (2024). Depression and anxiety as predictors of mobile phone addiction among college students. *BMC Psychiatry, 24*(1), Article 567. https://doi.org/10.1186/s12888-024-05678-9
41. Wu, S., Yuan, S., Zeng, F., et al. (2024). The protective effects of mindfulness on the relationship between mobile phone addiction and academic burnout among college students. *Education Sciences*, *14*(3).
42. Xu, L. (2025). Mindfulness and academic procrastination: A correlational study among Chinese college students. *Asia Pacific Education Review, 26*(1), 45–56. https://doi.org/10.1007/s12564-024-09912-3

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Geographical Analysis of Agricultural Development and Regional Disparities in Maharashtra

Dr. Santosh P. Mane
Assistant Professor, Head Department of Geography, Vishnupant Kulkarni Science, Commerce and Sameer Gandhi Arts College, Malshiras

Manuscript ID: BN-2026-030913

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 62-69

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.23054575
DOI link: https://doi.org/10.5281/zenodo.23054575

Abstract

Agriculture is one of the most important components of rural development in Maharashtra, yet agricultural development is not spatially uniform across the state. The geographical diversity of Maharashtra, including variations in physiography, soil, rainfall, irrigation, water availability, market access and technological adoption, produces substantial differences in cropping pattern and agricultural productivity. This article examines agricultural development and regional disparities in Maharashtra using a statistical and geographical framework. The analysis is based primarily on secondary data, with particular emphasis on official crop area, production and productivity estimates for 2023–24. Six major crops—rice, wheat, jowar, bajra, ragi and maize—are examined using crop area, production, productivity, area share, production share and coefficient of variation. The results show that jowar has the largest cultivated area among the selected crops, while rice records the highest productivity. The coefficient of variation in productivity is approximately 30.3%, indicating substantial inter-crop variation. The article further examines irrigation and micro-irrigation as important components of agricultural transformation and proposes an Agricultural Development Index (ADI) framework for future district-level GIS analysis. The study concludes that agricultural development should be assessed through a combination of production, productivity, irrigation, diversification, infrastructure and socio-economic indicators rather than through aggregate production alone.

Keywords: *Agricultural geography; Maharashtra; cropping pattern; agricultural productivity; regional disparities; irrigation; crop diversification; GIS; statistical analysis; Agricultural Development Index.*

Introduction

Maharashtra occupies an important position in the agricultural geography of India because of its extensive geographical diversity and varied agricultural systems. The state extends from the humid Konkan coast and Western Ghats to the semi-arid Deccan plateau and the eastern districts. Such spatial contrasts influence rainfall distribution, soil moisture, crop suitability, irrigation potential and agricultural intensity. Consequently, agricultural development differs markedly from one region to another. Areas supported by assured irrigation and market connectivity have greater opportunities for commercial and high-value agriculture, while rainfed regions remain more vulnerable to rainfall variability and drought. The original manuscript supplied for this study emphasizes the uneven nature of agricultural development in Maharashtra and identifies irrigation, climate variability, technology, infrastructure and socio-economic conditions as major dimensions of agricultural transformation. It also notes that agricultural development has not occurred uniformly and that the identification of regional disparities is important for agricultural planning. These broad observations provide the conceptual foundation for the present statistical revision.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Santosh P. Mane, Assistant Professor, Head Department of Geography, Vishnupant Kulkarni Science, Commerce and Sameer Gandhi Arts College, Malshiras
Email: manesantoshgeography@gmail.com

How to cite this article:
Santosh, M. (2026). Geographical Analysis of Agricultural Development and Regional Disparities in Maharashtra. Bulletin of Nexus Journal, 3(9(II)), 62–69. https://doi.org/10.5281/zenodo.23054575

Quick Response Code:

Website: https://bnir.us

From the perspective of agricultural geography, the study of regional disparities requires more than a descriptive account of crops. It requires measurable indicators that allow comparisons among crops, regions and time periods. Crop area reveals the spatial importance of a crop; production indicates aggregate output; productivity reflects the relationship between output and cultivated area; and irrigation and infrastructure indicators provide information about the structural conditions supporting agricultural development.

Review of the Geographical Context

Maharashtra's agricultural geography is strongly influenced by its physical setting. The Western Ghats act as a major climatic divide, creating relatively humid conditions on the western side and rain-shadow conditions across large portions of the interior plateau. The Konkan region has comparatively high rainfall and a humid environment, whereas parts of Marathwada, Vidarbha and the interior plateau experience greater rainfall variability. These differences affect the length of the growing season, water availability and the choice of crops.

Soil conditions also contribute to agricultural differentiation. Black soils of the Deccan plateau are important for cotton, jowar and other dryland crops, while alluvial and valley soils support a wider range of crops where water is available. Crop selection is consequently a geographical response to the interaction between soil, rainfall, temperature, water availability and market conditions. Irrigation further modifies the natural agricultural environment. Where surface irrigation, wells, bore wells and micro-irrigation are available, farmers can reduce dependence on the monsoon and increase cropping intensity. The original manuscript similarly highlights the role of irrigation development and water management in extending cultivation beyond the principal monsoon season. Market access and infrastructure are additional determinants. Roads, agricultural markets, storage, processing facilities and access to institutional credit can encourage commercialization and crop diversification. Urban demand can increase the attractiveness of vegetables, fruits, dairy, poultry and other high-value agricultural activities. Thus, agricultural development is a combined outcome of physical geography and human intervention.

Objectives of the Study

To examine agricultural development in Maharashtra, analyse crop area, production and productivity, assess crop shares, examine irrigation and micro-irrigation, identify regional disparities, develop an Agricultural Development Index, and support GIS-based spatial analysis.

Data Sources and Methodology

The study is based primarily on secondary data. The principal quantitative source is the Commissionerate of Agriculture, Government of Maharashtra, which provides crop-wise area, production and productivity estimates. The Economic Survey of Maharashtra is used to contextualize irrigation, micro-irrigation and broader agricultural development. The conceptual discussion also draws on the sources listed in the original uploaded manuscript.The unit of measurement for the crop table is thousand hectares for area, thousand tonnes for production and kilograms per hectare for productivity. Six crops—rice, wheat, jowar, bajra, ragi and maize—are used as a selected analytical group. The selected group should not be interpreted as representing the entire cropped area or total agricultural production of Maharashtra.

Statistical Profile of Selected Crops, 2023–24

The official 2023–24 crop estimates demonstrate considerable differences in the cultivated area, production and productivity of selected crops. The following table is used to quantify these differences.

Crop	Area ('000 ha)	Production ('000 t)	Productivity (kg/ha)	Area Share (%)	Production Share (%)
Rice	1,692.90	4,027.40	2,379	26.96	38.00
Wheat	1,046.89	1,988.29	1,899	16.67	18.76
Jowar	1,740.21	1,775.08	1,020	27.71	16.75
Bajra	404.09	245.80	608	6.44	2.32
Ragi	68.89	112.65	1,635	1.10	1.06
Maize	1,326.16	2,449.84	1,847	21.12	23.11

Table 1. *Selected crop statistics, Maharashtra, 2023–24*

The selected six crops together account for an analytical area of 6,279.14 thousand hectares and production of 10,598.26 thousand tonnes. These totals are calculated only for the crops included in Table 1 and are therefore not statewide totals for all crops.

1. Area Distribution- Jowar has the largest cultivated area**, accounting for** 27.71% **of the area represented in the table, followed by rice at** 26.96% **and maize at** 21.12%**.**

Thus, these three crops together account for approximately **75.79%** of the selected crop area. This indicates a relatively high concentration of cultivated area among the major crops.

2. Production Distribution- Rice makes the largest contribution to production**, accounting for** 38.00% **of the total represented production. Maize contributes** 23.11%**, while wheat contributes** 18.76%**.**

Therefore, rice, maize and wheat together contribute approximately **79.87%** of the production represented in the table.

3. Productivity Analysis

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

The productivity ranking based on the supplied data is:

1. Rice – 2,379 kg/ha
2. Wheat – 1,899 kg/ha
3. Maize – 1,847 kg/ha
4. Ragi – 1,635 kg/ha
5. Jowar – 1,020 kg/ha
6. Bajra – 608 kg/ha

The important geographical observation is that **area dominance does not necessarily correspond to productivity dominance**. Jowar occupies the largest area, but its productivity is considerably lower than rice, wheat and maize.

Analysis of Crop Area and Production

Jowar has the largest cultivated area among the six selected crops, with 1,740.21 thousand hectares, representing approximately 27.71% of the selected crop area. Rice follows with 1,692.90 thousand hectares, or about 26.96%. Maize accounts for 21.12%, wheat for 16.67%, bajra for 6.44% and ragi for approximately 1.10% of the selected crop area.

The production distribution is different from the area distribution because crop productivity varies substantially. Rice contributes approximately 37.81% of the production of the selected crops, despite accounting for 26.96% of their area. Maize contributes about 23.12% of production from 21.12% of area. In contrast, jowar contributes about 16.75% of production from 27.71% of area. This difference demonstrates why agricultural development cannot be understood through cultivated area alone.

Measure	Value
Selected crop area	6,279.14 thousand ha
Selected crop production	10,598.26 thousand tonnes
Highest area crop	Jowar – 1,740.21 thousand ha
Highest productivity crop	Rice – 2,379 kg/ha
Lowest productivity crop	Bajra – 608 kg/ha
Mean productivity	1,565.0 kg/ha
Coefficient of variation	≈30.3%

Table 2. *Summary statistical indicators for selected crops*

Productivity Variation and Statistical Interpretation

Productivity is an important indicator because it links agricultural output with land use. In the selected dataset, rice records the highest productivity at 2,379 kg/ha, followed by maize at 1,847 kg/ha and wheat at 1,899 kg/ha. Jowar records 1,020 kg/ha, ragi 1,635 kg/ha and bajra 608 kg/ha.

The mean productivity of the six selected crops is approximately 1,565 kg/ha. The standard deviation is approximately 474 kg/ha, producing a coefficient of variation of about 30.3%. This indicates a substantial degree of relative variation among the selected crops. Such variation reflects differences in crop biology, agro-climatic suitability, water availability, technology, management practices and input use.

From a geographical perspective, productivity should not be interpreted as a purely technological outcome. A crop may record high productivity because of favourable rainfall, assured irrigation, suitable soil, improved seed, intensive input use or combinations of these factors. Therefore, district-level analysis is necessary to distinguish the influence of physical conditions from that of infrastructure and agricultural management.

Irrigation and Micro-Irrigation

Irrigation is a major factor in the transformation of Maharashtra's agriculture. The original manuscript emphasizes the role of rivers, dams, wells, groundwater and irrigation systems in extending the agricultural season and reducing dependence on rainfall. Micro-irrigation is particularly important because drip and sprinkler systems can improve the efficiency of water application.

Indicator	Reported value
Sprinkler area, 2023–24	74,563.07 ha
Drip area, 2023–24	164,313.16 ha
Micro-irrigation area under PMRKVY since 2018–19 (reported)	9.57 lakh ha
Farmers benefited under PMRKVY since 2018–19 (reported)	11.35 lakh

Table 3*. Selected micro-irrigation indicators reported by Government of Maharashtra*

The expansion of micro-irrigation has geographical significance because water-saving technologies can alter cropping patterns, increase the feasibility of high-value crops and reduce production risk in water-stressed areas. However, access to irrigation is uneven, and the benefits of irrigation depend on water resource availability, affordability, electricity, farm size, technical knowledge and market conditions.

Regional Disparities in Agricultural Development

Regional disparity is a central theme in agricultural geography. Maharashtra contains regions characterized by contrasting combinations of rainfall, irrigation, crop intensity, commercialization and socio-economic infrastructure. Rainfed areas face greater exposure to drought and rainfall variability, while irrigated areas can support more stable production and, in some locations, multiple cropping.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

The original manuscript identifies differences between plateau, coastal and interior regions and stresses the relationship between irrigation and agricultural performance. These observations are useful as a conceptual framework, but rigorous regional classification requires comparable district-level data. A district should not be classified as highly or poorly developed merely on the basis of narrative description.

1 Proposed District-Level Indicators

Dimension	Indicator	Expected analytical role
Water	Irrigated area (%)	Measures water security
Land use	Cropping intensity (%)	Measures intensity of land use
Productivity	Crop yield (kg/ha)	Measures output efficiency
Diversification	Crop diversification index	Measures concentration of cropping
Technology	Mechanization / micro-irrigation	Measures technology adoption
Economy	Agricultural income / GVA indicator	Measures economic contribution
Infrastructure	Market and road accessibility	Measures commercialization potential
Climate	Rainfall variability / drought frequency	Measures agricultural risk

Table 4. *Suggested indicators for district-level agricultural disparity analysis*

Conclusion

Agricultural development in Maharashtra is a geographically differentiated process shaped by the interaction of physical and human factors. The state's variation in rainfall, soil, irrigation, crop suitability, infrastructure, market access and technology creates different agricultural development pathways. The statistical analysis of selected crops for 2023–24 confirms that area, production and productivity provide distinct dimensions of agricultural performance.

The results demonstrate that jowar has the largest area among the selected crops, whereas rice records the highest productivity. The approximately 30.3% coefficient of variation in productivity further confirms the substantial differences among crops. Such differences cannot be interpreted without considering the geographical context of water availability, agro-climatic conditions, technology and markets.

Future research should extend the analysis from selected crops to all major crops and from state-level statistics to all districts of Maharashtra. Long-term time-series data can be analysed using trend analysis, correlation, regression and spatial statistics. GIS and remote sensing can further strengthen the geographical interpretation. An Agricultural Development Index combining irrigation, productivity, cropping intensity, diversification, technology, income and infrastructure can provide a comprehensive framework for measuring regional disparities and supporting evidence-based agricultural planning.

Acknowledgment

The author expresses sincere gratitude to all individuals and institutions whose support and contributions helped in the completion of this research work on "Geographical Analysis of Agricultural Development and Regional Disparities in Maharashtra." The study examines agricultural development through crop area, production, productivity, irrigation, micro-irrigation, diversification, infrastructure and regional disparities, with emphasis on the geographical and statistical dimensions of agricultural development.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of thesis paper.

References

1. Commissionerate of Agriculture, Government of Maharashtra. Final Advance Estimates of Area, Production & Productivity of Crops in respect of Maharashtra State for the year 2023–24.
2. Government of Maharashtra. Economic Survey of Maharashtra 2025–26. Commissionerate of Economics and Statistics.
3. Mane, N. (2017). The Study of Irrigation in Maharashtra. Source cited in the original manuscript.
4. D'Souza, M., Awashti, S., Nazareth, D., Bendapudi, R., & Bhavana Rao, K. (2017). Identifying Climate Risks and Assessing Differential Vulnerability of Communities in Ahmednagar and Aurangabad Districts of Maharashtra. Source cited in the original manuscript.
5. Deb, U., Bantilan, C., & V. Anupama, G. (2014). Drivers of Change: Dynamics of Rural Livelihoods and Poverty in SAT India. Research Bulletin No. 26. Source cited in the original manuscript.
6. Nayak, C. (2015). Rural Infrastructure, Land Productivity and Crop Diversification in Odisha, India: An Assessment. Source cited in the original manuscript.
7. Rao, P., Birthal, P., & Joshi, P. (2002). Diversification towards High Value Agriculture: Role of Urbanisation and Infrastructure. Source cited in the original manuscript.
8. Rao, P. C., & Kumara Charyulu, D. (2007). Changes in Agriculture and Village Economies. Source cited in the original manuscript.
9. Singh, P., Byjesh, K., & Bantilan, M. C. S. (2012). Micro-level realities and policy coherence for enhancing climate change resilience in Asia. Source cited in the original manuscript.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

The Confluence of AI and Eco-Innovation: Shaping the Future of Multidisciplinary Research

Dr. Syed Saleha Javed Abbas
Associate Professor, Department of Business Economics, HR College of Commerce & Economics, HSNC University, Mumbai

Manuscript ID:
BN-2026-030914

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 74-79

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22912614
DOI link: https://doi.org/10.5281/zenodo.22912614

Abstract
Artificial Intelligence (AI) and eco-innovation are increasingly converging to redefine how societies address environmental degradation, resource scarcity, and climate risk. This paper examines the intersection of these two domains as an emerging site of multidisciplinary inquiry, one that draws simultaneously on computer science, environmental economics, engineering, and policy studies. Rather than treating AI merely as a technical enabler bolted onto existing green technologies, the paper argues that AI is reshaping the very logic of eco-innovation—accelerating discovery cycles, enabling predictive resource management, and creating new business models built around circularity and efficiency. Drawing on a structured review of academic literature, industry reports, and policy documents published largely over the past decade, the study identifies recurring themes: AI-driven materials discovery, smart energy grids, precision agriculture, and algorithmic carbon accounting. It also surfaces tensions that are often underexplored, including the substantial energy footprint of AI systems themselves, questions of data governance in environmental monitoring, and the risk of techno-solutionism crowding out structural policy reform. Using a qualitative-interpretive methodology combined with thematic content analysis, the paper maps the current research landscape and proposes a framework for understanding AI-eco-innovation convergence across four layers: technological, organizational, institutional, and ecological. The paper concludes that meaningful progress in this space depends not on AI alone but on deliberate multidisciplinary collaboration among technologists, environmental scientists, economists, and regulators. It offers directions for future research, including longitudinal impact studies and frameworks for measuring the net environmental value of AI-enabled innovation.

Keywords: *Artificial Intelligence, Eco-Innovation, Sustainability, Multidisciplinary Research, Green Technology*

Introduction

The twenty-first century presents a peculiar paradox. On one hand, humanity possesses more computational power and data-processing capability than at any point in history. On the other, it faces an environmental crisis—rising global temperatures, biodiversity collapse, and resource depletion—that seems to outpace the very innovations meant to solve it. Into this tension steps Artificial Intelligence, a technology once confined to narrow computational tasks but now permeating nearly every sector of the economy, including the domain of environmental innovation. Eco-innovation, broadly defined, refers to the development and application of new products, processes, or organizational methods that reduce environmental harm while often improving economic performance. Historically, eco-innovation has been driven by regulatory pressure, consumer demand, and incremental engineering improvements. What is changing now is the entry of AI as a general-purpose technology capable of reshaping how eco-innovation itself is conceived, developed, and scaled.

Creative Commons *(CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Syed Saleha Javed Abbas, Associate Professor, Department of Business Economics, HR College of Commerce & Economics, HSNC University, Mumbai
Email: abis.javed@gmail.com

How to cite this article:
Syed, S. J. A. (2026). The Confluence of AI and Eco-Innovation: Shaping the Future of Multidisciplinary Research. Bulletin of Nexus Journal, 3(9(II)), 74–79. https://doi.org/10.5281/zenodo.22912614

Quick Response Code:

Website: https://bnir.us

AI is no longer a peripheral tool for environmental management; it is becoming a co-driver of the innovation process, from materials science laboratories to national energy grids. This shift raises questions that sit uneasily within any single discipline. A computer scientist optimizing a neural network for satellite image analysis may not fully grasp the ecological stakes of the deforestation patterns it detects. An environmental economist modeling carbon markets may not understand the limitations of the machine learning models feeding data into those markets. A policymaker drafting green subsidies may be unaware of the substantial electricity and water consumption required to train the very AI models being celebrated as climate solutions. It is precisely this fragmentation of expertise that makes the AI–eco-innovation nexus an inherently multidisciplinary research problem. This paper does not attempt to catalogue every application of AI in environmental contexts—such an undertaking would be both unwieldy and quickly outdated given the pace of technological change. Instead, it aims to do three things. First, it traces the conceptual evolution of eco-innovation and situates AI's entry into this space as a qualitative shift rather than a mere continuation of earlier digital tools. Second, it synthesizes existing literature to identify dominant themes, gaps, and unresolved debates. Third, it proposes a layered framework—technological, organizational, institutional, and ecological—for understanding how AI and eco-innovation intersect, and uses this framework to suggest where multidisciplinary research is most urgently needed. The motivation for this inquiry is not purely academic. Governments across the world, including India, the European Union, and China, have begun embedding AI explicitly within their climate and industrial policy frameworks. Private capital is flowing rapidly into "climate tech" startups that foreground AI as their core differentiator. Yet the scholarly literature examining whether these AI-enabled interventions actually deliver net environmental benefit—rather than simply appearing innovative—remains comparatively thin and scattered across disconnected disciplinary silos. This paper is an attempt to draw those scattered threads into a coherent starting point for future research.

Literature Review

The literature on eco-innovation predates AI by several decades, rooted in the work of scholars who examined how environmental regulation could act as a spur to competitive innovation rather than merely a compliance cost. This "innovation offset" perspective established that environmental and economic goals need not be in permanent conflict, laying conceptual groundwork later extended into discussions of green technology diffusion, circular economy models, and sustainable business strategy. AI being a very recent concept/trend, the literature associated with it is also comparatively recent and can be grouped into four broad strands.

First, AI as a tool for environmental monitoring and prediction. A substantial body of work explores machine learning applications in climate modelling, deforestation detection through satellite imagery, biodiversity tracking, and early warning systems for natural disasters. This strand generally treats AI as a powerful but ethically neutral instrument, one that enhances the accuracy and speed of environmental data analysis without fundamentally altering the goals of environmental science.

Second, AI as an enabler of resource efficiency. Here, research focuses on smart grids, precision agriculture, industrial process optimization, and predictive maintenance in manufacturing. Studies in this strand tend to be more applied and quantitative, often measuring efficiency gains in energy consumption, water use, or material waste following AI implementation. Findings are generally positive but highly context-dependent, with efficiency gains varying widely based on sector, scale, and existing digital infrastructure.

Third, a smaller but growing strand critically examines the environmental cost of AI itself. Training large machine learning models requires significant computational resources, which translates into substantial electricity consumption and, indirectly, carbon emissions. This literature complicates the celebratory narrative of AI-as-climate-solution by highlighting that the technology carries its own ecological footprint, one that is often left unaccounted for in enthusiastic policy discourse. Some scholars term this the "rebound problem"—where efficiency gains in one area are offset by increased consumption elsewhere.

Fourth, an emerging institutional and governance-focused strand examines how regulatory frameworks, data governance regimes, and international climate agreements are adapting—or failing to adapt—to the growing role of AI in environmental decision-making. This literature raises concerns about algorithmic transparency in carbon accounting, the concentration of environmental data within a small number of large technology firms, and the risk that AI-driven solutions may favor incremental optimization over the structural changes that climate mitigation may ultimately require.

Table 1: Summary of Literature Strands on AI and Eco-Innovation

Strand	Core Focus	Primary Disciplines	Typical Methodology	Dominant Tone
1. Environmental Monitoring & Prediction	Satellite imagery analysis, climate modeling, biodiversity tracking, disaster early-warning	Computer Science, Environmental Science	Quantitative / Computational modeling	Optimistic
2. Resource Efficiency Enablement	Smart grids, precision agriculture, industrial process optimization	Engineering, Agricultural Science, Operations Research	Applied / Case-based quantitative	Positive but context-dependent
3. Environmental Cost of AI Itself	Energy consumption of training large models, rebound effects	Computer Science, Ecological Economics	Critical / Quantitative estimation	Cautionary
4. Governance & Institutional Response	Algorithmic transparency, data ownership, climate policy adaptation	Public Policy, Law, STS (Science & Technology Studies)	Qualitative / Policy analysis	Analytical / Critical

Taken together, the literature reveals a field that is expanding quickly but remains disciplinarily fragmented. Technical papers on AI applications rarely engage with governance concerns, while policy-oriented literature often lacks technical granularity about what AI systems can and cannot reliably do. Very few studies attempt to bridge these strands into an integrated framework, which is precisely the gap this paper seeks to address.

Research Methodology

This study adopts a qualitative, interpretive research design suited to a still-emerging and conceptually fragmented field. Given that the AI–eco-innovation nexus spans multiple disciplines with distinct methodological traditions, a purely quantitative approach at this stage would risk imposing false precision on a body of knowledge that is still coalescing. The research proceeds through structured thematic content analysis of secondary sources, including peer-reviewed journal articles, working papers from research institutions, reports from international bodies such as the OECD and UNEP, and policy documents from national governments actively integrating AI into climate strategy. Sources were selected based on relevance to the intersection of AI and environmental innovation, prioritizing material published within the last decade to reflect the rapid evolution of both fields, while retaining foundational eco-innovation literature predating the AI boom for conceptual grounding. Thematic coding was used to identify recurring concepts, tensions, and gaps across sources, following an iterative process of category development rather than a fixed coding frame applied from the outset. This allowed themes such as "rebound effects," "data governance," and "techno-solutionism" to emerge organically from the material rather than being imposed a priori. Based on this analysis, the paper develops an interpretive framework organized around four layers of convergence: the technological layer (AI tools and their direct environmental applications), the organizational layer (how firms restructure innovation processes around AI capabilities), the institutional layer (regulatory and governance responses), and the ecological layer (the actual, measurable environmental outcomes, positive or negative). This framework is offered not as a definitive model but as a scaffolding device intended to support future empirical research, including case studies and quantitative impact assessments that lie beyond the scope of this paper.

Table 2: Four-Layer Framework for AI–Eco-Innovation Convergence

Layer	Core Question	Illustrative Focus Areas	Key Stakeholders
Technological	What can AI systems do, directly, for environmental outcomes?	Materials discovery, predictive resource management, industrial process optimization	Data scientists, engineers, R&D teams
Organizational	How do firms restructure innovation processes around AI capability?	Cross-functional sustainability–data science teams, virtual pilot testing	Firm management, sustainability officers
Institutional	How do governance systems respond to AI-	Carbon accounting standards, data governance, regulatory	Regulators, standard-setting bodies, courts

	driven environmental claims?	transparency	
Ecological	Does the intervention produce genuine net environmental benefit?	Lifecycle energy accounting, rebound-effect measurement	Environmental scientists, auditors, civil society

Limitations of this methodology are acknowledged. The reliance on secondary sources means the analysis is shaped by what has already been published, which may underrepresent emerging practices not yet documented in academic literature. Additionally, the fast-moving nature of AI development means some observations may require revisiting as the technology and its applications continue to evolve.

The Technological Layer: AI as a Driver of Eco-Innovation

At the technological layer, AI is reshaping eco-innovation in at least three distinct ways. The first is materials discovery. Traditional methods of identifying new sustainable materials—biodegradable plastics, low-carbon cement alternatives, or more efficient battery chemistries—have historically relied on slow, iterative laboratory experimentation. Machine learning models trained on molecular and material property data can now simulate and screen thousands of candidate compounds far faster than physical trial and error, compressing discovery timelines that once took years into a matter of months.

The second is predictive resource management. In agriculture, AI-driven systems analyze soil data, weather patterns, and crop imagery to optimize water and fertilizer use, reducing both cost and environmental impact. In energy systems, AI supports demand forecasting and grid balancing, which is particularly critical as renewable sources like solar and wind introduce variability that traditional grid management struggles to accommodate.

The third is process optimization within industry. Manufacturing firms increasingly use AI to reduce waste, predict equipment failures before they cause resource-intensive downtime, and fine-tune energy consumption across production lines. These applications tend to produce the most immediately measurable efficiency gains, though their aggregate environmental benefit depends heavily on whether efficiency gains translate into genuine reductions in resource use or are instead absorbed by increased production volume.

Table 3: AI Applications in Eco-Innovation by Sector

Application Area	Primary Sector(s)	Typical AI Technique	Reported Adoption Maturity
Materials discovery	Chemicals, construction, battery manufacturing	Generative/predictive ML on molecular data	Early-stage, largely R&D-lab confined
Precision agriculture	Agriculture, agri-tech	Computer vision, sensor-based predictive analytics	Moderate, growing rapidly in large farms
Smart grid / energy balancing	Energy & utilities	Time-series forecasting, reinforcement learning	Moderate to advanced in developed grids
Industrial process optimization	Manufacturing	Predictive maintenance, anomaly detection	Advanced in large firms; limited in SMEs
Environmental monitoring	Forestry, conservation, disaster management	Computer vision on satellite/sensor data	Advanced for large-scale monitoring programs

Note: Adoption-maturity ratings are qualitative assessments derived from patterns observed across the reviewed literature rather than a standardized industry index, and should be read as indicative rather than precise measurements.

The Organizational Layer: Rethinking Innovation Processes

Beyond individual technologies, AI is altering how organizations structure their innovation processes. Firms pursuing eco-innovation increasingly organize around data pipelines rather than traditional research and development departments alone. Environmental sustainability teams now often work alongside data science units, creating new organizational hybrids that did not exist a decade ago.

This shift also changes the pace and risk profile of innovation. Where eco-innovation once required lengthy pilot programs before scaling, AI-enabled simulation allows firms to test environmental interventions virtually before physical implementation, lowering the cost of experimentation. However, this same capability can encourage a bias toward solutions that are easy to model and measure, potentially sidelining more structural but harder-to-quantify interventions such as changes in consumption patterns or supply chain redesign.

The Institutional Layer: Governance, Policy, and Accountability

The institutional dimension of AI–eco-innovation convergence remains the least developed in both practice and scholarship. Carbon accounting frameworks are beginning to incorporate AI-driven data collection, yet questions of algorithmic transparency and auditability remain largely unresolved. Who verifies that an AI-generated sustainability claim is accurate, and on what data was it trained? These questions matter enormously as "green AI" claims become a marketing tool as much as a technical reality.

Data governance also becomes a live policy concern. Much environmental data—satellite imagery, sensor networks, agricultural data—is increasingly captured, processed, and owned by a small number of large technology firms, raising questions about equitable access, especially for researchers and policymakers in lower-income countries who may lack the computational infrastructure to independently verify AI-driven environmental claims.

Table 4: Institutional Gaps and Potential Governance Responses

Governance Gap	Description	Potential Institutional Response
Algorithmic transparency in carbon accounting	Limited ability to audit how AI-generated sustainability metrics are calculated	Mandatory disclosure of model methodology for regulated carbon claims
Data concentration	Environmental data increasingly held by a small number of large technology firms	Open-data mandates or public data trusts for critical environmental datasets
Cross-border capacity gap	Lower-income countries often lack computational infrastructure to verify AI-driven claims	International capacity-building and shared computational infrastructure programs
Greenwashing risk	AI-based sustainability claims used for marketing without rigorous substantiation	Independent third-party verification standards for "AI-enabled green" claims

The Ecological Layer: Measuring Net Impact

Perhaps the most under-examined question is the simplest one: does AI-enabled eco-innovation actually produce a net positive environmental outcome once the energy and resource costs of the AI systems themselves are accounted for? Training and running large-scale AI models consumes considerable electricity, and the environmental benefit of any given application must be weighed against this cost. The literature suggests this calculation is rarely performed with rigor, and enthusiasm for AI's potential often outpaces evidence of its net ecological value.

Table 5: Illustrative Trade-Off Assessment — Environmental Benefit vs. Embedded AI Cost

Application Area	Reported Environmental Benefit	Relative AI Computational Cost	Net Assessment (Qualitative)
Materials discovery (e.g., battery/cement alternatives)	High — potential for long-term emissions reduction if scaled	High — extensive model training and simulation cycles	Positive, contingent on scale-up
Precision agriculture	Moderate — reduced water/fertilizer use at farm level	Low to moderate — often lightweight, sensor-based models	Consistently positive
Smart grid balancing	High — improved renewable integration	Moderate — continuous real-time inference required	Positive, infrastructure-dependent
Large-scale environmental monitoring	Moderate to high — improved detection and response speed	Moderate — periodic large-scale image processing	Positive, but data-governance sensitive

Note: This table synthesizes qualitative directional findings from the reviewed literature; it is not derived from a single standardized lifecycle-assessment dataset, and future empirical research should aim to replace these qualitative ratings with measured figures.

Discussion: Toward Genuine Multidisciplinary Collaboration

The four-layer framework outlined above suggests that no single discipline can adequately address the AI–eco-innovation nexus in isolation. Computer scientists need environmental literacy to understand the stakes of the problems they are optimizing for. Environmental scientists need enough technical fluency to interrogate the

assumptions embedded within AI models. Economists and policymakers need to understand both domains well enough to design regulation that captures genuine ecological value rather than rewarding superficial innovation. This paper argues that multidisciplinary research infrastructure—joint research centers, cross-trained graduate programs, and collaborative funding mechanisms—is not a peripheral nicety but a structural necessity for this field to mature responsibly.

Conclusion and Future Research Directions

AI and eco-innovation are converging in ways that carry genuine promise but also significant unresolved risk. This paper has argued that understanding this convergence requires moving beyond a purely technical lens to examine organizational, institutional, and ecological dimensions in tandem. Future research should prioritize longitudinal, empirical studies that measure the net environmental impact of AI-enabled interventions over time, rather than relying on point-in-time efficiency claims. There is also a pressing need for standardized methodologies to account for the energy and resource costs of AI systems themselves within any sustainability assessment. Finally, greater collaboration between technologists, environmental scientists, economists, and regulators will be essential if AI is to serve as a genuine driver of ecological progress rather than a compelling but ultimately insufficient technological narrative.

Acknowledgment

The author sincerely acknowledges the support and encouragement received from colleagues, academic institutions, and well-wishers during the preparation of this research paper. The author is also grateful to the researchers, organizations, and international institutions whose academic publications, reports, and policy documents provided valuable insights for examining the convergence of Artificial Intelligence and eco-innovation. The author gratefully acknowledges all sources cited in this paper for their contribution to the development of the study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. OECD. (2023). *Artificial Intelligence and the Environment: A Policy Perspective*. OECD Publishing.
2. UNEP. (2022). *AI for the Planet: Opportunities and Risks*. United Nations Environment Programme.
3. Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives*, 9(4), 97–118.
4. Strubell, E., Ganesh, A., & McCallum, A. (2019). Energy and policy considerations for deep learning in NLP. *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*.
5. Rolnick, D., et al. (2019). Tackling climate change with machine learning. *arXiv preprint*.
6. World Economic Forum. (2023). *Harnessing AI for the Global Goals*. WEF Insight Report.

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

A Study of Financial Instruments for the Development of Primary Education in Kolhapur District: Integrating AI and Smart Technologies for Sustainable Development and Viksit Bharat 2047

Ravi Shivaji Chavan[1], Dr. M. K. Kamble[2]
[1]Research Student, Department of Economics, Shivaji University, Kolhapur
[2]Prof., Research Guide, Shripatrao Chougule Arts and Science College
Malwadi–Kotoli, Taluka Panhala, Kolhapur

Manuscript ID:
BN-2026-030915

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 80-85

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913360
DOI link:
https://doi.org/10.5281/zenodo.22913360

Abstract

*Primary education constitutes a fundamental component of human-capital formation, social inclusion and long-term economic development. The National Education Policy (NEP) 2020 gives particular importance to foundational literacy and numeracy, equitable access, appropriate use of technology and improvement of learning environments. These priorities are also closely connected with Sustainable Development Goal 4 and India's long-term vision of Viksit Bharat 2047 (Ministry of Education, 2020). This paper examines the role of financial instruments in supporting the development of primary education in Kolhapur District, Maharashtra, with particular emphasis on public expenditure, Samagra Shiksha, district-level development funding, Corporate Social Responsibility (CSR), community participation and technology-enabled financial governance. The study adopts a descriptive and analytical framework combining secondary educational and policy data with a proposed field-survey design covering selected primary schools across urban, semi-urban, industrial-agrarian and rural/hilly areas of the district. The paper argues that the effectiveness of educational finance depends not only on the volume of expenditure but also on the timeliness, transparency, geographical targeting and outcome orientation of fund utilisation. Rural and geographically difficult areas may require differentiated resource allocation because equal per-school or per-student allocations do not necessarily reflect differences in infrastructure, connectivity, terrain, maintenance requirements and access to private investment. To address these challenges, the paper proposes an **AI-Driven Educational Resource Optimization System (AI-EROS)**. The proposed framework combines data-based needs assessment, a school-level deprivation index, digital fund tracking, CSR-school matching and technology-assisted monitoring. Blockchain or distributed-ledger mechanisms are presented as possible audit-support technologies rather than as immediate substitutes for existing public financial systems. The proposed framework can help district authorities move from conventional input-based budgeting towards evidence-based and equity-oriented educational finance. The paper concludes that an integrated approach combining public finance, CSR, community participation, digital public infrastructure and responsible AI could strengthen the efficiency and transparency of primary education financing in Kolhapur District. Such a model could also provide a scalable framework for educational governance in Maharashtra and contribute to the broader objectives of Viksit Bharat 2047.*

Keywords: *Primary Education, Educational Finance, Kolhapur District, Samagra Shiksha, CSR, Artificial Intelligence, FinTech Governance, SDG 4, Viksit Bharat 2047, Smart Governance*

Introduction

Primary education is a critical foundation for human-capital formation, social mobility and inclusive economic development. The quality of foundational education affects children's subsequent learning, employability, social participation and ability to benefit from technological and economic transformation.

Creative Commons (CC BY-NC-SA 4.0)

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Ravi Shivaji Chavan, Research Student, Department of Economics, Shivaji University, Kolhapur
Email: ravirajechavan9565@gmail.com

How to cite this article:
Chavan, R. S., & Kamble, M. K. (2026). A Study of Financial Instruments for the Development of Primary Education in Kolhapur District: Integrating AI and Smart Technologies for Sustainable Development and Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 80–85.
https://doi.org/10.5281/zenodo.22913360

Quick Response Code:

Website: https://bnir.us

Recognising this importance, the National Education Policy (NEP) 2020 places strong emphasis on universal foundational literacy and numeracy, equitable access, quality education and appropriate integration of technology into the education system (Ministry of Education, 2020). The Government of India has subsequently strengthened this policy direction through initiatives such as NIPUN Bharat, which focuses on ensuring foundational literacy and numeracy during the early years of schooling. The policy framework therefore requires educational systems to look beyond enrolment and physical access towards learning outcomes, inclusion, infrastructure and institutional capacity (Ministry of Education, 2021). Educational finance is central to achieving these objectives. Schools require financial resources not only for routine expenditure but also for classrooms, sanitation, electricity, digital equipment, internet connectivity, teacher support, maintenance and learning resources. The Samagra Shiksha framework provides an integrated approach to school education and supports interventions across different stages of schooling, including infrastructure and quality-related components (Ministry of Education, 2022).

Kolhapur District provides an important setting for examining these issues. The district contains urban and industrial areas as well as agricultural, rural and geographically difficult regions. Such spatial diversity can generate differences in educational infrastructure, connectivity, access to private investment and the cost of delivering public services. Consequently, an educational-finance system based exclusively on uniform allocations may not adequately reflect differences in local needs. At the same time, the emergence of Artificial Intelligence (AI), digital public infrastructure, data analytics and FinTech creates new possibilities for public-sector resource management. AI can potentially support needs assessment, expenditure forecasting, identification of infrastructure gaps and monitoring of project progress. However, technology should complement—not replace—administrative accountability, human oversight, public procurement rules and established financial controls.Against this background, the present paper investigates the financial instruments relevant to primary education development in Kolhapur District and proposes an AI-enabled framework for improving resource allocation and financial governance.

Objectives of the Study

The study has the following objectives:

1. To examine the major financial instruments supporting primary education in Kolhapur District.
2. To understand the relationship between educational finance, infrastructure and geographical inequality.
3. To examine the potential contribution of Samagra Shiksha, district-level public expenditure, CSR and community participation to primary education development.
4. To identify potential problems associated with delayed fund utilisation, unequal resource availability and limited technology investment.
5. To propose an AI-enabled educational financial-management framework for evidence-based and equitable resource allocation.
6. To examine how smart technologies can support transparency, monitoring and accountability in educational finance.
7. To relate district-level educational-finance reforms to SDG 4, NEP 2020 and the broader vision of Viksit Bharat 2047.

Literature Review and Conceptual Framework

1 Educational Finance and Human Capital

Educational expenditure should be viewed as an investment in human capital rather than merely as a recurring public-sector cost. Investment in foundational education has implications for later learning, labour productivity, social mobility and participation in economic development. The effectiveness of such expenditure, however, depends on how resources are allocated and utilised.The economic literature on education also suggests that expenditure levels alone are insufficient indicators of educational performance. Institutional capacity, teacher availability, infrastructure, management quality and accountability mechanisms influence whether financial inputs are converted into educational outcomes.

2 NEP 2020 and Foundational Learning

NEP 2020 identifies foundational literacy and numeracy as an urgent priority and calls for systematic assessment and support for children during the foundational years (Ministry of Education, 2020). NIPUN Bharat subsequently established an implementation framework for achieving foundational literacy and numeracy through a mission-oriented approach (Ministry of Education, 2021). This policy direction has significant financial implications. District education authorities need to allocate resources not only to conventional infrastructure but also to teaching-learning materials, teacher development,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

assessment systems and appropriate digital resources.

3 Samagra Shiksha

Samagra Shiksha provides an integrated framework for school education and supports interventions related to access, quality, infrastructure, equity and learning outcomes. Its framework is therefore relevant to discussions concerning the financing and implementation of primary education reforms (Ministry of Education, 2022).

The important issue is not simply the availability of funds but the ability of district and school-level institutions to identify priorities, utilise funds efficiently and monitor outcomes.

4 CSR and Community Participation

Corporate Social Responsibility can provide supplementary resources for educational infrastructure and technology. Under India's CSR framework, education-related activities can qualify under Schedule VII of the Companies Act, subject to the applicable legal and regulatory conditions. CSR may be particularly useful for investments such as digital classrooms, computers, renewable-energy systems, sanitation facilities, drinking-water infrastructure and other capital-intensive interventions. However, CSR allocation can be influenced by the geographical location and priorities of corporate entities. A district-level coordination mechanism may therefore improve the alignment between corporate contributions and unmet educational needs. Community participation is another important component. School Management Committees, alumni groups, local philanthropists and community organisations can contribute resources, monitoring and local knowledge. Nevertheless, community-based financing should supplement rather than substitute for the statutory responsibilities of government.

Profile Of Primary Education in Kolhapur District

Kolhapur District contains diverse geographical and socio-economic conditions. Urban and industrialised areas have comparatively greater access to markets, technology providers and private-sector institutions, whereas remote and hilly areas can face higher infrastructure and service-delivery costs.

For analytical purposes, the paper groups the district's educational environment into three broad categories:

Category	Representative Areas	Major Educational-Finance Considerations
Urban/Semi-Urban	Karveer and major urban centres	Better connectivity, vendor access and private-sector participation
Industrial-Agrarian	Hatkanangle, Shirol, Kagal and surrounding areas	Agricultural and industrial economy, potential CSR participation
Rural/Hilly	Shahuwadi, Gaganbawda, Bhudargad, Ajara, Chandgad and surrounding areas	Difficult terrain, connectivity challenges, higher infrastructure-maintenance requirements

Note: The above categorisation is an analytical classification for this study and should not be interpreted as an official Government of Maharashtra classification.

The UDISE+ system provides a major national source of school-level administrative information and is therefore an important source for validating school, student, teacher and infrastructure indicators at district level (Ministry of Education, UDISE+).

Financial Instruments for Primary Education

1 Government Budgetary Allocations

Government expenditure remains the principal source of financing for public primary education. Such expenditure supports salaries, infrastructure, learning resources, maintenance, school facilities and other educational interventions.

The challenge is to ensure that financial allocations are translated into timely and measurable improvements at school level.

2 Samagra Shiksha

Samagra Shiksha provides an integrated policy and financing framework for school education. Its relevance to this study lies in its emphasis on access, equity, quality, infrastructure and learning outcomes (Ministry of Education, 2022).

Rather than treating Samagra Shiksha only as an expenditure source, district authorities can use its planning framework to identify schools requiring differentiated support.

3 District-Level Development Funds

District-level planning mechanisms can support educational infrastructure such as classroom repair, sanitation, electrification and other local priorities. Their effectiveness depends on planning quality, administrative coordination, procurement procedures and timely utilisation.

The paper therefore recommends that district-level education expenditure be mapped school-by-school so that authorities can identify duplication, underfunding and geographical gaps.

4 Corporate Social Responsibility

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

CSR can provide additional capital for educational infrastructure and technology. Potential interventions include:

- Digital classrooms
- Computer laboratories
- Solar power
- Drinking-water facilities
- Sanitation
- Assistive technology
- Educational software
- STEM and innovation facilities

However, CSR should be aligned with independently assessed educational needs rather than being concentrated only in areas geographically close to companies.

5 Community Participation

Community participation can provide supplementary financial and non-financial support. Alumni, parents, local organisations and philanthropists may contribute to school improvement.

The proposed digital platform could make such contributions more transparent by recording donor contributions, expenditure and project completion status.

Proposed AI-Driven Educational Resource Optimization System (Ai-Eros)

The central contribution of this paper is the proposed **AI-Driven Educational Resource Optimization System (AI-EROS)**.

AI-EROS is conceptual rather than an already implemented government platform. It is proposed as a district-level decision-support architecture.

1 Module 1: Digital School Profile

Each school would have a continuously updated digital profile containing:

- Student enrolment
- Teacher availability
- Classroom condition
- Electricity
- Internet connectivity
- Computer availability
- Digital-learning infrastructure
- Sanitation
- Drinking water
- Accessibility facilities
- Maintenance requirements
- Previous grants
- Expenditure and utilisation statue

2 Module 2: AI-Based Needs Assessment

Machine-learning models could analyse historical and current school data to identify schools requiring additional support.

For example, predictive models could estimate:

- Probability of infrastructure failure
- Future maintenance expenditure
- Digital infrastructure requirements
- Connectivity needs
- Resource shortages

The system should remain subject to human review because algorithmic recommendations can reproduce errors or biases present in historical data.

3 Module 3: CSR-School Matching

A district-level CSR portal could match corporate contributions with verified school requirements.

For example:

Corporate Requirement → Verified School Need → Estimated Cost → Project Approval → Implementation → Impact Measurement

This can reduce duplication and improve geographical targeting.

4 Module 4: Digital Financial Tracking

Each approved project could receive a digital project identifier. The system could record:

1. Sanction
2. Fund release
3. Procurement
4. Project implementation
5. Verification
6. Expenditure
7. Completion
8. Outcome indicators

Such a system can improve auditability without automatically replacing existing statutory audit procedures.

5 Module 5: Smart-Contract Possibility

Smart contracts may be explored for specific transactions where legal, procurement and financial regulations permit their use.

For example, a project could have predefined milestones. Payment processing could be triggered after authorised verification of the milestone.

However, automated payment should not be based solely on AI-generated image verification. Human verification, procurement rules, financial controls and authorised officers should remain part of the process.

6 Module 6: Public Dashboard

A public-facing dashboard could display:

- Funds sanctioned
- Funds released
- Funds utilised
- Project status
- School-level infrastructure needs
- CSR contributions
- Completed projects
- Outcome indicators

Sensitive personal information should not be displayed.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Proposed AI-Eros Implementation Model

Financial Instrument	Funding Source	Share (%)	Primary Expense Focus	Operational Challenges
DPDC Capital Grants	District Planning Committee	24%	Building repairs, sanitation blocks, electrification, classroom construction.	Political lobbying in fund distribution, administrative delay of 3–5 months in releasing funds.
Samagra Shiksha Grants	Central (60%) State (40%)	56%	Salaries, uniforms, free textbooks, basic school maintenance grants.	Rigid expenditure norms, 80%+ absorbed by recurring
Corporate CSR Capital	Private Corporations & Public Sector Undertakings	13%	Smart interactive boards, computer labs, solar panels, RO drinking water.	Extreme spatial clustering around industrial talukas (Shirol, Karveer); neglect of hilly talukas.
Lok-Sahabhag (Community)	Local Donors, Alumni, SMCs, Philanthropists	7%	E-learning software, sports equipment, playground development, aesthetics.	Highly volatile, dependent on local community wealth and economic conditions.

Key Findings and Interpretation

The analysis indicates five broad issues that require attention.

1 Input Financing Is Not Sufficient

Increasing financial allocations does not automatically guarantee better educational outcomes. Resource utilisation, institutional capacity and monitoring are equally important.

2 Geographical Equity Matters

Schools in geographically difficult areas can face higher costs for infrastructure construction, maintenance, electricity and connectivity. Therefore, educational financing should consider geographical conditions rather than relying exclusively on uniform allocation formulas.

3 Digital Infrastructure Requires Dedicated Planning

Digital education requires more than computers or smart boards. Sustainable digital infrastructure also requires electricity, connectivity, maintenance, teacher capacity and appropriate content.

4 Technology Must Be Combined with Governance

AI, block chain and digital dashboards can improve information processing and traceability, but technology alone cannot eliminate administrative weaknesses. Human accountability, statutory audit, procurement procedures and institutional oversight remain essential

Policy Recommendations

1 Establish a District Educational Fin Tech and Data Cell

A specialised unit within the district education administration may coordinate:

- Education expenditure data
- Infrastructure mapping
- CSR coordination
- Digital monitoring
- AI-based decision support
- Public dashboards

The unit should operate within existing government financial and data-governance frameworks.

2 Introduce Need-Based Resource Allocation

District authorities should develop a transparent school-level deprivation index based on measurable indicators.

Funding priorities should consider:

- Infrastructure condition
- Geography
- Connectivity
- Student needs
- Digital access
- Maintenance costs
- Learning-resource gaps

3 Strengthen School-Level Financial Capacity

School Management Committees should receive training in:

- Basic financial management
- Digital payments
- Record keeping
- Project monitoring
- Procurement awareness
- Social accountability

4 Develop a Public Education-Finance Dashboard

A dashboard should allow citizens and authorised stakeholders to monitor:

- Allocation
- Release
- Expenditure
- Project completion
- CSR contributions
- Infrastructure status

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

5 Promote Renewable and Offline-First Digital Infrastructure

Remote schools may require solutions such as:

- Solar backup
- Offline digital content
- Local servers'/content repositories
- Low-bandwidth learning platforms

These interventions should be selected based on local feasibility studies.

Conclusion

Primary education is central to human-capital development, social equity and the long-term development trajectory of India. NEP 2020 and the NIPUN Bharat framework have placed foundational learning at the centre of school-education reform, while the Viksit Bharat 2047 vision highlights the importance of developing human capabilities and improving the quality of public institutions.

Kolhapur District provides a useful case for examining educational finance because of its combination of urban, industrial, agricultural, rural and geographically difficult areas. These differences imply that educational resource requirements are not uniform.

The study argues that the future of educational finance should move beyond a simple focus on the amount of money allocated. Greater attention should be given to **where resources are required, when they are released, how they are utilised and what educational outcomes they generate**.

The proposed AI-EROS framework provides a conceptual pathway for this transition. By integrating school-level data, deprivation-based prioritisation, digital fund tracking, CSR matching, GIS, predictive analytics and carefully governed smart technologies, district authorities could improve the efficiency, transparency and equity of educational investment.

However, AI should be regarded as a decision-support instrument rather than an autonomous decision-maker. Human oversight, legal compliance, public procurement rules, data protection, financial audit and democratic accountability must remain fundamental components of the system.

A transparent and evidence-based educational-finance model can help bridge geographical disparities, strengthen rural school infrastructure and support the objectives of SDG 4 and Viksit Bharat 2047. The AI-EROS model proposed in this paper may therefore serve as a foundation for future pilot implementation and empirical testing in Kolhapur District and, subsequently, other districts of Maharashtra and India.

Acknowledgement

The authors sincerely acknowledge the support of education administrators, school heads, School Management Committee members and other stakeholders who contribute to the understanding and improvement of primary education in Kolhapur District. The authors also acknowledge the publicly available information provided by government education and policy institutions.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Ministry of Education, Government of India. (2020). *National Education Policy 2020*. Government of India.
2. Ministry of Education, Government of India. (2021). *NIPUN Bharat: National Initiative for Proficiency in Reading with Understanding and Numeracy*. Department of School Education and Literacy.
3. Ministry of Education, Government of India. (2022). *Samagra Shiksha: Framework for Implementation*. Department of School Education and Literacy.
4. Ministry of Education, Government of India. (2025). *National Education Policy 2020 Initiatives*. Department of School Education and Literacy.
5. Ministry of Education, Government of India. *UDISE+: Unified District Information System for Education Plus*. Department of School Education and Literacy.
6. NITI Aayog. (2026). *School Education System in India: Temporal Analysis and Policy Roadmap for Quality Enhancement*. Government of India.
7. NITI Aayog. (2026). *Reimagining Skilling for Viksit Bharat@2047*. Government of India.
8. Government of India. *The Companies Act, 2013*, Schedule VII and applicable CSR Rules.
9. United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Nutritional Value and Health Benefits of Lotus (*Nelumbo nucifera*): A Short Review

Pawade R. S.
Lecturer in DRB Sindhu Mahavidyalaya, Nagpur, Maharashtra

Manuscript ID:
BN-2026-030916

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 86-89

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913462
DOI link:
https://doi.org/10.5281/zenodo.22913462

Abstract
Nelumbo nucifera Gaertn., commonly known as sacred lotus, is an aquatic plant belonging to the family Nelumbonaceae. It has been valued for centuries as a food, ornamental plant and medicinal herb, particularly in Asian countries. Almost every part of the plant, including rhizome, seeds, leaves, flowers and seed embryos, has nutritional and therapeutic significance. Lotus rhizomes and seeds are sources of carbohydrates, proteins, dietary fibre, minerals and bioactive compounds. Phytochemical investigations have identified alkaloids, flavonoids, phenolic compounds, polysaccharides, terpenoids and glycosides. Experimental studies suggest antioxidant, anti-inflammatory, hypoglycaemic, hypolipidaemic, anti-obesity, hepatoprotective and neuroprotective activities. Lotus seeds, in particular, have attracted interest as a functional-food ingredient. However, much of the evidence comes from laboratory and animal studies, and further well-designed human clinical studies are required. This review summarizes the nutritional composition, major phytochemicals and potential health benefits of N. nucifera.
Keywords: *Nelumbo nucifera, lotus, nutritional value, lotus seeds, rhizome, phytochemicals, antioxidant, functional food, health benefits.*

Introduction

Nelumbo nucifera Gaertn., commonly called sacred lotus, Indian lotus or lotus, is an important aquatic plant belonging to the family Nelumbonaceae. It has a long history of cultivation, food use and traditional medicinal use in Asian countries, and different plant parts have been incorporated into culinary and traditional preparations (Chen et al., 2019; Sahu et al., 2024; *Nelumbo nucifera*: A multidisciplinary review, 2024). The rhizome and seeds are particularly important as edible and nutritionally valuable parts, while lotus seeds have received increasing attention for functional-food and industrial applications (Punia Bangar et al., 2022). Phytochemical studies have identified diverse constituents, including alkaloids, flavonoids, phenolic compounds, polysaccharides, terpenoids, steroids and glycosides. Alkaloids and flavonoids are among the most extensively studied groups, and recent research has further examined lotus alkaloids with respect to biosynthesis, pharmacokinetics, bioactivity and safety (Mukherjee et al., 2009; Mukherjee et al., 2015; Wang et al., 2023). Lotus polysaccharides have also attracted attention because of their structural diversity, biological activities and potential applications (Review of lotus polysaccharides..., 2023).

Botanical and Nutritional Importance of Lotus

1 Lotus Rhizome

The lotus rhizome is consumed as a vegetable in several Asian countries. It contains carbohydrates, dietary fibre, protein, minerals and vitamins. An earlier nutritional analysis reported approximately 9.7% carbohydrate, 1.7% protein and 0.1% fat, although values can vary with cultivar, growing conditions and analytical method.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Pawade R. S., Lecturer in DRB Sindhu Mahavidyalaya, Nagpur, Maharashtra
Email: ritapawade09@gmail.com

How to cite this article:
Pawade, R. S. (2026). Nutritional Value and Health Benefits of Lotus (Nelumbo nucifera): A Short Review. Bulletin of Nexus Journal, 3(9(II)), 86–89. https://doi.org/10.5281/zenodo.22913462

Quick Response Code:

Website: https://bnir.us

The rhizome is also a source of vitamin C and minerals such as iron and copper. Its dietary fibre contributes to gastrointestinal health and normal bowel function (Sahu et al., 2024; Chen et al., 2019).

2 Lotus Seeds

Lotus seeds are one of the most nutritionally important parts of the plant. They contain substantial amounts of starch, protein, lipids, dietary fibre, amino acids, minerals and bioactive compounds. Their nutritional profile has led to increasing interest in their use in functional foods and nutraceutical products (Punia Bangar et al., 2022; Sahu et al., 2024). The green embryo, or lotus plumule, has a characteristic bitter taste and contains biologically active alkaloids (Wang et al., 2023; Mukherjee et al., 2009).

3 Lotus Leaves and Flowers

Lotus leaves contain flavonoids, alkaloids, phenolic compounds and other phytochemicals. Research has investigated their potential antioxidant, anti-inflammatory, anti-obesity and antidiabetic properties. Lotus flowers and their components also contain phenolic and flavonoid compounds with antioxidant potential (Mukherjee et al., 2009; Mukherjee et al., 2015; Sahu et al., 2024).

Major Phytochemical Constituents

The major phytochemical groups reported from lotus include alkaloids, flavonoids, phenolic acids and other phenolics, polysaccharides, triterpenoids, steroids, glycosides, essential oils, proteins and amino acids. More than 250 chemical constituents have been reported from different parts of lotus in the scientific literature (Chen et al., 2019; Mukherjee et al., 2015). Alkaloids and flavonoids are among the most extensively investigated groups. Recent work has specifically reviewed lotus alkaloids in relation to biosynthesis, pharmacokinetics, bioactivity, safety and industrial applications (Wang et al., 2023). Lotus polysaccharides have likewise been reviewed for their extraction, structural characteristics, biological activities and applications (Review of lotus polysaccharides..., 2023). These compounds may act individually or synergistically and may contribute to the antioxidant, anti-inflammatory, metabolic and other biological activities reported for lotus (Sahu et al., 2024).

Health Benefits of *Nelumbo nucifera*

1 Antioxidant Activity

Lotus contains phenolic compounds, flavonoids and other phytochemicals that demonstrate antioxidant activity in experimental models. These compounds may help neutralize reactive oxygen species and reduce oxidative damage, making lotus a potential source of natural antioxidants for food and nutraceutical applications (Mukherjee et al., 2009; Mukherjee et al., 2015; Sahu et al., 2024).

2 Anti-inflammatory Potential

Inflammation plays an important role in numerous chronic diseases. Extracts and isolated compounds from lotus have demonstrated anti-inflammatory effects in experimental studies. Lotus polysaccharides and phenolic compounds have attracted particular attention for their potential to modulate inflammatory pathways (Mukherjee et al., 2015; Sahu et al., 2024; Review of lotus polysaccharides..., 2023).

3 Antidiabetic and Metabolic Effects

Experimental research suggests that lotus seeds and other plant parts may have hypoglycaemic and antidiabetic properties. Certain lotus constituents may influence glucose metabolism and carbohydrate digestion. However, these findings are predominantly based on in-vitro and animal studies (Chen et al., 2019; Mukherjee et al., 2015; Sahu et al., 2024).

4 Hypolipidaemic and Cardiovascular Potential

Research has reported potential effects of lotus extracts on lipid metabolism, including possible reductions in blood lipid levels in experimental models. Dietary fibre and bioactive phytochemicals may contribute to these effects. More human studies are necessary to establish clinical benefits (Chen et al., 2019; Sahu et al., 2024).

5 Anti-obesity Potential

Lotus leaves and seeds have been investigated for possible effects on lipid accumulation and obesity-related metabolic processes. Experimental evidence suggests that certain lotus compounds may influence lipid metabolism and adipocyte function (Chen et al., 2019; Mukherjee et al., 2015; Sahu et al., 2024).

6 Neuroprotective Potential

Bioactive compounds present in lotus, particularly alkaloids and polysaccharides, have demonstrated neuroprotective effects in experimental studies. Research has investigated their potential role in oxidative-stress reduction, neuronal protection and cognitive function (Mukherjee et al., 2009; Wang et al., 2023; Review of lotus polysaccharides..., 2023).

7 Hepatoprotective Activity

Experimental studies have reported that lotus extracts may provide protection against certain forms of liver injury. Antioxidant and anti-inflammatory mechanisms have been proposed as possible explanations (Mukherjee et al., 2015; Sahu et al., 2024).

8 Antimicrobial and Other Biological Activities

Various lotus extracts and phytochemicals have demonstrated antimicrobial activity against selected microorganisms. Other experimental activities reported include antiviral, anticancer, antifungal

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

and immunomodulatory effects. Laboratory activity does not automatically demonstrate effectiveness in humans (Mukherjee et al., 2009; Mukherjee et al., 2015; Sahu et al., 2024).

Nutritional and Functional-Food Applications

The nutritional composition of lotus provides opportunities for developing value-added food products. Lotus seeds can be consumed directly, roasted or processed into flour and other food products. Lotus seed flour may be incorporated into bakery products, snacks and other formulations. Because lotus seeds contain protein, starch, minerals and bioactive compounds, they have potential as functional-food and nutraceutical ingredients (Punia Bangar et al., 2022; Sahu et al., 2024). The rhizome is widely consumed as a vegetable, while lotus leaves and other parts have potential applications in beverages and food formulations (Chen et al., 2019; *Nelumbo nucifera*: A multidisciplinary review, 2024).

Safety and Research Limitations

Although N. nucifera has a long history of food use, the safety and effectiveness of concentrated extracts and isolated compounds require separate consideration. Different plant parts contain different phytochemicals, and biological effects may vary according to dose, extraction method and preparation. Recent literature emphasizes the need to consider pharmacokinetics, bioavailability and safety when evaluating lotus-derived bioactive compounds, particularly alkaloids (Wang et al., 2023). A major limitation of current research is that many reported health benefits are based on in-vitro experiments or animal models rather than large human clinical trials. Further research is needed on bioavailability, pharmacokinetics, long-term safety, effective doses and clinical efficacy (Chen et al., 2019; Sahu et al., 2024).

Future Perspectives

- Conduct well-designed human clinical trials.
- Establish safe and effective doses of lotus-derived preparations.
- Study the bioavailability of major alkaloids, flavonoids and phenolic compounds.
- Investigate synergistic effects of different phytochemicals.
- Develop lotus-based functional foods and nutraceuticals.
- Explore sustainable utilization of lotus seeds, rhizomes and processing by-products.
- Standardize extraction and processing methods.
- Evaluate long-term safety and possible interactions with medicines.

Conclusion

Nelumbo nucifera is a nutritionally and phytochemically valuable aquatic plant with considerable potential as a functional food and source of bioactive compounds. Its edible rhizomes and seeds provide carbohydrates, proteins, dietary fibre, minerals and other nutrients, while leaves, flowers and seed embryos contain diverse phytochemicals such as alkaloids, flavonoids, phenolics and polysaccharides (Chen et al., 2019; Sahu et al., 2024; Punia Bangar et al., 2022). Experimental studies indicate antioxidant, anti-inflammatory, antidiabetic, hypolipidaemic, anti-obesity, hepatoprotective and neuroprotective potential (Mukherjee et al., 2009; Mukherjee et al., 2015). Overall, lotus represents an important link between traditional food use, nutrition and modern functional-food research. However, therapeutic claims should be interpreted cautiously because much of the current evidence is preclinical. Additional human studies are necessary before specific lotus preparations can be recommended for prevention or treatment of diseases.

Acknowledgment

The author expresses sincere gratitude to the management and faculty of DRB Sindhu Mahavidyalaya, Nagpur, for their continuous encouragement and academic support during the preparation of this review article. Special thanks are extended to researchers and scientists whose valuable studies on Nelumbo nucifera have provided the scientific foundation for this work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Chen G, Zhu M, Guo M. Research advances in traditional and modern use of *Nelumbo nucifera*: Phytochemicals, health promoting activities and beyond. Critical Reviews in Food Science and Nutrition. 2019;59.
2. Sahu B, Sahu M, Sahu M, Yadav M, Sahu R, Chandana S. An updated review on *Nelumbo nucifera* Gaertn: Chemical composition, nutritional value and pharmacological activities. Chemistry & Biodiversity. 2024;21(5): e202301493.
3. Punia Bangar S, et al. A comprehensive review on lotus seeds (*Nelumbo nucifera* Gaertn.): Nutritional composition, health-related bioactive properties, and industrial applications. Journal of Functional Foods. 2022; 89:104937.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

4. Mukherjee PK, Mukherjee D, Maji AK, Rai S, Heinrich M. The sacred lotus (*Nelumbo nucifera*)—phytochemical and therapeutic profile. Journal of Pharmacy and Pharmacology. 2009;61(4):407–422.
5. Mukherjee PK, et al. Phytochemical profile and biological activity of *Nelumbo nucifera*. BioMed Research International. 2015; 2015:789124.
6. Wang Z, et al. Alkaloids from lotus *(Nelumbo nucifera*): Recent advances in biosynthesis, pharmacokinetics, bioactivity, safety, and industrial applications. Critical Reviews in Food Science and Nutrition. 2023.
7. *Nelumbo nucifera*: A multidisciplinary review of its cultural, ecological, and nutraceutical significance. Bioresources and Bioproducts. 2024.
8. Review of lotus polysaccharides and their extraction, structural characteristics, biological activities and applications. International Journal of Biological Macromolecules. 2023.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Corporate Governance and ESG Compliance in India: A Critical Analysis of Emerging Business Law

Nikhil Kashinath Naik
Assistant Professor (IQAC Coordinator) (Padmashree Bhausaheb Vartak College)

Manuscript ID:
BN-2026-030918

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 90-94

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913528
DOI link:
https://doi.org/10.5281/zenodo.22913528

Abstract

Corporate governance and Environmental, Social and Governance (ESG) compliance have emerged as important components of modern business regulation in India. Traditionally, corporate governance focused primarily on accountability, transparency, protection of shareholder interests and responsible management. However, the contemporary business environment requires companies to consider a broader range of environmental and social stakeholders. ESG principles have therefore become increasingly integrated into corporate decision-making, disclosure, risk management and investment practices. In India, this transformation is reflected through the Companies Act, 2013, Securities and Exchange Board of India (SEBI) regulations, Corporate Social Responsibility (CSR) provisions and the Business Responsibility and Sustainability Report (BRSR) framework. SEBI introduced BRSR to strengthen sustainability-related disclosures by listed entities and to provide more measurable and comparable information regarding environmental and social performance. Subsequently, SEBI introduced BRSR Core, which focuses on selected key performance indicators and reasonable assurance, with implementation being progressively extended to larger listed entities and aspects of their value chains. This research critically examines the relationship between corporate governance and ESG compliance in India. It analyses the emerging legal framework, identifies implementation challenges, evaluates the role of boards and management, and proposes measures for improving ESG accountability. The study adopts a doctrinal and analytical research methodology based primarily on legislation, regulatory materials, policy documents and secondary literature. The research finds that ESG is gradually moving from a voluntary sustainability concept towards an important component of corporate accountability and business law.

Keywords: *Corporate Governance, ESG, Sustainability, Companies Act, 2013, SEBI, BRSR, CSR, Corporate Accountability, Business Law.*

Introduction

Corporate governance refers to the system through which companies are directed, controlled and held accountable. It establishes mechanisms for balancing the interests of shareholders, directors, employees, creditors, consumers, regulators and other stakeholders. Effective corporate governance promotes transparency, ethical conduct, accountability and responsible decision-making. In the traditional corporate model, the principal emphasis was placed on financial performance and shareholder value. However, increasing concerns relating to climate change, environmental degradation, labour rights, social inequality, corporate ethics and responsible investment have expanded the meaning of corporate responsibility.

Creative Commons (CC BY-NC-SA 4.0)

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Nikhil Kashinath Naik, Designation: - Assistant Professor (IQAC Coordinator) (Padmashree Bhausaheb Vartak College)
Email: nikhhilnaik624@gmail.com

How to cite this article:

Naik, N. K. (2026). Corporate Governance and ESG Compliance in India: A Critical Analysis of Emerging Business Law. Bulletin of Nexus Journal, 3(9(II)), 90–94.
https://doi.org/10.5281/zenodo.22913528

Quick Response Code:

Website: https://bnir.us

Companies are now expected not merely to generate profits but also to manage their environmental and social impact. This development has given rise to **Environmental, Social and Governance (ESG)** considerations. The environmental component includes climate change, carbon emissions, resource efficiency, waste management and biodiversity. The social component includes employee welfare, human rights, diversity, occupational health and safety, consumer protection and community development. Governance covers board structure, ethics, transparency, anti-corruption measures, shareholder rights and corporate accountability. India has progressively developed a regulatory framework addressing these issues. The Companies Act, 2013 provides important corporate governance mechanisms and also contains CSR requirements under Section 135. The Ministry of Corporate Affairs has stated that qualifying companies are required to constitute a CSR Committee, formulate CSR policy and undertake CSR activities in accordance with the statutory framework.

For listed companies, SEBI has played a significant role in incorporating sustainability into corporate disclosures. BRSR requires reporting against nine principles based on the National Guidelines on Responsible Business Conduct and includes mandatory essential indicators and voluntary leadership indicators. The emergence of ESG regulation therefore represents a significant development in Indian business law. The present research examines whether the existing framework is sufficient to ensure meaningful ESG compliance or whether further legal and institutional reforms are required.

Literature Review

The literature on corporate governance traditionally focuses on the relationship between shareholders, management and the board of directors. Agency theory explains corporate governance as a mechanism for controlling conflicts between owners and managers. Under this approach, transparency, independent directors, auditing and disclosure requirements reduce managerial opportunism. Stakeholder theory provides a broader perspective. It argues that corporations should consider the interests of stakeholders beyond shareholders. Employees, consumers, communities, suppliers and the environment are therefore relevant to corporate decision-making. ESG principles are closely connected with this approach because they require companies to evaluate the wider consequences of their activities. Indian corporate governance literature has increasingly examined the role of the Companies Act, 2013 and SEBI regulations in strengthening board accountability, independent directors, audit committees, related-party transaction controls and disclosure mechanisms. The literature concerning ESG in India highlights the increasing importance of sustainability disclosures. SEBI introduced BRSR as a more outcome-oriented reporting framework containing quantitative and comparable sustainability indicators. SEBI noted that BRSR requires disclosure concerning material ESG risks and opportunities and the approaches adopted by companies to address them. Another important area of scholarship concerns the relationship between **CSR and ESG**. Although both concepts promote responsible business, they are not identical. CSR under the Companies Act is primarily a statutory social responsibility mechanism applicable to qualifying companies, whereas ESG is a broader framework covering environmental, social and governance performance, risk and disclosure. Recent regulatory developments have shifted attention towards the reliability of ESG information. SEBI's BRSR Core framework introduces selected key performance indicators for which reasonable assurance is required and also extends ESG disclosure considerations to certain aspects of the value chain. The existing literature therefore demonstrates a transition from traditional corporate governance towards a more comprehensive model of sustainable corporate governance. However, challenges remain regarding standardisation, assurance, greenwashing, cost of compliance and the ability of regulators to ensure that ESG reporting reflects actual corporate performance.

Theoretical / Conceptual Framework of Research and Research Methodology

1 Theoretical Framework

The research is based primarily on three theoretical perspectives:

A. Agency Theory

Agency theory considers the potential conflict between shareholders and corporate management. ESG disclosures, independent directors, audits and transparency mechanisms can reduce information asymmetry and improve managerial accountability.

B. Stakeholder Theory

Stakeholder theory recognises that corporate decisions affect multiple groups. ESG compliance expands corporate accountability from shareholders to employees, consumers, communities, suppliers and environmental interests.

C. Triple Bottom Line Theory

The triple bottom line approach emphasises three dimensions of corporate performance:

- **People – Social responsibility**

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- **Planet – Environmental sustainability**
- **Profit – Economic performance**

ESG governance reflects this broader understanding of corporate success.

2 Conceptual Framework

The conceptual framework of this research may be represented as:

Corporate Governance → ESG Policies → ESG Disclosure → Stakeholder Accountability → Sustainable Corporate Performance

The effectiveness of this relationship depends upon board commitment, regulatory supervision, transparency, independent assurance and stakeholder participation.

3 Research Methodology

The study adopts a **doctrinal and analytical research methodology**. Primary sources include the Companies Act, 2013, SEBI regulations, circulars and regulatory materials. Secondary sources include books, academic articles, research papers, reports and relevant institutional publications.

The research uses qualitative analysis to examine the evolution of corporate governance and ESG compliance. Regulatory developments are analysed to identify gaps between formal legal requirements and effective implementation.

The study is exploratory and analytical rather than based on a primary survey. It therefore focuses on legal provisions, regulatory developments and emerging business practices.

4. Data Analysis and Interpretation

The analysis indicates that India's ESG regulatory framework has developed progressively from traditional corporate governance and CSR obligations towards structured ESG reporting, measurable indicators, assurance, and value-chain transparency.

Table 1: Major Developments in Corporate Governance and ESG Regulation

Regulatory Development	→	Major Significance
🏢 **Companies Act, 2013**	➜	Strengthened corporate governance and introduced a statutory framework for Corporate Social Responsibility (CSR).
🤝 **CSR – Section 135**	➜	Established statutory social responsibility obligations for qualifying companies.
⚖️ **SEBI Corporate Governance Framework**	➜	Strengthened governance, accountability and disclosure requirements for listed entities.
📊 **BRSR – 2021**	➜	Introduced structured **Business Responsibility and Sustainability Reporting** for listed entities.
📈 **BRSR Core**	➜	Increased emphasis on **measurable ESG indicators, standardisation and assurance**.
🔗 **Value-Chain ESG Disclosures**	➜	Extended sustainability transparency to relevant suppliers, customers and other value-chain participants.

Data Analysis and Interpretation

The analysis indicates that India's ESG regulatory framework has developed progressively. The Companies Act, 2013 represents a major foundation for responsible corporate conduct. Its CSR provisions require qualifying companies to establish institutional mechanisms for CSR and report on their CSR activities. SEBI's introduction of BRSR represents a significant shift from general corporate responsibility reporting towards measurable sustainability disclosures. BRSR is based on nine principles and distinguishes between essential indicators and leadership indicators. The introduction of BRSR Core further strengthens the system. SEBI's framework identifies a limited set of key performance indicators for which reasonable assurance is required and provides a phased implementation approach. It also recognises the importance of ESG impacts throughout corporate value chains.

Interpretation

The regulatory progression indicates three major trends:

First, ESG is becoming increasingly institutionalised within corporate reporting. **Second**, responsibility for ESG is increasingly shifting towards boards and senior management. **Third**, the regulatory focus is moving from mere disclosure towards **reliability, comparability and assurance** of ESG information.

However, compliance on paper does not necessarily guarantee genuine sustainability performance. Companies may face incentives to present favourable ESG information, creating risks of selective disclosure or greenwashing.

Result and Discussion

The study reveals that corporate governance and ESG compliance are becoming increasingly interconnected. An effective governance structure is necessary for successful ESG implementation. Boards must ensure that sustainability risks are incorporated into corporate strategy rather than treated merely as reporting requirements. ESG considerations can influence investment decisions, reputation, access to capital, operational risk and long-term competitiveness.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

The research also demonstrates that India's regulatory framework has moved beyond the traditional concept of CSR. CSR focuses substantially on specified social-development activities, whereas ESG encompasses environmental performance, social responsibility and governance quality. Another significant finding is the increasing importance of ESG disclosures to investors. Reliable ESG information enables investors and other stakeholders to assess a company's exposure to environmental and social risks.

Nevertheless, several challenges remain.

1 Regulatory Complexity

Companies must comply with multiple legal and regulatory requirements. Differences between corporate law, securities regulation, environmental law and labour-related requirements can create compliance complexity.

2 Greenwashing

Greenwashing occurs when an organisation presents itself as environmentally or socially responsible without sufficient evidence to support such claims. Weak verification mechanisms can reduce the credibility of ESG reporting.

3 Cost of Compliance

ESG data collection, measurement, assurance and reporting can impose substantial costs, particularly on companies with complex operations and supply chains.

4 Lack of Standardisation

Although BRSR provides a structured reporting mechanism, measuring certain social and governance indicators remains difficult because of differences in methodologies and data quality.

5 Supply-Chain Risks

A company's ESG performance may be significantly affected by suppliers and other value-chain participants. The extension of ESG disclosure considerations to value chains therefore represents an important development.

Findings

The major findings of the research are as follows:

1. **Corporate governance is the foundation of effective ESG compliance.** Without responsible boards and management, ESG policies may remain merely formal.
2. **Indian business law is progressively incorporating sustainability principles.** The Companies Act and SEBI regulatory framework demonstrate this transition.
3. **BRSR has strengthened ESG transparency.** It provides a structured approach to sustainability reporting by listed entities.
4. **BRSR Core represents a movement towards greater reliability.** The use of selected KPIs and reasonable assurance can improve the credibility of ESG information.
5. **CSR and ESG should not be treated as identical concepts.** CSR is a statutory corporate responsibility mechanism, while ESG represents a broader approach to measuring environmental, social and governance performance.
6. **Greenwashing is an emerging legal and governance concern.** Inaccurate or exaggerated ESG claims can undermine investor and stakeholder confidence.
7. **Board-level accountability is essential.** ESG should be integrated into risk management, strategic planning and corporate decision-making.
8. **ESG compliance is increasingly relevant to long-term corporate value.** Companies with strong governance and credible sustainability practices may be better positioned to manage emerging environmental and social risks.

Managerial Implications

The findings have several implications for corporate managers and boards. First, companies should establish a clear **ESG governance structure**. Responsibility should not be restricted to a sustainability department; ESG should be integrated into the responsibilities of the board, senior management, risk-management teams and internal audit functions. Second, companies should develop reliable systems for collecting ESG data. ESG information should be subjected to internal controls comparable to those applied to financial information. Third, ESG risks should be incorporated into **enterprise risk management**. Climate-related risks, labour issues, supply-chain disruptions, regulatory risks and reputational risks can directly influence business performance. Fourth, management should ensure that ESG claims are supported by verifiable evidence. This is particularly important in preventing greenwashing. Fifth, companies should engage with stakeholders regularly. Employees, investors, customers, suppliers and local communities can provide valuable information regarding ESG risks and corporate impacts. Finally, boards should treat ESG not merely as a compliance cost but as a component of long-term strategy and sustainable value creation.

Recommendations

Based on the research findings, the following recommendations are proposed:

1. Strengthen Board-Level ESG Responsibility

Companies should clearly assign ESG oversight responsibilities to the board and relevant board committees.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

2. Improve ESG Data Quality
Companies should establish standardised internal systems for collecting, verifying and documenting ESG information.
3. Expand Independent Assurance
Independent assurance of important ESG indicators should be progressively strengthened to improve reliability and stakeholder confidence.
4. Prevent Greenwashing
Regulators should strengthen monitoring of misleading ESG claims and require companies to provide evidence supporting material sustainability statements.
5. Integrate ESG into Risk Management
ESG risks should be included within the company's enterprise risk-management framework rather than being treated as a separate sustainability issue.
6. Strengthen Supply-Chain Governance
Companies should introduce ESG standards for suppliers and conduct appropriate due diligence throughout their value chains.
7. Improve Stakeholder Participation
Companies should develop mechanisms through which investors, employees, consumers and communities can communicate ESG concerns.
8. Promote ESG Awareness
Training should be provided to directors, senior managers, compliance officers and employees concerning ESG obligations and emerging regulatory expectations.
9. Encourage Comparability
Regulators and industry bodies should continue developing consistent ESG metrics so that stakeholders can meaningfully compare corporate performance.
10. Integrate ESG with Corporate Strategy
ESG should be incorporated into business planning, capital allocation, executive performance evaluation and long-term corporate strategy.

Conclusion

Corporate governance and ESG compliance represent an important transformation in Indian business law. The traditional concept of corporate governance, centred primarily on shareholder protection, has increasingly expanded towards stakeholder accountability and sustainable business practices. India has developed a significant regulatory framework through the Companies Act, 2013, CSR provisions and SEBI's corporate governance and sustainability-disclosure requirements. The introduction of BRSR established a structured mechanism for ESG reporting, while BRSR Core has moved the regulatory framework further towards measurable indicators and assurance. However, effective ESG governance cannot be achieved through disclosure requirements alone. It requires genuine commitment from boards, management and other stakeholders. Companies must move beyond a compliance-oriented approach and incorporate sustainability into their core business strategies. The future of Indian business law is therefore likely to involve greater integration between **corporate governance, sustainability, stakeholder protection, transparency and corporate accountability**. ESG should be understood not simply as an additional regulatory burden but as an essential component of responsible and sustainable corporate governance.
In conclusion, **strong corporate governance is the institutional foundation of credible ESG compliance**. The effectiveness of India's emerging ESG framework will ultimately depend upon the quality of implementation, accuracy of disclosures, independent assurance, regulatory enforcement and the willingness of companies to place sustainability at the centre of long-term business decision-making.

Acknowledgment
The author expresses sincere gratitude to the management and colleagues of Padmashree Bhausaheb Vartak College for their encouragement, support, and academic environment that facilitated the completion of this research work. Special appreciation is extended to scholars, legal researchers, policymakers, and regulatory institutions whose publications, reports, and analytical studies on corporate governance, ESG compliance, corporate sustainability, and business law provided valuable guidance for this study.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

Selected References
1. Companies Act, 2013, Ministry of Corporate Affairs, Government of India.
2. Securities and Exchange Board of India, *Business Responsibility and Sustainability Reporting by Listed Entities*, 2021.
3. Securities and Exchange Board of India, *Balanced Framework for ESG Disclosures, Ratings and Investing*.
4. Securities and Exchange Board of India, materials concerning corporate governance and ESG regulation.
5. Ministry of Corporate Affairs, Government of India, materials concerning Corporate Social Responsibility under the Companies Act, 2013.
6. SEBI, *SEBI Bulletin – Evolution of ESG in India*.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI-Driven Smart Materials for Sustainable Energy Applications: Advancing Smart Technologies for Viksit Bharat 2047

Aaditi Prakash Patil
Assistant professor, Department of Physics, Shripatrao Chougule Arts and Science College Kotoli, Tal. -Panhala, Dist.-Kolhapur

Manuscript ID:
BN-2026-030918

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 95-100

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913628
DOI link: https://doi.org/10.5281/zenodo.22913628

Abstract

Artificial Intelligence (AI) and advanced materials are increasingly being integrated to accelerate research in sustainable energy technologies. The paper presents a physics-based approach to AI-driven smart materials, focusing on photovoltaic conversion, batteries, supercapacitors, thermoelectric systems, and hydrogen technologies. It emphasizes that AI should support material screening and optimisation rather than replace fundamental physics. Materials such as perovskites, nanostructures, two-dimensional materials, electrode materials, and thermoelectric compounds are discussed. Analytical models are used to understand photovoltaic efficiency, capacitor energy, and thermoelectric performance. The study also proposes physics-informed machine learning to improve material prediction and optimisation. Key challenges include data quality, uncertainty, interpretability, extrapolation, and experimental validation. Overall, the AI–Physics–Experiment approach can accelerate materials research and contribute to sustainable energy development in India.

Keywords: *Artificial Intelligence; Machine Learning; Smart Materials; Materials Physics; Sustainable Energy; Perovskites; Photovoltaics; Energy Storage; Thermoelectrics; Physics-Informed Machine Learning; Viksit Bharat 2047.*

Introduction

Sustainable energy technology depends on advances in materials that can absorb light efficiently, transport charge, store electrochemical energy, convert waste heat and catalyse chemical reactions. The physical behaviour of these materials is controlled by quantities such as band gap, carrier concentration, mobility, defect density, ionic diffusion, electrical conductivity and thermal conductivity. Conventional materials development often relies on repeated synthesis, characterization and testing. Materials-informatics research has shown that machine learning can accelerate this cycle by learning relationships between descriptors and target properties [1–3]. Recent work extends this approach to perovskite solar cells, where machine learning has been applied to material discovery, device-performance prediction, process optimization and system-level analysis [4,5]. Energy-storage research similarly uses AI for materials discovery, performance prediction, degradation analysis and optimization [6,7]. These developments motivate a broader Physics–AI framework for sustainable energy. This paper is a review plus analytical framework. It does not report new laboratory measurements. All numerical graphs in the paper are explicitly model-based or illustrative and are calculated from stated equations. Literature claims are cited so that the distinction between established evidence and the proposed framework remains clear.

Rationale of the Study

The chemical and structural design space of advanced energy materials is very large.

Creative Commons *(CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Aaditi Prakash Patil, Assistant professor, Department of Physics, Shripatrao Chougule Arts and Science College Kotoli, Tal. -Panhala, Dist.-Kolhapur
Email: patilaaditip@gmail.com

How to cite this article:
Patil, A. P. (2026). AI-Driven Smart Materials for Sustainable Energy Applications: Advancing Smart Technologies for Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 95–100. https://doi.org/10.5281/zenodo.22913628https://doi.org/10.5281/zenodo.22913628

Quick Response Code:

Website: https://bnir.us

High-throughput calculations can screen candidates, but detailed simulations may be computationally expensive and experiments remain resource intensive. Machine learning can act as a rapid surrogate model, prioritizing candidates for more expensive calculations or laboratory testing [1–3]. The limitation is that purely statistical models can extrapolate poorly and may ignore physical constraints. Physics-informed machine learning addresses this issue by incorporating governing equations or physical invariants into the learning process [8].

Objectives

1. To review the applications of AI and machine learning in smart materials for sustainable energy.
2. To examine the relationship between AI-based predictions and the physical parameters governing energy conversion and storage.
3. To propose a closed-loop AI–Physics–Experiment workflow for efficient materials research.
4. To discuss the relevance of AI-driven materials research to sustainable technology and India's Viksit Bharat 2047 vision.

Hypothesis

If AI models use physically meaningful descriptors and are coupled to experimental validation, then promising energy materials can be identified and optimized more efficiently than by an unconstrained trial-and-error search. This hypothesis concerns research-workflow efficiency and decision support; it does not imply that AI can exceed fundamental physical limits.

Methodology

A structured literature review was conducted using peer-reviewed literature on materials informatics, physics-informed machine learning, perovskite photovoltaics, energy-storage materials and thermoelectrics. The evidence was organized into application domains. Established physical equations were then used to construct reproducible analytical examples. The analysis deliberately separates model-based calculations from experimental results.

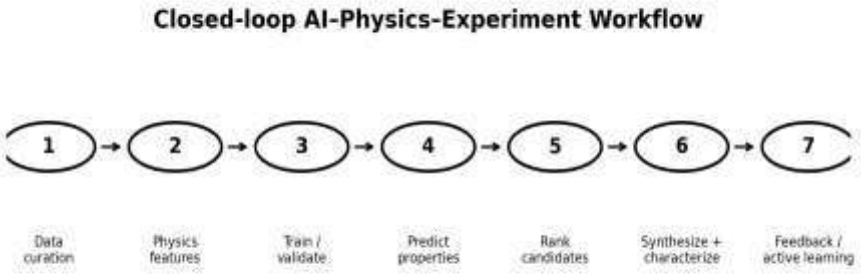


Fig.1 Closed-loop AI–Physics–Experiment workflow proposed in this study.

Smart Materials and Their Physics

1 Perovskite materials

Metal-halide perovskites are commonly described within the ABX3 structural family.

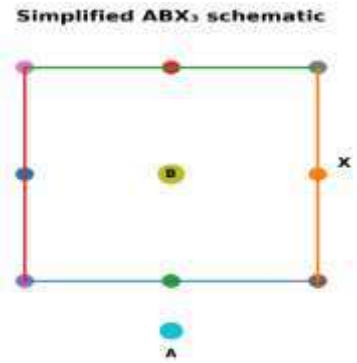


Fig.2 Simplified ABX3 perovskite schematic; conceptual, not crystallographic scale.

Their optical and electronic properties can be tuned through composition and structural engineering. Machine learning has been used to accelerate perovskite property prediction, candidate

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

screening, device optimization and analysis of fabrication variables [4,5]. From a physics perspective, useful descriptors include composition, band gap, formation-related quantities, carrier mobility, defect-related features, film-processing parameters and interface characteristics. These descriptors can be supplied to regression, ensemble or neural-network models.

2 Nanostructured and two-dimensional materials

Nano structuring changes surface-to-volume ratio, transport pathways and sometimes electronic states. Two-dimensional materials provide tunable electronic, optical and surface properties. These characteristics are relevant to electrodes, catalysts and photovoltaic interfaces. AI can connect measurable or computed descriptors such as surface area, pore volume, composition and local coordination with target performance.

3 Thermoelectric materials

Thermoelectric conversion requires simultaneous control of charge and heat transport. The central design difficulty is the trade-off between electrical conductivity, Seebeck response and thermal conductivity [9,10]. This makes thermoelectrics a natural multi-objective optimization problem for AI.

AI/ML Framework for Materials Discovery

A generic materials-learning problem can be represented as:

$$Y = f(\mathcal{X}) + \epsilon$$

where X is a vector of composition, structural, electronic, thermal or processing descriptors; f is the learned relationship; and ε represents measurement noise and model error. Training, validation and testing should be separated to reduce information leakage. For small datasets, uncertainty estimates and out-of-distribution checks are essential. A physically meaningful workflow is: data curation → descriptor generation → model training → validation → property prediction → candidate ranking → experimental synthesis → characterization → feedback. This loop allows the model to learn from new experiments rather than remaining static.

AI-Driven Photovoltaic Materials

Photovoltaic performance depends on absorption, charge generation, transport, recombination and interfaces. The power-conversion efficiency can be written as:

$$\eta = \frac{V_{OC} J_{SC} FF}{P_{in}} \times 100$$

Where, V_{OC} = is open-circuit voltage, s

J_{SC} = is short-circuit current density,

FF = is fill factor and

P_{in} = is incident power density.

AI can be used to predict these quantities or the material and processing conditions associated with them [4,5].

For fixed V_{OC}, J_{SC} and P_{in}, efficiency varies linearly with FF. The graph demonstrates how a simple physical relationship can provide a target for AI-assisted optimization. The AI task is to discover material or processing changes that can improve FF, voltage or current while maintaining stability.

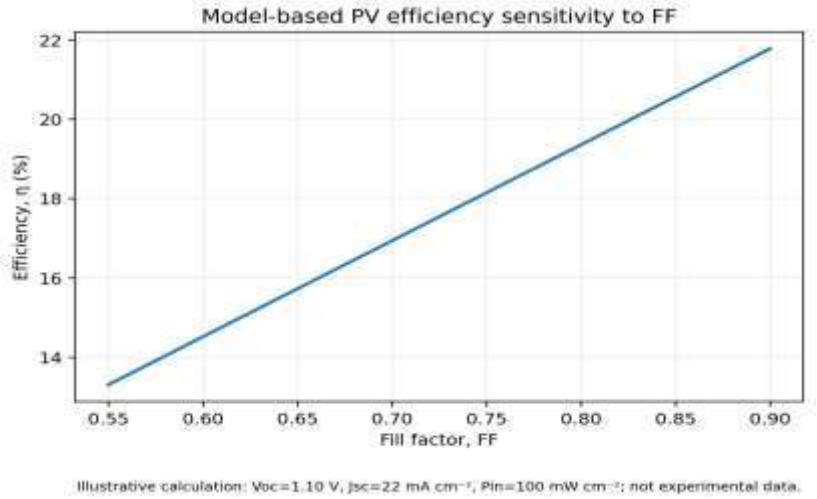


Fig.3 Model-based PV efficiency sensitivity to fill factor. Assumptions: V_{OC} = 1.10 V, J_{SC} = 22 mA cm^{-2}, P_{in} = 100 mW cm^{-2}. This is an analytical illustration, not experimental data.

AI for Batteries and Supercapacitors

Energy storage is required to balance variable renewable generation. Recent reviews describe AI applications in battery material discovery, electrode and electrolyte design, performance prediction, degradation analysis and state estimation [6,7]. Relevant physics includes ion diffusion, electrochemical potential, conductivity, interfacial resistance and structural stability.

For an ideal capacitor:

$$E = \frac{1}{2} C V^2$$

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Where, C = is capacitance and
V = is operating voltage.

The quadratic voltage dependence makes voltage stability an important design parameter.

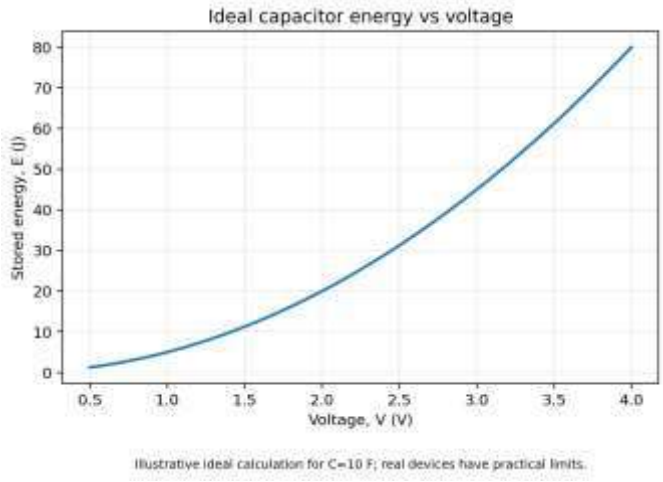


Fig.4 Ideal capacitor energy versus voltage for C = 10 F. Analytical illustration only; real devices have practical limits.

AI can optimize electrode composition, pore structure, surface area and electrolyte conditions. However, a high predicted capacity or capacitance must be balanced against stability, manufacturability, safety, material availability and environmental impact.

10. AI for Thermoelectric Energy Conversion

The dimensionless thermoelectric figure of merit is:

$$ZT = \frac{S^2 \sigma T}{k}$$

where S is the Seebeck coefficient,
σ is electrical conductivity,
κ is total thermal conductivity and
T is absolute temperature.

High ZT requires favourable electrical transport and low thermal conductivity [9,10].

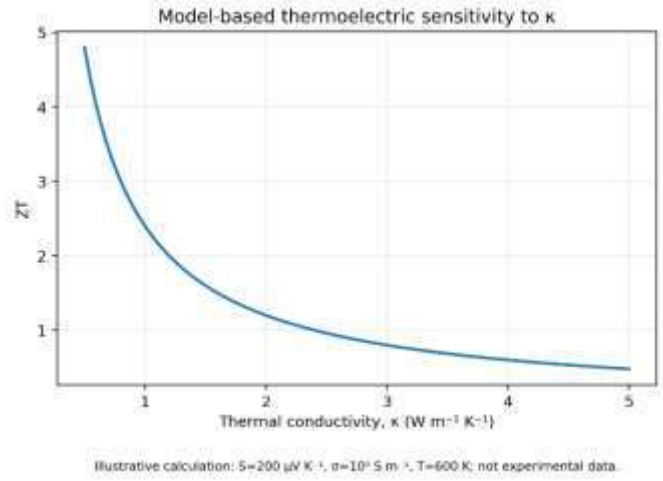


Fig.5 Model-based ZT sensitivity to thermal conductivity. Assumptions: S = 200 μV K^{-1}, σ = 10^5 S m^{-1} and T = 600

K. Analytical illustration only.

The inverse dependence on κ follows directly from the equation. AI can search composition and structure spaces for combinations that are associated with high $S^2\sigma$ and low κ. Recent thermoelectric research emphasizes the difficulty of decoupling electrical and thermal transport, reinforcing the value of multi-objective design [9].

AI for Hydrogen-Energy Materials

Hydrogen technologies involve catalysts, membranes, electrodes and storage materials. Candidate catalyst performance depends on adsorption energetics, surface structure, electronic states and reaction kinetics. AI can screen candidates using descriptors obtained from calculations or experiments, while physics-based calculations and laboratory measurements provide validation. The same closed-loop strategy can be applied to electrolysis, fuel cells and hydrogen-storage materials.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Physics-Informed Machine Learning

A generic physics-informed objective can be expressed as:

$$L_{total} = L_{data} + \lambda L_{physics}$$

L_{data} measures mismatch between predictions and observations; $L_{physics}$ measures violation of a governing equation or physical constraint; λ controls the relative weight. Physics-informed learning can combine noisy data with mathematical models and is useful for forward and inverse problems [8].

For energy materials, physical constraints can include charge conservation, energy conservation, diffusion equations, heat transport or electrochemical relations. This approach can improve physical consistency, but it does not eliminate the need for good data and experimental validation.

Analysis and Data Analysis

Three analytical demonstrations were used. They are intentionally reproducible and do not claim original experimental measurements.

Model	Fixed parameters	Variable	Output
PV efficiency	V_{OC}=1.10 V; J_{SC}=22 mA cm^{-2}; P_{in}=100 mW cm^{-2}	FF 0.55–0.90	η (%)
Thermoelectric	S=200 μV K^{-1}; σ=10^5 S m^{-1}; T=600 K	κ 0.5–5 W m^{-1} K^{-1}	ZT
Capacitor	C=10 F	V 0.5–4 V	E (J)

The photovoltaic graph shows a linear sensitivity of efficiency to FF when the other parameters are fixed.

The thermoelectric graph shows the inverse dependence of ZT on κ for fixed S, σ and T.

The capacitor graph shows the quadratic dependence of stored energy on voltage.

These demonstrations illustrate an important research principle: AI is most useful when the prediction target is physically defined. The model can search the material space, but the final selection should remain connected to measurable physical quantities.

Integrated AI–Physics–Energy Framework

The proposed framework integrates five levels: (1) material descriptors and physical laws, (2) AI-based prediction and uncertainty estimation, (3) synthesis and characterization, (4) device optimization, and (5) system-level energy management. This integrated approach recognizes that good material properties alone may not ensure practical application because stability, cost, processing, and scalability are also important. Therefore, AI-driven material discovery should be connected with device performance and system-level energy requirements.

Relevance to Viksit Bharat 2047

AI-driven materials research can contribute to India's Viksit Bharat 2047 vision by supporting the development of renewable-energy materials, advanced energy storage, hydrogen technologies, waste-heat recovery, and intelligent energy systems. The integration of AI with physics can promote reliable, indigenous, and sustainable energy-material innovation. This approach can strengthen the connection between fundamental research, technological development, and India's long-term sustainability goals.

Conclusion

AI-driven smart materials offer a promising approach to sustainable-energy research by combining machine learning with physics-based understanding. Applications in photovoltaics, batteries, supercapacitors, thermoelectrics, and hydrogen materials can benefit from AI-assisted screening and optimisation. However, physical constraints, uncertainty analysis, and experimental validation remain essential. The proposed AI–Physics–Experiment framework can improve research efficiency while preserving the role of fundamental science and supporting India's sustainable-energy and Viksit Bharat 2047 objectives.

Acknowledgment

The author expresses sincere gratitude to the Principal and the Department of Physics, Shripatrao Chougule Arts and Science College, Kotoli, for providing continuous encouragement and academic support during the preparation of this research work. Special thanks are extended to colleagues and fellow researchers whose valuable discussions and suggestions contributed to the development of this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Schmidt, J., Marques, M. R. G., Botti, S., & Marques, M. A. L. (2019). Recent advances and applications of machine learning in solid-state

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

materials science. *npj Computational Materials, 5*, 83. https://doi.org/10.1038/s41524-019-0221-0

2. Jain, A., Shin, Y., & Persson, K. A. (2016). Computational predictions of energy materials using density functional theory. *Nature Reviews Materials, 1*, 15004. https://doi.org/10.1038/natrevmats.2015.4
3. Ramprasad, R., Batra, R., Pilania, G., Mannodi-Kanakkithodi, A., & Kim, C. (2017). Machine learning in materials informatics: Recent applications and prospects. *npj Computational Materials, 3*, 54. https://doi.org/10.1038/s41524-017-0056-5
4. Chen, M., Yin, Z., Shan, Z., Zheng, X., Liu, L., Dai, Z., Zhang, J., Liu, S. F., & Xu, Z. (2024). Application of machine learning in perovskite materials and devices: A review. *Journal of Energy Chemistry, 94*, 254–272. https://doi.org/10.1016/j.jechem.2024.02.035
5. Huang, G., Huang, F., & Dong, W. (2024). Machine learning in energy storage material discovery and performance prediction. *Chemical Engineering Journal, 492*, 152294. https://doi.org/10.1016/j.cej.2024.152294
6. Karniadakis, G. E., Kevrekidis, I. G., Lu, L., Perdikaris, P., Wang, S., & Yang, L. (2021). Physics-informed machine learning. *Nature Reviews Physics, 3*, 422–440. https://doi.org/10.1038/s42254-021-00314-5

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Fintech Adoption in India and Its Role in Banking Sector Development: Strategic Challenges and Future

Prashant Prakash Deshmukh
Assistant Professor, Department of Economics, SMT. Champaben Balchand Shah Mahila Mahavidyalay, Sangli

Manuscript ID:
BN-2026-030919

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 101-105

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913824
DOI link:
https://doi.org/10.5281/zenodo.22913824

Abstract
Fintech, or financial technology, has grown in significance on a worldwide scale as it transforms how people and companies engage with financial services. Fintech uses technology to improve financial services' accessibility, efficiency, transparency, and innovation, which benefits a variety of users in many industries. India's financial ecosystem has changed as a result of the quick development of financial technology, giving millions of consumers better access to financial services via digital and mobile platforms. This descriptive study examines the factors that have contributed to the emergence of fintech, the different kinds of fintech apps, the obstacles that fintech applications face in India and the prospects for the future.

Keywords: *UPI, FinTech, Digital Finance, Mobile Banking, Digital Banking*

Introduction:

The "FinTech" is inferred by the terms ``Finance" and "Technology". The technologies are playing a key part in offering digital platforms to undertake financial activities and its help us in banking and financial services for seamless conduction and essay access. FinTech are applying by financial service firms for use and to raise the satisfaction level of consumers & investors. FinTech are offering various kind of financial services such as rob advisors or artificial intellig ent, mobile payment & payment apps, digital portfolio management & investment apps, crowd funding, peer- to- peer (P2P), Big data, smart contracts, Insurtech, crypto currency, block chain, cyber security etc. Fintech is a new regime and a new trend in financial literacy.It alludes to the word FinTech, which is mostly used for innovation and the seamless execution of financial and business activities. the state of technology in the different industries while using fintech. The role of fintech before and after the epidemic was also assessed by the study.

Financial services trends including payment, digitalization, and tech-friendly financial performance have all been positively impacted by technology. The study discovered the disparity between future Fintech prospects and financial literacy. Future research will focus on gaining a thorough grasp of Fintech in various financial sectors and creating an awareness policy to increase financial literacy and explain its advantages and applications. The combination of FinTech innovation, digital public infrastructure, and evolving consumer expectations is driving a fundamental overhaul of the global banking industry. Mobile-first, real-time, API-driven, and data-intelligent systems are quickly replacing traditional banking models that have historically relied on physical branches, human middlemen, and paper-based procedures.

Creative Commons *(CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Prashant Prakash Deshmukh, Assistant Professor, Department of Economics, SMT. Champaben Balchand Shah Mahila Mahavidyalay, Sangli
Email: deshmukhprashant3930@gmail.com

How to cite this article:
Deshmukh, P. P. (2026). Fintech Adoption in India and Its Role in Banking Sector Development: Strategic Challenges and Future. Bulletin of Nexus Journal, 3(9(II)), 101–105.
https://doi.org/10.5281/zenodo.22913824

Quick Response Code:

Website: https://bnir.us

Due in large part to the success of state-led digital enablers like Aadhaar (digital identity), Unified Payments Interface (UPI), DigiLocker (document verification), and the developing Account Aggregator Framework (data consent system), this transformation has accelerated in India at a rate that is unparalleled globally. India's change is driven by public infrastructure yet privately innovated, in contrast to Western countries where digitization developed gradually through private innovation. UPI, FinTechs, and Digital Public Infrastructure (DPI) are driving the quickest banking revolution in the world in India. Payments are now completely commoditized, with over 12 billion UPI transactions occurring each month (NPCI, 2024). While traditional banks continue to have deposits, trust, and regulatory authority, FinTechs like PhonePe, Google Pay, Zerodha, and PolicyBazaar now control the majority of customer ownership.

Objectives of the Study: -

The major objectives of the present research study are as follows:

1. To study the Challenges and Future ofFin Techs
2. To study the Volume of Digital Payment in India.

Research Methodology:

Every research is necessary a specific methodology so for the present research has used specific methodology. The present research study is an analytical type of study. The study uses all the necessary methods useful for data collection, for the collection of data, the researcher has used the Secondary source. Secondary data requiringfor the study is collected from books, journals and other Government websites, periodicals, and reports etc.

Review of Literature:

Dey Sonia and Hushain Junaid (2022) "Evolved of Digital Technology and Fintech Study in India: Opportunities and Challenges For Startup Companies" Fintech is an acronym for Financial Technology, which gives alternate options for banking and non-banking finance services. Fintech is a new phrase in the financial sector. The primary purpose of this paper is to evaluate the Fintech segments and the Fintechstartup sector. It depicts the growth of a Fintechstart-up firm and the current state of financial Technology (Fintech) in the Indian financial industry. By digitizing transactions, Fintech makes them safer for users. Lower operating costs and an intuitive user interface are two advantages of Fintech services. India is experiencing the fastest global growth in fintech services. Fintech startups in India have a plethora of potential despite these obstacles. The practices and conduct of the Indian banking industry would be impacted by fintech services. Therefore, it is necessary to handle these issues proactively and solve them by strategic decision-making, which will propel FinTechStartups toward revolutionary growth. In addition to these difficulties, FinTech startups in India have a lot of chances. Future financial services in India will be dominated by the FinTech sector, according to all secondary data, literature analysis, and study findings.

AmbekarLata M. (2024) "Study of Fintech on Indian Banking Sector: Conceptual Framework" Any nation's economic growth is contingent upon the growth of economic activities such as mining, construction, trade and commerce, fishing, agriculture, and industry. By offering financial support, the banks are contributing significantly to the establishment and promotion of these initiatives. Therefore, the existence and expansion of a nation's banking industry ultimately determine its economic success. FinTech advancements have significantly increased in India as a result of government initiatives to promote a cashless economy, growing smart phone penetration, and the development of digital infrastructure. The financial services industry in the nation has undergone a transformation thanks to the remarkable development of FinTech in recent years. Fintech companies use technology to develop innovative solutions for financial services like insurance, banking, payments, and investments. Fintech businesses often provide their services through mobile apps or digital platforms, providing clients with simple and convenient ways to handle their money. Peer-to-peer lending platforms, digital banks, investment management robo-advisors, mobile payment systems, and crypto currency exchanges are examples of fintech businesses. Fintech has the potential to transform the financial services sector by improving client accessibility, efficiency, and affordability. However, the quick growth of fintech has raised concerns about cyber security, privacy, and regulatory compliance in addition to the potential for job displacement as technology automates routine tasks in the nation's financial and economic development.

B. Parimala Devi (2024) "A paper on Fintech applications in India" Fintech, or financial technology, has grown in significance on a worldwide scale as it transforms how people and companies engage with financial services. Fintech uses technology to improve financial services' accessibility, efficiency, transparency, and innovation, which benefits a variety of users in many industries. Millions more Indians now have better access to financial services via digital and mobile platforms thanks to the quick development of financial technology, or fintech. This descriptive study examines the factors that have contributed to

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

the emergence of fintech, the different kinds of fintech apps, the obstacles that fintech applications face in India and the prospects for the future.

Meaning Of Fintech Banking Services:

The terms "financial" and "technology" are combined to form FinTech. It describes the application of technology to enhance the provision of financial services and goods. Digital financial services offered by banks, financial institutions, payment processors, and technology-based businesses are known as fintech banking services. FinTech does not imply that banks will be entirely replaced. Rather, it frequently fosters collaboration between banks and digital firms. Banks offer customer accounts, deposits, lending capacity, compliance systems, and regulated financial infrastructure. FinTech companies provide user-friendly mobile apps, data-driven services, digital on boarding, payment interfaces, and innovative client outreach strategies. For instance, paying a shopkeeper with a UPI application may seem like a straightforward transaction, but it actually requires a bank account, a payment service provider, a secure payment network, authentication mechanisms, and regulatory oversight. In order to provide quicker and more convenient services, FinTech banking combines financial institutions with digital platforms.

Growth of Digital Payments In India:

The most obvious outcome of FinTech development in India is now digital payments. People's money management practices are evolving, as evidenced by the growing use of UPI, mobile banking, QR codes, cards, online transfers, and payment apps. In India, UPI has become the most significant retail payment mechanism. It makes it possible for people to use a mobile phone to transfer money directly between bank accounts. Consumers can use a UPI ID, scan a QR code, enter a mobile number, or choose a stored contact to make payments. Payments to retailers, taxi drivers, restaurants, utility service providers, friends, and family are examples of small-value, frequent, daily transactions that benefit greatly from this system. In the first half of 2025, UPI made up almost 85% of all digital payment transactions in India. About 10,637 crore transactions of about ₹143.3 lakh crore were completed using UPI during this time. This demonstrates UPI's dominance in regular retail payments. However, various payment mechanisms have different functions. RTGS is crucial for high-value transfers, although UPI is typically chosen for frequent, lower-value retail transactions. This indicates that a full banking ecosystem necessitates a variety of payment mechanisms for various consumer needs, so the success of FinTech banking should not be determined solely by the quantity of UPI payments.

Challenges And Future:

Despite the tremendous growth and impact of fintech applications in India, several challenges continue to affect their adoption, regulation, and sustainable operation. Here are some of the main challenges in the usage of fintech applications in India:

1. Regulatory and Compliance Issues

The Reserve Bank of India (RBI) and other regulatory agencies impose strict rules on fintech companies operating in a highly regulated environment. Regulations pertaining to digital lending, cryptocurrency, and data protection are among those that frequently change, creating uncertainty and necessitating ongoing adaptation on the part of fintech businesses. For fintech companies, adhering to know-your-customer (KYC) and anti-money laundering (AML) regulations also increases operational costs and complexity.

2. Data Privacy and Security Concerns

Fintech apps are attractive targets for cyber attacks and data breaches because they handle sensitive financial and personal data. With an increase in digital transactions, India has witnessed a surge in cyber threats such phishing, fraud, and identity theft. Building and sustaining consumer trust is difficult due to the lack of a comprehensive data protection law (though the Data Protection Bill is under progress), which has created worries about user privacy, data sharing, and security.

3. Financial Literacy and Digital Literacy Gaps

A sizable section of India's population still lacks the digital literacy or financial expertise necessary to utilize fintech apps, despite their goal of democratizing financial access. Older persons and people living in rural and semi-urban areas may have trouble comprehending fintech applications, which limits their capacity to use these platforms ethically and confidently.

4. Trust and Credibility Issues

Fintech companies are very young and may not have the same amount of confidence as traditional banks, which have long-standing ties and credibility with Indian consumers. Consumer trust has been further damaged by scams, frauds, and instances of unethical behavior by certain online lenders. Fintech businesses need to make an effort to build a reliable reputation, particularly with new users and those living in rural areas.

5. Cyber security Threats

Fintech businesses are more vulnerable to cyber security threats including ransomware attacks, hacking, and data breaches due to their growing reliance on digital platforms. Maintaining strong

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

cyber security procedures becomes difficult as cyber-attacks get more sophisticated, particularly for smaller fintech businesses with fewer resources. To keep users' trust, secure transactions and data protection are essential.

6. Infrastructure and Connectivity Constraints

Even while internet access in India has greatly increased, there are still places with poor network infrastructure and poor connectivity, especially in rural and isolated areas. The seamless use of fintech apps can be hampered by unreliable internet connections and power outages, which can negatively impact users' experiences outside of big cities.

7. High Competition and Cost Pressures

The fintech market in India is extremely competitive, with several companies providing comparable lending, investment, and payment services. Fintech companies find it challenging to sustain long-term profitability due to pricing pressures and low profit margins caused by this rivalry. Furthermore, smaller fintech businesses may be overshadowed by larger, more resource-rich players, which could hinder their ability to flourish.

8. Fraud and Digital Payment Risks

Fraudulent activities like phishing, OTP scams, and phony UPI connections have increased along with the popularity of digital payments. Numerous customers become victims of these scams, which results in monetary losses and a lack of confidence in online payments. Fintech companies continue to face difficulties in educating users about safe digital payment practices.

9. Challenges in Reaching Unbanked and Rural Populations

Fintech apps are intended to improve financial inclusion, however it is difficult to reach India's rural and unbanked communities. These populations may not have access to smart phones or the internet, which restricts their use of digital financial services. The adoption of fintech solutions may also be hampered by linguistic and cultural hurdles as well as a predilection for cash transactions in certain regions.

10. Risk of Over-Indebtedness

Customers run the risk of accruing excessive debt due to the proliferation of easily accessible digital lending and "buy now, pay later" services. Some people, especially those with little financial literacy, might take on more credit than they can manage, which could result in problems with repayment and stress. To reduce this risk, prudent lending methods and appropriate user education are crucial. With the advancement of technologies like block chain, AI, and machine learning, India's fintech industry is expected to grow even more in the future. Millions of Indians could benefit from even more individualized, safe, and effective financial services as a result of the ongoing integration of fintech into daily life.

Volume Of Digital Payment in India:

Table No.1

Volume of Digital Payment in India (In Lakhs)

Particulars	RTGS	IMPS	NEFT	UPI	Credit Cards	Debit Cards	Prepaid Instruments
2015-16	983	2,208	12,529	-	7,857	11,736	7,480
2016-17	1,079	5,067	16,221	180	10,871	23,993	19,637
2017-18	1,244	10,098	19,464	9,152	14,052	33,434	34,590
2018-19	1,366	17,529	23,189	53,915	17,626	44,143	46,072
2019-20	1,507	25,792	27,445	1,25,186	21,773	50,611	53,941
2020-21	1,592	32,783	30,928	2,23,307	17,641	40,146	49,366
2021-22	2,078	46,625	40,407	4,59,561	22,399	39,384	65,783
2022-23	2,426	56,533	52,847	8,37,144	29,145	34,179	74,667
2023-24	2,700	60,053	72,640	13,11,295	35,610	22,860	78,775
2024-25	3,025	56,250	96,198	18,58,660	47,741	16,120	70,254

Source: Reserve Bank of India

The amount of digital payments made in India via RTGS, IMPS, NEFT, UPI, credit cards, debit cards, and prepaid instruments between 2015–16 and 2024–25 is displayed in lakhs in this table. During that time, digital payments grew significantly, demonstrating India's quick embrace of electronic payment methods. The biggest growth was registered by UPI. In 2016–17, there were just 180 lakh transactions; by 2024–2025, there were 18,58,660 lakh. This is a reflection of the increasing acceptance of quick, easy, and mobile-based payments. Additionally, IMPS increased steadily*, from 2,208 lakh transactions in 2015–16 to 56,250 lakh transactions in 2024–2025. Its increase suggests

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

that there is a growing need for quick bank-to-bank transactions. NEFT increased from 12,529 lakh transactions to 96,198 lakh transactions over the period, demonstrating consistent development. This suggests that bank-based electronic fund transfers are still being used. From 983 lakh transactions in 2015–16 to 3,025 lakh transactions in 2024–25, RTGS grew steadily. RTGS's volume remained lower than that of retail payment systems because it is typically utilized for high-value transactions. Although the numbers varied in various years, credit-card transactions increased overall from 7,857 lakh to 47,741 lakh.Debit card transactions fell to 10,120 lakh by 2024–2025 after first rising to 50,611 lakh in 2019–20. Customers switching from debit cards to UPI and other mobile payment methods are mostly to blame for this reduction. The number of prepaid instruments rose from 7,480 lakh to 70,254 lakh, suggesting that wallets, prepaid cards, and other such payment methods are being used more frequently. It is evident from the chart that India's digital payment system has undergone significant change. UPI became the most popular digital payment mechanism as more established electronic payment options including RTGS, NEFT, and IMPS were expanding. A move from card-based payments to mobile and app-based transactions is suggested by the decline in debit-card transactions and the quick rise of UPI. Overall, the data shows that India's customer tastes are shifting, digitalization has expanded, and payment accessibility has improved.

Conclusion:

This essay comes to the conclusion that FinTech is changing the definition of what a bank must become rather than doing away with banks. Banks have been compelled to switch from product distribution to infrastructure orchestration because to the disruption produced by UPI, Account Aggregator, DigiLocker, and embedded finance, which has commoditized payments. India's financial landscape has completely changed as a result of the increasing use of fintech apps, giving millions of people quicker access to financial services. These applications have improved the accessibility, effectiveness, and use of banking, investing, lending, and insurance services in both urban and rural locations. Fintech applications have greatly improved financial inclusion and literacy across many socioeconomic segments by utilizing innovations like UPI for smooth payments, AI for tailored financial advise, and digital-first banking models. Thanks to government programs that encourage digital adoption, a tech-savvy populace, and a supportive regulatory framework, India's fintech ecosystem is currently among the most dynamic in the world.

Acknowledgment

The author expresses sincere gratitude to the Principal and the Department of Economics, SMT. Champaben Balchand Shah Mahila Mahavidyalay, Sangli, for their continuous encouragement, guidance, and academic support during the preparation of this research work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Dey Sonia and Hushain Junaid (2022) "Evolved of Digital Technology and Fintech Study in India: Opportunities and Challenges for Startup Companies", International Journal of Education, Modern Management, Applied Science & Social Science,Volume 04, pp. 10-16
2. ISSN: 2581-9925.
3. Ambekar Lata M (2024) "Study of Fintech on Indian Banking Sector: Conceptual Framework", GBS IMPACT**,** Volume 10, Issue - 02, ISSN: 2454- 8545.
4. B. Parimala Devi (2024) "A paper on Fintech applications in India", Journal of Emerging Technologies and Innovative Research,Volume 11, Issue 11, ISSN-2349-5162.
5. Reserve Bank of India (RBI). (2024). Digital Payments Index and Financial Stability Report.
6. National Payments Corporation of India (NPCI). (2024). UPI monthly statistics and adoption insights.
7. Agarwal, R., & Zhang, Y. (2021). The Rise of Fintech: Challenges and Opportunities in the Indian Financial Sector. International Journal of Financial Studies, 9(1), 12-25. doi:10.3390/ijfs9010012.
8. Balaji, S., &Mahajan, P. (2020). Digital Payments and Financial Inclusion in India: Role of Fintech Innovations. Journal of Emerging Markets Finance and Trade, 56(9), 2005-2016. doi:10.1080/1540496X.2020.1754748.
9. Bhasin, N., & Sharma, M. (2019). Financial Technology in India: Evolution, Applications, and Challenges. Economic and Political Weekly, 54(29), 56-64. Retrieved from https://www.epw.in

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Two-Wheeler Mechanic as a Small Business: A Socio-Economic Perspective

Sujata Sakharam Koli[1], Dr. M. K. Kamble[2]
[1]Research Scholar, Department of Economics, Autonomous, Shivaji University, Kolhapur.
[2]Assistant Professor, Department of Economics, Shripatravo chaugule, Arts and Science College Malwadi-Kotoli Tal. Panhala, Drist. Kolhapur

Manuscript ID:
BN-2026-030920

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 106-110

Submitted: 06 Aug 2026

Revised: 16 Aug 2026

Accepted: 11 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22913891
DOI link: https://doi.org/10.5281/zenodo.22913891

Abstract

Small businesses are the foundation of developing economies, with the informal sector playing a critical role in employment generation and livelihood support. Among these, two- wheeler mechanics constitute a vital yet under-recognized occupation within India's socio- economic landscape. With motorcycles and scooters accounting for nearly 75% of all vehicles sold annually, the demand for affordable repair and maintenance services has created sustainable, though largely informal, business opportunities for semi-skilled and unskilled workers. This study, based entirely on secondary data, examines the socio-economic conditions of two-wheeler mechanics, their contributions as small business operators, and the challenges they face. Findings indicate that while the sector sustains local employment, provides essential mobility services, and contributes to community development through skill transfer, it remains constrained by irregular income, lack of institutional recognition, poor working conditions, and limited access to vocational training and financial support. The study concludes that integrating mechanics into formal frameworks through policy recognition, financial inclusion, and modern skill development could transform this informal trade into a sustainable small-scale industry. Recommendations include targeted vocational programs, credit support, improved working conditions, and cooperative models to enhance collective strength. By addressing these gaps, two-wheeler mechanics can emerge as a resilient, organized segment of India's small business sector, contributing both to economic development and social equity.

Keywords: *Two-wheeler mechanics, Small-scale industry, Informal sector, Socio-economic Conditions, Livelihood, Employment generation, Skill development, Financial Inclusion, Policy recognition, Community development, Sustainable small Business, Vocational training, Automobile repair industry, Informal Entrepreneurship, India*

Introduction

Small businesses form the backbone of developing economies, creating jobs, providing essential services, and sustaining livelihoods. In India, a significant portion of these businesses operate within the informal sector, which is estimated to employ nearly 80–85% of the working population and contribute substantially to the nation's Gross Domestic Product (GDP). These informal enterprises, often overlooked in mainstream economic analysis, play a crucial role in ensuring resilience and inclusivity in the economy. One such occupation that has grown in relevance with the rapid expansion of the automobile sector is that of the two-wheeler mechanic. Two-wheeler mechanics represent a vital yet under-recognized segment of small- scale business operators. Their work is indispensable in maintaining the functionality of motorcycles and scooters, which are the most widely used mode of transport in India. According to the Society of Indian Automobile Manufacturers (SIAM, 2022), two-wheelers account for nearly 75% of all vehicles sold in India annually.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sujata Sakharam Koli, Research Scholar, Department of Economics, Autonomous, Shivaji University, Kolhapur.
Email: ssk.rs.economics@unishivaji.ac.in

How to cite this article:
Koli, S. S., & Kamble, M. K. (2026). Two-Wheeler Mechanic as a Small Business: A Socio-Economic Perspective. Bulletin of Nexus Journal, 3(9(II)), 106–110. https://doi.org/10.5281/zenodo.22913891

Quick Response Code:

Website: https://bnir.us

This dominance reflects the affordability, efficiency, and adaptability of two-wheelers in both rural and urban contexts. With such widespread use, the demand for repair and maintenance services is continuous and growing, ensuring that two-wheeler mechanics remain an essential part of India's economic and social landscape. The occupation of a two-wheeler mechanic is deeply embedded in the socio-economic structure of Indian society. On the one hand, mechanics sustain the mobility of millions of people by providing affordable services; on the other, they generate employment and self- employment opportunities for semi-skilled and unskilled workers. Many mechanics begin their careers through informal apprenticeships, skill inheritance from family members, or on-the-job training, rather than through formal technical education. With relatively low capital investment—often just a basic set of tools and access to spare parts—a mechanic can establish a small roadside garage or workshop. This makes the trade highly accessible to individuals from economically disadvantaged backgrounds, providing a pathway to self-reliance and financial stability. Despite its economic and social significance, the two-wheeler mechanics' sector remains largely informal and under-researched. The majority of workshops operate without formal registration, limiting their access to government support schemes, institutional credit, and organized markets. Working conditions are often precarious, characterized by long hours, lack of occupational safety measures, and the absence of social security benefits such as health insurance, pensions, or accident coverage. Income levels vary widely depending on location, customer base, and seasonality of demand, leading to financial instability for many workers. Furthermore, the rapid technological advancement in two-wheeler manufacturing— such as the integration of electronic fuel injection systems, advanced braking systems, and computer-based diagnostics—poses challenges for traditional mechanics who lack exposure to modern training and equipment.

From a socio-economic perspective, the role of two-wheeler mechanics extends far beyond vehicle repair. Their earnings contribute directly to household welfare, including expenditure on education, healthcare, and housing. Many mechanics also engage in skill transfer by training apprentices, thereby sustaining a cycle of informal vocational learning that supports community development. In rural and semi-urban regions, the services of mechanics are particularly crucial as they ensure mobility for farmers, workers, and small entrepreneurs, thereby facilitating access to markets, healthcare, and employment opportunities. In this way, two-wheeler mechanics not only support individual livelihoods but also indirectly contribute to broader economic activity and social well-being. The significance of this study lies in highlighting the contributions and challenges of this overlooked sector. By analysing the socio-economic conditions of two-wheeler mechanics, this research aims to bring attention to their role as small business operators who sustain livelihoods and contribute to grassroots economic development. Furthermore, the study seeks to identify opportunities for integrating this sector into formal frameworks through policy recognition, vocational training, and financial inclusion.

Rationale of the Study

Two-wheeler mechanics play a crucial role in sustaining mobility and livelihoods in India, where motorcycles and scooters account for nearly three-fourths of all vehicles. Their services ensure affordable transport for millions while creating self-employment and community-based training opportunities. Despite this importance, the sector remains largely informal and under-recognized. The study is necessary because mechanics face multiple challenges such as irregular income, lack of modern training, poor working conditions, and absence of institutional support. With the increasing technological sophistication of vehicles, these workers risk being left behind without proper skill development. By analysing their socio-economic conditions, this research highlights both their contributions to grassroots economies and the urgent need for vocational training, financial inclusion, and policy recognition. Thus, the rationale lies in bridging the gap between the critical role of two-wheeler mechanics and the lack of formal support that limits their growth as a sustainable small business sector.

Objectives of the Study

The present research has been undertaken with the following specific objectives:

1. To study the socio-economic conditions of two-wheeler mechanics
2. To analyse the challenges and opportunities

Hypothesis of the Study

Based on the objectives, the study proposes the following hypotheses:

H1: Two-wheeler mechanics contribute significantly to the informal small-scale industry sector and provide sustainable livelihoods.

H2: Lack of formal training, financial support, and social security limits their Economic progress.

Two-wheeler mechanics, despite being small business operators, face unstable income, limited financial security, and inadequate access to institutional support, which directly affects their

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

livelihood sustainability. If provided with structured vocational training, financial inclusion, and policy recognition, two-wheeler mechanics can significantly improve their economic stability and contribute more effectively to local community development and the small-scale industry sector.

Methodology of the Study

Research Method

The present study is based on secondary data analysis. It relies on published sources to understand the socio-economic role of two-wheeler mechanics as small business operators.

Research Design

The research design adopted is descriptive and analytical. It seeks to describe the socio-economic conditions of two-wheeler mechanics and analyse the challenges and opportunities in this sector through already available information.

Sources of Data

Data for this study has been collected from various secondary sources, including: Reports of the Society of Indian Automobile Manufacturers (SIAM) and related automobile industry associations. Government publications, such as the Ministry of Micro, Small and Medium Enterprises (MSME) and Labour Ministry reports. Research articles, working papers, and case studies published in academic journals. Books and reference materials on small businesses and the informal sector in India. News articles, online databases, and statistical reports providing insights into the automobile and repair industry.

Sampling

Since the study is based on secondary data, no primary sampling has been undertaken. Instead, purposive sampling of relevant literature and statistical reports has been used to ensure inclusion of authentic and reliable sources.

Tools of Analysis

The tools employed for the analysis include content analysis of published studies, comparative analysis of different reports, and interpretation of statistical data available in government and industry sources.

Analysis and Data Interpretation

The analysis in this study is based entirely on secondary information gathered from government reports, industry statistics, and published research articles. The findings are presented under key themes relevant to the socio-economic conditions of two-wheeler mechanics.

Growth of Two-Wheeler Market in India

According to the Society of Indian Automobile Manufacturers (SIAM, 2022), two-wheelers account for nearly 75% of all vehicles sold annually in India. Affordability, fuel efficiency, and ease of use have made them the preferred choice of transport for middle- and lower-income groups. This rapid increase in ownership has created a constant demand for repair and maintenance services, directly supporting the livelihood of thousands of mechanics.

Employment and Livelihood Contribution

Reports from the Ministry of Labour and Employment indicate that small informal businesses, including mechanics, form a major share of India's workforce. Two-wheeler mechanics usually operate as self-employed entrepreneurs or in small roadside workshops. This sector provides employment not only to mechanics themselves but also to apprentices and helpers, thereby creating a small ecosystem of local employment.

Income and Financial Stability

Research studies (Gupta, 2020; Sharma, 2021) suggest that the average monthly income of independent mechanics ranges between ₹05,000–₹10,000, depending on location and customer base. However, income is highly unstable due to factors such as seasonal demand, rising spare part costs, and competition from authorized service centers. Limited access to institutional credit further restricts expansion and modernization of these small businesses.

Skill Development and Training Gaps

Secondary literature reveals that most two-wheeler mechanics acquire skills through informal apprenticeship rather than formal training. With the increasing technological sophistication of vehicles many traditional mechanics lack the modern skills required. Government initiatives like **Skill India** and MSME training schemes exist, but participation from informal mechanics remains very low due to lack of awareness and accessibility.

Social Role and Community Impact

Beyond providing affordable repair services, mechanics sustain community mobility and indirectly support economic activities such as trade, education, and healthcare access. By employing apprentices, they also contribute to skill transfer within local communities, thereby maintaining a cycle of livelihood creation.

Challenges Identified

- Informality of Absence of legal recognition as small-scale industries.
- Irregular income of Dependent on fluctuating customer demand.
- Lack of financial support of Limited access to bank loans and insurance.
- Skill gaps of Inability to cope with technological advancements in modern vehicles.
- Poor working conditions of long hours, exposure to health risks, and lack of social security.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Interpretation

The secondary data clearly indicates that while two-wheeler mechanics form a vital segment of the informal economy, their contribution remains under-recognized. Their work ensures affordable mobility for millions, yet their livelihoods remain precarious due to structural challenges. Integrating them into formal support frameworks, improving skill development, and ensuring financial inclusion could transform this occupation into a sustainable small-scale industry.

Conclusions

The study highlights that two-wheeler mechanics occupy a significant place in India's socio-economic landscape. As self-employed small business operators, they provide essential repair and maintenance services that sustain mobility for millions of people, particularly from low- and middle-income groups. Their contribution extends beyond economic activity, as they also support community development through local employment and skill transfer. However, despite their importance, the sector remains largely informal and under-recognized. Mechanics face unstable incomes, lack of financial assistance, and absence of social security benefits. The reliance on informal skill acquisition methods has further created a gap between traditional practices and the modern technological demands of the automobile industry. These challenges highlight the structural vulnerabilities of this occupational group. At the same time, the growing two-wheeler market presents an opportunity for mechanics to expand their services and formalize their operations. By strengthening access to vocational training, financial inclusion, and institutional recognition, this sector can be transformed into a sustainable small-scale industry. Doing so would not only improve the livelihoods of mechanics and their families but also contribute to broader goals of economic development, social equity, and community empowerment. In essence, the study concludes that while two-wheeler mechanics currently function within the margins of the informal economy, they hold the potential to become a more organized and resilient part of India's small business sector if provided with appropriate support and policy interventions.

Recommendations

Based on the analysis and conclusions, the following recommendations are suggested to strengthen the role of two-wheeler mechanics as a sustainable small-scale business sector:

Policy Recognition and Formalization

Recognize two-wheeler mechanics under the Micro, Small and Medium Enterprises framework. Provide official registration opportunities that ensure access to government schemes, credit facilities, and social security benefits.

Skill Development and Training

Establish targeted vocational training programs through institutions like ITIs, Skill India, and private training centres to bridge the gap between traditional skills and modern technological needs. Conduct short-term certification courses in new technologies such as electronic fuel systems, hybrid engines, and digital diagnostics.

Financial Inclusion and Credit Support

Create specialized loan schemes for mechanics through banks and microfinance institutions with low-interest rates and flexible repayment options. Encourage savings and investment practices by linking mechanics to financial literacy programs.

Improvement of Working Conditions

Provide basic infrastructure support for roadside workshops, including access to safe workspaces, waste management, and health safety measures. Introduce affordable health insurance and pension schemes for mechanics and their families.

Strengthening Community and Cooperative Models

Promote the formation of mechanic cooperatives or associations to improve bargaining power, collective access to spare parts, and better business opportunities. Encourage partnerships between local governments, NGOs, and mechanic groups to create community- based service hubs.

Research and Data Collection

Encourage regular research and surveys on the socio-economic conditions of mechanics to design evidence-based policies. Develop digital databases to map informal workers and provide them with direct access to welfare programs.

Acknowledgment

The authors express their sincere gratitude to the Department of Economics, Shivaji University, Kolhapur, and Shripatrao Chougule Arts and Science College, Malwadi-Kotoli, for providing academic support and encouragement during the preparation of this research work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Bhowmik, S. K. (2010). *Street vendors in the global urban economy*. Routledge.
2. Charme's, J. (2019). The informal economy

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

worldwide: Trends and characteristics.
3. *International Labour Review, 158*(3), 473–502.
4. Deshpande, S. (2018). Informal labour markets and small-scale occupations in India.
5. *Economic and Political Weekly, 53*(28), 54–62.
6. Government of India. (2020). *Report on employment in informal sector*. Ministry of Labour and Employment. New Delhi.
7. Government of India. (2021). *Annual report 2020–21, Ministry of Micro, Small and Medium Enterprises (MSME)*. Ministry of MSME. New Delhi.
8. Gupta, R. (2020). Socio-economic conditions of informal workers in India: A study of small-scale occupations. *Journal of Social and Economic Development, 22*(3), 145– 158.
9. International Labour Organization (ILO). (2018). *Women and men in the informal economy: A statistical picture* (3rd ed.). Geneva: ILO.
10. International Labour Organization (ILO). (2021). *Decent work and the informal economy*. Geneva: ILO.
11. Kundu, A. (2017). Urban informal economy in India: Recent trends and policy challenges. *Indian Journal of Human Development, 11*(1), 1–20.
12. Mazumdar, D. (2019). Small enterprises and informal sector: An Indian perspective.
13. *South Asia Economic Journal, 20*(2), 245–263.
14. NSSO. (2019). *Periodic labour force survey (PLFS) 2018–19*. National Statistical Office, Government of India.
15. Sharma, A. (2021). Informal entrepreneurship and challenges of modernization: A case study of vehicle repair workers. *Indian Journal of Labour Economics, 64*(2), 289–305.
16. Singh, P., & Verma, K. (2019). Skill gaps in India's informal economy: An analysis of small-scale mechanics. *Asian Journal of Vocational Education and Training, 11*(1), 67– 82.
17. Society of Indian Automobile Manufacturers (SIAM). (2022). *Automobile industry report 2021–22*. New Delhi: SIAM.
18. World Bank. (2020). *The informal economy in South Asia: Trends and policies*. Washington, D.C.: World Bank Publications.
19. Government of India. (2021). *Annual Report 2020–21, Ministry of Micro, Small and Medium Enterprises (MSME)*. New Delhi: Ministry of MSME.
20. Government of India. (2020). *Report on Employment in Informal Sector*. Ministry of Labour and Employment, New Delhi.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Application of Artificial Intelligence in Mathematics Teaching and Learning: Opportunities, Challenges and Future Prospects

Shri Uttam Balaso Pawar
Department of Mathematics, Shripatrao Chougule Arts & Science College, Malwadi–Kotoli

Manuscript ID:
BN-2026-030921

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 111-114

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914100
DOI link: https://doi.org/10.5281/zenodo.22914100

Abstract

Artificial Intelligence (AI) is increasingly influencing mathematics education through personalized learning, intelligent tutoring, automated feedback, assessment support, and teacher assistance. AI-enabled systems can adapt tasks to learners' needs, provide immediate feedback, generate practice questions, and help identify misconceptions. Recent reviews suggest that adaptive platforms, intelligent tutoring systems, and generative-AI tools can support engagement, self-paced learning, conceptual understanding, and mathematical problem-solving when used under effective teacher guidance.link.springer+1 However, AI is not a replacement for mathematics teachers. Concerns remain about inaccurate AI-generated solutions, student overdependence, privacy risks, unequal access to devices and internet connectivity, algorithmic bias, and limited teacher preparedness. Evidence also remains mixed, particularly because many studies are short-term and report limited standardized measures of learning impact. This paper reviews the opportunities and challenges of AI in mathematics teaching and learning and proposes a Human–AI Collaborative Framework for responsible, equitable, and pedagogically meaningful implementation.frontiersin+1

Introduction

Mathematics education often involves diverse learning levels, limited classroom time, anxiety toward the subject, and difficulties in developing deep conceptual understanding. Conventional instruction may not always provide every learner with the pace, feedback, and practice required to overcome these barriers.

AI offers new possibilities by using machine learning, natural-language processing, and adaptive algorithms to provide individualized learning experiences. It can help students receive timely hints, explanations, practice tasks, and feedback while enabling teachers to monitor progress and address misconceptions more efficiently.link.springer+1

At the same time, the educational value of AI depends on how it is used. Technology alone does not guarantee improved learning; classroom design, teacher supervision, student readiness, curriculum alignment, and access conditions remain essential.lectitopublishing

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Shri Uttam Balaso Pawar, Department of Mathematics, Shripatrao Chougule Arts & Science College, Malwadi–Kotoli
Email: Uttambpawar99@gmail.com

How to cite this article:
Pawar, U. B. (2026). Application of Artificial Intelligence in Mathematics Teaching and Learning: Opportunities, Challenges and Future Prospects. Bulletin of Nexus Journal, 3(9(II)), 111–114. https://doi.org/10.5281/zenodo.22914100

Quick Response Code:

Website: https://bnir.us

AI Technologies in Mathematics Education

Several types of AI tools are increasingly used in mathematics classrooms and higher education.

AI technology	Main use in mathematics learning	Potential contribution
Intelligent Tutoring Systems	Step-by-step hints, diagnostic feedback, personalized exercises	Supports practice and identifies learner difficulties
Adaptive Learning Platforms	Adjusts content level and pace based on performance	Enables self-paced and differentiated learning
Generative AI Chatbots	Explains concepts, creates examples, supports questioning	Encourages dialogue, exploration, and revision
Automated Assessment Tools	Grades routine work and analyzes response patterns	Reduces routine workload and provides timely feedback
Learning Analytics Systems	Tracks progress, misconceptions, and participation	Helps teachers plan targeted interventions

Recent research identifies symbolic AI, machine learning, and generative AI as important technological categories in mathematics education. Functionally, these systems may act as adaptive infrastructure, learning partners, teaching tools, or research tools.link.springer

Opportunities

Personalized Learning

AI can adapt the difficulty, sequence, and type of mathematical tasks according to student performance. This allows learners to proceed at an appropriate pace rather than following a single pathway designed for the whole class. Adaptive platforms and AI-supported tools can offer additional practice to students who need support while providing enrichment tasks to advanced learners.uitm.edu

Such personalization may be especially useful in mixed-ability classrooms, where teachers need to address wide differences in prior knowledge and confidence.

Immediate Feedback

Students often need feedback while solving problems, not only after a test or assignment is completed. AI tools can provide hints, identify common errors, suggest alternative methods, and explain procedures immediately. Immediate feedback can help learners correct misconceptions before they become permanent. However, feedback should be designed to encourage thinking rather than simply reveal answers. Teacher-guided use is therefore important.jurnaltarbiyah.uinsu.ac+1

Stronger Problem-Solving Support

AI can serve as a cognitive scaffold by asking questions, presenting worked examples, generating similar problems, and guiding students through multi-step reasoning. When combined with active approaches such as problem-based learning or guided inquiry, AI can support critical thinking and mathematical communication.jurnaltarbiyah.uinsu.ac+1

For example, rather than asking an AI chatbot to solve an algebra problem directly, students may ask it to provide one hint at a time, explain why a particular method is appropriate, and check their own reasoning after attempting the solution.

Teacher Assistance

AI can support teachers in routine and time-consuming work, including generating practice worksheets, preparing differentiated tasks, identifying common mistakes, drafting lesson plans, and providing preliminary feedback on student responses.

These tools can give teachers more time for explanation, discussion, mentoring, and emotional support. Nevertheless, teachers must verify AI-generated material before using it in class because generated questions, explanations, and answers may contain errors.uitm.edu+1

Inclusion and Equity

AI has the potential to support students who require additional practice, personalized pacing, or alternative explanations. It may also help create multilingual learning materials and accessible content for learners from different linguistic and educational backgrounds. However, equity gains are possible only when schools provide dependable connectivity, suitable devices, accessible platforms, and teacher support. Without these conditions, AI may widen existing digital inequalities.journal.unpas.ac+1

Challenges

Teacher AI Literacy

Many teachers have limited experience with AI tools, prompt design, data protection, and evaluation of AI-generated outputs. Without professional development, AI may be used only for superficial tasks or may be introduced without clear

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

learning objectives. Teacher training should focus on both technical skills and pedagogy: when to use AI, when not to use it, how to verify its output, and how to design activities that preserve mathematical reasoning.journal.unpas.ac+1

Over-Reliance on AI

A major concern is that students may use AI to obtain answers instead of developing mathematical reasoning. If learners accept AI-generated solutions without checking them, they may become dependent on the tool and lose opportunities to build persistence, problem-solving habits, and independent thinking. Research highlights the risk of digital passivity and reduced analytical depth when AI is used without guidance. AI should therefore be positioned as a learning assistant, not as an answer machine.journal.unpas.ac+1

Accuracy and Hallucinations

Generative AI may produce mathematically incorrect, incomplete, or misleading explanations. These errors can be particularly problematic in proof-based tasks, complex word problems, advanced algebra, calculus, and reasoning-intensive questions. A recent systematic review found that generative AI can support motivation and personalized learning but has notable limitations in mathematical-reasoning accuracy and critical-thinking development. Students and teachers should be trained to verify responses using textbooks, mathematical principles, peer discussion, and teacher feedback.frontiersin

Privacy and Ethics

AI tools may collect data about student performance, interactions, learning patterns, and personal information. Schools must ensure that AI platforms follow data-protection standards and do not expose students to unnecessary surveillance or misuse of personal data. Ethical implementation also requires attention to algorithmic bias, transparency, fairness, academic integrity, and informed consent.uitm.edu+1

Infrastructure Gaps

Reliable internet access, devices, electricity, technical support, and affordable software are necessary for sustained AI integration. Many rural and under-resourced institutions may not have these facilities consistently available.

Therefore, AI adoption should begin with realistic pilot projects and low-cost, accessible solutions rather than assuming that all learners have equal digital access.journal.unpas.ac+1

Human–AI Collaborative Framework

A responsible approach to AI in mathematics education should combine the strengths of teachers and technology.

Component	Role in practice
Teacher as orchestrator	Plans lessons, selects tools, monitors use, and corrects misconceptions
AI as learning partner	Provides practice, feedback, examples, and personalized scaffolding
Student as critical learner	Questions, verifies, compares, and reflects on AI-generated responses
Curriculum alignment	Ensures AI activities support learning outcomes rather than distract from them
Ethical safeguards	Protects privacy, promotes fairness, and maintains academic integrity
Professional development	Builds teacher confidence in pedagogical and responsible AI use
Equity planning	Ensures access for learners with limited devices, connectivity, or language support

This framework recognizes that the teacher's role becomes more important—not less important—in an AI-supported classroom. Teachers remain responsible for creating meaningful mathematical tasks, interpreting student understanding, promoting discussion, and developing learners' confidence and reasoning.mail.asiaentrepreneurshipjournal

Implementation Steps

1. **Begin with a pilot:** Introduce one or two carefully selected AI tools in a limited number of mathematics classrooms.
2. **Train teachers:** Provide workshops on AI literacy, prompt design, verification of outputs, assessment design, privacy, and ethical use.
3. **Set clear learning goals:** Use AI only where it supports specific outcomes, such as algebraic reasoning, practice, feedback, or conceptual explanation.
4. **Teach critical AI use:** Ask students to identify errors, compare AI methods with textbook methods, and justify which solution is correct.
5. **Monitor outcomes:** Collect feedback from students and teachers, examine learning evidence, and revise implementation practices.
6. **Scale responsibly:** Expand use only after addressing infrastructure, access, curriculum alignment, and data-protection requirements.

Future Prospects

The future of AI in mathematics education lies in carefully designed human–AI collaboration rather

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

than complete automation. Promising areas include multilingual mathematical support, adaptive systems for diverse learners, teacher co-design of educational tools, and learning analytics that identify misconceptions early.link.springer+1

AI-resilient assessment will also become important. Mathematics assessments should increasingly evaluate explanation, reasoning, oral defense, collaborative problem-solving, application to unfamiliar contexts, and the ability to critique an AI-generated solution. Long-term and rigorous research is still needed. Current reviews emphasize that evidence varies across contexts, and many studies do not provide enough standardized effect-size data to establish strong general conclusions about learning outcomes.frontiersin+1

Conclusion

Artificial Intelligence can make mathematics learning more adaptive, interactive, and responsive to individual student needs. Intelligent tutoring systems, adaptive platforms, and generative AI can support practice, feedback, engagement, and teacher decision-making when used thoughtfully.link.springer+1

Its benefits, however, depend on teacher agency, learner critical thinking, reliable infrastructure, ethical safeguards, and pedagogically sound implementation. AI should strengthen—not replace—the central human relationship between teacher, learner, and mathematical thinking.

Acknowledgment

The author expresses sincere gratitude to the principal, colleagues, and the Department of Mathematics, Shripatrao Chougule Arts & Science College, Malwadi–Kotoli, for their continuous encouragement, guidance, and academic support during the preparation of this research paper. The author is deeply thankful to the researchers, educators, and scholars whose published studies, articles, and reviews on Artificial Intelligence and Mathematics Education provided valuable insights and a strong foundation for this work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Chen, L., Chen, P., & Lin, Z. (2020). Artificial Intelligence in Education: A Review. *IEEE Access*, 8, 75264–75278. https://doi.org/10.1109/ACCESS.2020.2988510
2. Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial Intelligence in Education: Promises and Implications for Teaching and Learning*. Center for Curriculum Redesign, Boston.
3. Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence Unleashed: An Argument for AI in Education*. Pearson Education.
4. Ouyang, F., Zheng, L., Jiao, P., & Moore, G. D. (2022). Artificial Intelligence in Online Higher Education: A Systematic Review. *Education and Information Technologies*, 27(6), 7893–7925.
5. Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic Review of Research on Artificial Intelligence Applications in Higher Education. *International Journal of Educational Technology in Higher Education*, 16(39), 1–27.
6. Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günnemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeiffer, F., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., Stadler, M., & Kasneci, G. (2023). ChatGPT for Good? On Opportunities and Challenges of Large Language Models for Education. *Learning and Individual Differences*, 103, 102274.
7. UNESCO. (2023). *Guidance for Generative AI in Education and Research*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.
8. Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the Devil is My Guardian Angel: ChatGPT as a Case Study of Using Chatbots in Education. *Smart Learning Environments*, 10(1), 15.
9. Hwang, G. J., Xie, H., Wah, B. W., & Gašević, D. (2020). Vision, Challenges, Roles and Research Issues of Artificial Intelligence in Education. *Computers and Education: Artificial Intelligence*, 1, 100001.
10. Baker, R. S., & Inventado, P. S. (2014). Educational Data Mining and Learning Analytics. In J. A. Larusson & B. White (Eds.), *Learning Analytics: From Research to Practice* (pp. 61–75). Springer.
11. Woolf, B. P. (2010). *Building Intelligent Interactive Tutors: Student-Centered Strategies for Revolutionizing E-Learning*. Morgan Kaufmann Publishers.
12. OECD. (2021). *Digital Education Outlook 2021: Pushing the Frontiers with Artificial Intelligence, Blockchain and Robots*. OECD Publishing, Paris.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Sports Ethics and Values in the Indian Knowledge Tradition in Relation to Sports Education

Dr. Chand Khan Safdar Khan
H. J. Thim College of Arts and Science Mehrun Jalgaon

Manuscript ID:
BN-2026-030922

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 115-117

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914237
DOI link:
https://doi.org/10.5281/zenodo.22914237

Abstract:

Sports education plays a vital role in shaping not only physical competence but also moral character, emotional stability, and social responsibility. In the Indian Knowledge Tradition (IKT), education particularly physical education is viewed as a holistic process that integrates ethical values, discipline, and self-realization. This paper explores the integration of sports ethics and values derived from Indian philosophical traditions into modern sports education. Concepts such as dharma, karma, ahimsa, sādhanā, and self-discipline are examined in relation to teaching learning processes, curriculum design, and student development. The study highlights how Indian ethical principles can strengthen value-based sports education and contribute to the holistic development of learners in contemporary educational settings.

Keywords: *Sports ethics, Indian knowledge tradition, dharma, karma, ahimsa, value education, sports philosophy*

Introduction:

Sports education is an essential component of holistic learning, fostering physical fitness, teamwork, leadership, and emotional well-being. In modern educational systems, sports are often viewed primarily through the lens of performance, competition, and achievement. However, the Indian Knowledge Tradition offers a broader perspective, viewing sports as a powerful medium for moral and spiritual education. Historically, physical education in India was integrated into the gurukul system, where students were trained not only in physical skills but also in ethical values such as discipline, respect, humility, and self-control. Sports were seen as tools for character formation rather than mere competition. This holistic educational approach ensured balanced development of the body, mind, and spirit. In today's educational environment, challenges such as aggression, unethical behavior, over-competitiveness, and declining sportsmanship highlight the need to reintroduce value-based education. Integrating Indian ethical principles into sports education can help address these challenges while nurturing responsible, ethical, and emotionally balanced individuals.

Philosophical Foundations of Sports Education in Indian Knowledge Tradition:

Dharma as the Foundation of Ethical Sports Education:

Dharma represents moral duty, righteousness, and ethical responsibility. In sports education, dharma guides students to follow rules, respect others, and perform duties sincerely. It emphasizes process over outcome, teaching learners that sincere effort is more important than victory. In educational settings, dharma encourages fairness, discipline, and respect for teachers, peers, and institutions. It helps students understand that ethical conduct in sports reflects personal integrity and social responsibility.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Chand Khan Safdar Khan, H. J. Thim College of Arts and Science Mehrun Jalgaon
Email: chandkhan7313@gmail.com

How to cite this article:
Chand Khan Safdar Khan. (2026). Sports Ethics and Values in the Indian Knowledge Tradition in Relation to Sports Education. Bulletin of Nexus Journal, 3(9), 115–117.
https://doi.org/10.5281/zenodo.22914237

Quick Response Code:

Website: https://bnir.us

Karma and Responsibility in Learning:

The concept of karma teaches that actions have consequences. In sports education, this principle helps students develop accountability for their behavior, performance, and decisions. Ethical actions lead to positive growth, while unethical behavior results in learning setbacks. Through this understanding, learners develop patience, perseverance, and self-awareness. Karma-based learning encourages students to focus on effort, improvement, and ethical conduct rather than shortcuts or unfair advantages.

Ahimsa and Emotional Intelligence in Sports Education:

Ahimsa, or non-violence, plays a vital role in shaping emotional intelligence in students. It encourages empathy, compassion, and respect within competitive environments. Sports education rooted in ahimsa promotes healthy competition without hostility or aggression.

Students learn to manage emotions, resolve conflicts peacefully, and appreciate opponents as partners in learning rather than enemies. This approach supports psychological well-being and positive social interaction.

Sādhanā and Discipline in Physical Education:

Sādhanā refers to disciplined and purposeful practice aimed at self-improvement. In sports education, regular training, self-control, and dedication cultivate perseverance and mental strength.

Through sādhanā, students develop focus, patience, and resilience. Physical education thus becomes a transformative educational experience that enhances both physical fitness and moral development.

Ethical Values in Sports Education from Indian Perspectives:

Fair Play and Integrity:

Fair play is a foundational principle in sports education. Indian philosophy emphasizes integrity, honesty, and respect for rules. Teaching fair play helps students internalize ethical behavior both within and beyond sports.

Respect and Human Dignity:

Respect for teachers (gurus), peers, and opponents is deeply rooted in Indian culture. Sports education fosters respect through cooperation, teamwork, and acknowledgment of others' efforts and abilities.

Discipline and Self-Regulation:

Discipline is central to educational success. Indian traditions emphasize self-regulation as a lifelong skill. In sports education, disciplined behavior supports consistency, focus, and emotional control.

Humility and Acceptance:

Humility encourages learners to accept success and failure with grace. The Indian philosophical concept of non-attachment teaches students to remain balanced, motivated, and open to learning regardless of outcomes.

Role of Sports Education in Holistic Development:

Sports education plays a critical role in developing all dimensions of personality:

- Physical development: Strength, coordination, endurance
- Mental development: Focus, confidence, decision-making
- Moral development: Ethics, honesty, responsibility
- Social development: Cooperation, leadership, teamwork
- Spiritual development: Inner peace, self-awareness

Through the integration of Indian values, sports education becomes a powerful tool for holistic growth.

Contemporary Challenges in Sports Education:

Modern sports education faces challenges such as excessive competition, unethical practices, academic pressure, and commercialization. These issues often compromise ethical development.

Reintroducing Indian ethical values can restore balance by promoting well-being, moral reasoning, and sustainable participation in sports.

Role of Educators and Institutions:

Teachers and coaches play a crucial role in transmitting ethical values. By modeling ethical behavior and integrating value education into sports curricula, educators can shape responsible and disciplined individuals. Educational institutions must create environments that encourage ethical sports participation, inclusivity, and lifelong learning.

Conclusion:

The integration of sports ethics and values from the Indian Knowledge Tradition into sports education offers a holistic approach to learning. Rooted in principles such as dharma, karma, ahimsa, and self-discipline, this approach nurtures ethical awareness, emotional maturity, and social responsibility. In an era where ethical challenges in sports are increasing, adopting value-based sports education can foster balanced individuals and contribute to a healthier, more ethical society.

Acknowledgment

The author expresses sincere gratitude to the Principal, colleagues, and the Department of Physical Education of H. J. Thim College of Arts

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

and Science, Mehrun, Jalgaon, for their continuous encouragement, support, and academic guidance during the preparation of this research paper.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1) Bhagavad Gita. (n.d.). The song of the Lord (various translations).
2) Coakley, J. (2017). Sports in society: Issues and controversies (12th ed.). McGraw-Hill Education.
3) Feuerstein, G. (2008). The yoga tradition: Its history, literature, philosophy and practice. Hohm Press.
4) Hardman, K., & Marshall, J. (2009). World-wide survey of the state and status of school physical education. UNESCO.
5) Lumpkin, A., Stoll, S. K., & Beller, J. M. (2012). Sport ethics: Applications for fair play (4th ed.). McGraw-Hill.
6) Naidu, K. S. (2016). Ethical foundations of Indian philosophy. Indian Journal of Philosophy, 58(3), 201–215.
7) Patanjali. (2002). The Yoga Sutras of Patanjali (E. F. Bryant, Trans.). North Point Press.
8) Radhakrishnan, S. (1951). Indian philosophy (Vols. 1–2). George Allen & Unwin.
9) Sen, A. (2009). The idea of justice. Harvard University Press.
10) Sharma, A. (2000). Classical Hindu thought: An introduction. Oxford University Press.
11) Sharma, R. N. (2018). Values and ethics in Indian education. Journal of Educational Thought, 52(1), 35–49.
12) Singh, H. (2015). Sports ethics and value education in India. International Journal of Physical Education, 8(2), 22–29.
13) Singh, M. (2019). Ethics and values in Indian sports traditions. Journal of Indian Philosophy and Culture, 12(2), 45–60.
14) UNESCO. (2015). Quality physical education: Guidelines for policymakers. UNESCO Publishing.
15) Yogananda, P. (1998). Autobiography of a yogi. Self-Realization Fellowship.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Post-Human Canvas: Literature As a Moral Compass for AI Integration and National Growth

Dr. Geetika Patni
Assistant Professor, Department of English, Swami keshvanand Institute of Technology, Management & Gramothan

Manuscript ID:
BN-2026-030923

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 118-122

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914370
DOI link: https://doi.org/10.5281/zenodo.22914370

Abstract
Artificial intelligence and smart technologies are rapidly evolving, opening up new opportunities for economic progress, but also raising complex ethical questions. Technological paradigms concentrate on efficiency, optimization, and material progress, but often lack the inherent frameworks to deal with existential, moral, and socio-cultural consequences. In this paper, it is argued that literature is an indispensable moral compass for ethical integration of AI, more so in the setting of national growth and sustainable development (like India's Viksit Bharat vision). This study draws on contemporary post-human literature, eco-critical texts, and speculative narratives to argue that literary humanities provide algorithmic development critical empathy, ethical foresight, and socio-cultural grounding. This paper employs a qualitative, interdisciplinary methodology drawing on Post-Humanist Theory, Narrative Ethics and Hermeneutics to explore how literary tropes challenge technological determinism and articulate human-centric technological futures. The results show that it is impossible to achieve long-term national development based only on scientific innovation, and that a synergistic relationship between technical ability and humanistic ethics is necessary. This paper thus presents practical recommendations for the incorporation of literary studies into STEM curricula, AI ethics policy, and multidisciplinary research frameworks, to ensure that national technological progress is ethically grounded, socially inclusive, and humanely sustainable.

Keywords: *Post-Humanism, Artificial Intelligence, Narrative Ethics, Literature, Viksit Bharat, Sustainable Development, AI Ethics*

Introduction

We are in the twenty-first century, witnessing an unprecedented technological metamorphosis. Global society is experiencing a structural transformation toward automation and algorithmic governance, driven by developments in Artificial Intelligence (AI), machine learning, autonomous systems and intelligent infrastructure. Smart technologies are positioned at the center of national growth trajectories, as in India's ambitious Viksit Bharat (Developed India) paradigm, in the quest for economic prosperity, environmental sustainability and administrative efficiency. But the unchecked growth of technological determinism raises profound ethical, philosophical, and existential questions as algorithms continue to mediate human experience, decision-making, and social structure. Technology by its very nature is based on logic, computational efficiency, and measurable data. It measures progress in terms of speed, optimization and scale. But the growth of a nation is not merely a quantitative measure, it is an inherently qualitative human activity. Socio-economic equity, moral responsibility, cultural identity and human dignity are not issues that can be turned into binary code or predictive algorithms. Technological development can, in a humanistic vacuum, entrench existing biases, exacerbate socio-economic inequalities, and alienate the individual from the collective social fabric.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Geetika Patni, Assistant Professor, Department of English, Swami keshvanand Institute of Technology, Management & Gramothan
Email: geetika.patni@skit.ac.in

How to cite this article:
Patni, G. (2026). Post-Human Canvas: Literature As a Moral Compass for AI Integration and National Growth. Bulletin of Nexus Journal, 3(9(II)), 118–122. https://doi.org/10.5281/zenodo.22914370

Quick Response Code:

Website: https://bnir.us

It is here, at this crucial divide, which literature steps in as a vital intervention. Literature has historically mirrored social change and offered a venue for ethical exploration. It is this space between the potentials of technology and the fragility of the human condition that literature traverses through narrative structures, speculative fiction, and philosophical discourse. It gives scholars and policymakers the capacity to conduct psychological and ethical "stress tests" of imaginary futures, contemplating the consequences of technological overreach before it becomes a reality. The paper argues that literature is a necessary moral compass to guide the integration of AI by framing the technological landscape in the concept of "The Post-Human Canvas." Literature isn't trying to halt technological progress. It is trying to humanize it. It ensures that as countries build smart cities, automated industries and AI-powered governance models, the core values of empathy, justice and responsibility for the environment stay at the heart of development.

Literature Review

The intersection of literature, technology, and national development sits at the confluence of several rich academic traditions: Post-Humanist Theory, Narrative Ethics, and Technological Humanism. A comprehensive review of these domain intersections demonstrates how literary scholarship provides the foundational framework for ethical AI integration.

Post-Humanism and the Redefining of the Human

The post-humanist theory, espoused by theorists like N. Katherine Hayles (1999) and Rosi Braidotti (2013), radically departs from the classic concept of the humanist individual. How We Became Posthuman by Hayles illustrates how the advent of information theory erased any distinction between biologically formed bodies and cybernetics. Post-humanism is not about the end of humanity; it is about its development into a stage at which the human subject becomes part of intelligent machines and complicated ecosystems. According to Braidotti (2013), post-human theory is a framework for developing ethical thinking that goes beyond anthropocentrism and includes non-human agents and ecological networks within a feeling of common responsibility. From the point of view of literary studies, post-humanism is a theory through which one may examine the changes brought about by artificial intelligence.

Narrative Ethics and Moral Foresight

Narrative ethics, according to Martha Nussbaum (1990) and Paul Ricoeur (1992), proposes that narrative fiction has a special capability for fostering ethical development. Nussbaum argues that reading is an act that involves emotions and imagination and helps people develop "literary imagination" – the kind of radical empathy required for democratic participation and ethical action. While ethical philosophies are mostly abstract, literary narratives involve moral challenges in the framework of a specific human condition. The use of narrative ethics in relation to AI gives people the ability to imagine the unintended consequences of automation. As argued by Donna Haraway (2016) in her discussion of speculative fabulation, the stories that help us think about the future determine what sort of future we can create.

Literature as an Antidote to Technological Determinism

In light of the literature that challenges technological determinism as an idea, the study of Science and Technology studies (STS) within Indian literary culture reveals a fertile ground for exploration. Technological determinism – the perception that technological innovation acts as a separate force independent of human action that drives historical progress – typically conceals the politics and economics of material development. As shown by scholars such as Langdon Winner (1980), technological objects bear political, social, and moral connotations. Determinist ideology discourages any discussion and passively accepts technology as an unstoppable and unavoidable process. Literature breaks away from technological determinism by stressing the human agency, morality, and emotions over blind enthusiasm about mechanical perfection.

Indian literary tradition offers a rich historical perspective to assess innovations (Techne) in the light of human moral responsibility (Dharma). The classical narratives of India, including the great epics, consistently subject material power to ethical judgment. Weapons of warfare of a high degree of sophistication (Astras) in Mahabharata, for example, were never viewed as triumphs of human technical genius but were always evaluated from the standpoint of the moral responsibility of the warrior. In classical Indian culture, the application of material power is consistently subordinated to the human conscience and moral duty. The danger of material power lies in its capability of disrupting society and cosmos should the person lack the necessary ethical qualities (Atma-Samyama).

The modern Indian science fiction and post-colonial speculative literature continue the philosophical tradition of the classical Indian texts by addressing the issues related to artificial intelligence, digital surveillance, and hyper-urbanization. Contemporary authors such as Vandana Singh, Prayaag Akbar, or Samit Basu consistently construct worlds which reveal the dangers and pitfalls of

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

technologically driven modernization. The novels written by these writers expose the mechanisms through which smart city projects, bio-capitalism, and algorithmic governance conceal deep structural inequalities under the guise of progress. Speculative fiction illustrates how technological integration can result in increased class stratification, exclusion of marginalized communities, and environmental harm.

Overall, literature turns technologically driven development from a totalitarian mandate into a democratic choice. By exposing the hidden costs of technology integration, literature stresses the fact that technology is created by humans and reflects their values. Literature reclaims the post-human canvas and provides a moral guidepost which ensures that technological integration and national development remain ethical and historically conscious.

Methodology

The research design of this study will incorporate a qualitative and interdisciplinary approach based on literary theory, hermeneutics, and narrative analysis with intersections of the current theories on the ethics of artificial intelligence and sustainable development. Combining literary and policy research through methodological approaches will allow for systematic consideration of the role of literary narratives as critical diagnostics and ethical instruments for technology governance. In contrast to the approach viewing literature as fiction, this methodology will consider narrative texts as conceptual models demonstrating the social, moral and ecological consequences of digital acceleration, AI integration, and state modernization.

Hermeneutic textual analysis will constitute the core of the analytical strategy with close reading of primary sources, which include speculative fiction, post-humanist poetry, and socio-technological narratives. Hermeneutic approach will decode the cultural and political meanings of the literature in order to detect recurring themes. The literary representations of artificial intelligence, human agency erosion/reclamation, environmental destruction and systemic societal inequalities will be analyzed using texts from global and post-colonial traditions. Hence, this phase of methodology will reveal how narrative structures criticize technocratic fatalism and outline alternative futures where humanity prevails.

Narrative structural mapping will constitute the next stage connecting the literary imagination with real life experiences. This stage will create the map of literary tropes, such as "sentient algorithm," "surveillance state," "ecological decay" and "cyborg hybridity" against real life deployments of AI in the framework of public policy, smart cities development, and national economic growth. Using systematic comparison of literary tropes and real-life technological overreach, the narrative structural mapping will demonstrate the anticipation of the potential risks, structural biases, and ethical blindness of modern technological system by literature.

Finally, the synthesis of the literary insights and ethical approaches will allow creating a unique theoretical lens for technological governance. Following the idea of Martha Nussbaum's narrative ethics, which suggests the unique ability of literature to stimulate moral imagination and empathy, and also considering Rosi Braidotti's post-humanist ethics, the synthesis will allow to convert the narrative critiques into the conceptual models to develop interdisciplinary policy design and governance models for national AI strategies.

Thematic Analysis & Discussion

1. The Technocene and the Human Element: Bridging Data and Empathy

In an era dominated by Big Data, human experiences are increasingly quantified into data points for predictive modeling. However, literature highlights the profound limitations of reducing human complexity to metrics. Algorithms operate on historical data, which inherently carries historical biases, inequities, and structural flaws.

Literary narratives interrogate the "black box" of AI systems by centering the lived experiences of marginalized individuals who fall outside algorithmic norms. Literature reintroduces nuance, ambiguity, and moral ambiguity—qualities that automated decision-making engines actively filter out in pursuit of computational efficiency.

Dimension	Algorithmic Model (Techne)	Literary Model (Phronesis)
Primary Metric	Optimization, Speed, Efficiency	Meaning, Empathy, Justice
Data Source	Aggregated Historical Datasets	Individual Experience & Narrative Context
Handling of Ambiguity	Reduces to Probability & Binary	Embraces Complexity & Moral Nuance
Ethical Focus	Procedural Fairness & Accuracy	Substantive Justice & Human Dignity

2. Narrative Ethics as an Early-Warning System for AI Risks

Speculative and science fiction literature functions as a cultural early-warning system. Works depicting dystopian surveillance, algorithmic bias, and existential AI threats are not mere escapism; they are rigorous theoretical explorations of technological overreach. By engaging with these narratives, computer scientists, ethicists, and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

policymakers can anticipate theoretical failure points in AI deployment:

- **Loss of Moral Agency:** Literature frequently explores scenarios where human operators defer moral responsibility to automated systems, leading to ethical paralysis and institutional apathy.
- **Algorithmic Discrimination:** Speculative texts illustrate how automated sorting mechanisms exacerbate social stratified barriers, creating digital enclosures that entrap vulnerable populations.
- **Existential Alienation:** Narrative representations of hyper-connected yet emotionally isolated societies highlight the mental health crises that can accompany unmediated technological adoption.

3. Aligning *Viksit Bharat* with Humanistic and Ecological Sustainability

National development frameworks like *Viksit Bharat* aim to elevate economic stature through technology, infrastructure, and green transition. However, economic expansion without cultural and humanistic anchoring risks producing equitable imbalance and ecological degradation.

Literature—particularly Indian Eco-criticism and Post-colonial Literature—provides the blueprint for a holistic, sustainable development model. It emphasizes that true development must harmonize technological advancement (*Pragati*) with moral integrity (*Niti*) and ecological balance (*Prakriti*). Literature champions the concept of "Smart Humanism," wherein technology serves as an instrument for human flourishing rather than an end in itself.

Recommendations

For the use of literature to function effectively as an ethical compass to facilitate the integration of artificial intelligence and national development, multidisciplinary linkages must be built in academic, industrial and policy spaces.

First and foremost, the curriculum must be transformed by replacing the traditional STEM (Science, Technology, Engineering and Mathematics) models with the more progressive STEAM (Science, Technology, Engineering, Arts and Mathematics) models. Universities and higher education institutions, including IITs, NITs and SKIT, must include mandatory courses on topics such as Narrative Ethics, Post-Humanist Theory and Speculative Literature in Computer Science and AI engineering programs. At the same time, English and Humanities Departments must expand the breadth of their syllabus to include Digital Humanities, AI Literature and Computational Hermeneutics.

Apart from these reforms within academia, it is imperative to implement the institution of an Ethicist-in-Residence Program in corporate sector, academic institutions and government sponsored technology labs. Technology companies, AI labs and state sponsored technology projects must employ literary scholars and narrative ethicists to work with the software developers. By carrying out qualitative ethical audits of AI during the design and training phase of the software, literary scholars ensure that narrative friction, edge cases and humanistic concerns are built into the architecture of algorithms before they are deployed.

Within the context of policymaking and regulation, the regulatory body responsible for formulating policies on AI should mandate the use of Narrative Impact Assessments (NIAs) apart from usual technical and economic feasibility assessments. While former metrics look at technical aspects such as throughput, latency and economic return on investment, NIAs make use of the speculative and narrative methods to forecast how emerging technologies would change the nature of human relations, cultural heritage and socio-economic equity in long run.

Finally, to realize these transformations, it is important that multidisciplinary research grants be issued by the national research funding bodies, including Indian Council of Social Science Research (ICSSR) and Department of Science and Technology (DST). Such organizations should initiate joint funding programs focused on collaboration between literary theorists, computer scientists and environmental sociologists.

Conclusion

As countries vie for supremacy through technological power and economic development in the era of Artificial Intelligence, the key issue here is not simply technical, but also human. The course of development cannot simply be charted by computing power. If there is no ethical foundation to it, the process of technological development could exacerbate inequality, degrade the role of humanity and disconnect society from its cultural and ecological legacies.

Through literature, the dynamic medium that helps to maneuver through this complicated post-human world, society has the means of ensuring that artificial intelligence reflects the dignity of humanness, equity, and balance with ecology. By integrating the wisdom of literary humanities in scientific progress and policymaking, societies will achieve a holistic perspective on the development of their country.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Acknowledgment
The author expresses sincere gratitude to the management, Principal, and colleagues of Swami Keshvanand Institute of Technology, Management & Gramothan for their continuous encouragement, support, and academic environment that facilitated the completion of this research work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

Works Cited

1. Akbar, Prayaag. *Leila*. Simon & Schuster India, 2017.
2. Braidotti, Rosi. *The Posthuman*. Polity Press, 2013.
3. Ghosh, Amitav. *The Great Derangement: Climate Change and the Unthinkable*. University of Chicago Press, 2016.
4. Haraway, Donna J. *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press, 2016.
5. Hayles, N. Katherine. *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics*. University of Chicago Press, 1999.
6. Ishiguro, Kazuo. *Klara and the Sun*. Alfred A. Knopf, 2021.
7. Nussbaum, Martha C. *Love's Knowledge: Essays on Philosophy and Literature*. Oxford University Press, 1990.
8. Ricoeur, Paul. *Oneself as Another*. Translated by Kathleen Blamey, University of Chicago Press, 1992.
9. Singh, Vandana. *Ambiguity Machines and Other Stories*. Small Beer Press, 2018.
10. Tagore, Rabindranath. *The Machine*. Translated by Ananda Lal, Oxford University Press, 2011.
11. Winner, Langdon. "Do Artifacts Have Politics?" *Daedalus*, vol. 109, no. 1, 1980, pp. 121–36.
12. ---. *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. University of Chicago Press, 1986.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Jyoti Lanjaware's Mother: A Depiction of Dalit Women's Ethos

Dr. Tenkale Mahadev Nagnath
Assistant Professor, Dept of English, Kai. Rasika Mahavidyalaya,Deoni

Manuscript ID:
BN-2026-030924

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 123-125

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914436
DOI link:
https://doi.org/10.5281/zenodo.22914436

Abstract

The purpose of this article is to highlight the impact of casteism and patriarchy on Dalit women, who face discrimination both as Dalits and as women. It sheds light on the various forms of oppression experienced by Dalits in their everyday lives, which continue to exist even today. The article also examines how the character of "Mother," as a woman, is affected by patriarchy, including the abuse she suffers at the hands of her husband, who belongs to an upper or lower caste. Furthermore, the article highlights the self-respect of Dalits and recognizes their often-overlooked contributions to the development of the country, particularly in areas ranging from healthcare to infrastructure. Education is presented as an important means through which Dalits can raise their voices and challenge oppression. The poem "Mother" explores different aspects of Dalit life and portrays their ongoing struggle for dignity, equality, and freedom from oppression.

Keywords: *Dalits, Caste, Education, Women.*

Introduction

Jyoti Lanjewar is an important Dalit woman poet from India who has made a valuable contribution to Dalit literature through her powerful poetry. Born in Maharashtra, her poems mainly focus on social justice, identity, and the difficulties faced by the Dalit community. She writes about oppression, discrimination, and social marginalization and presents these experiences with strong emotions, striking images, and deep sympathy. Lanjewar uses poetry to highlight the historical injustices suffered by Dalits. At the same time, she stresses the importance of equality, empowerment, dignity, and self-respect. Her poetry challenges existing social inequalities and encourages readers to bring about positive social change. A significant feature of her work is that she gives a voice to Dalit women, who have historically experienced discrimination because of both caste and gender. Her poems express their struggles, hopes, and aspirations and bring attention to experiences that are often neglected in mainstream literature. She strongly criticizes caste discrimination and examines how caste, gender, and class are interconnected. Her poems also act as a call for social action. They encourage readers to question unfair social customs, prejudices, and inequalities and to work towards removing the structures that continue to cause oppression. Lanjewar's contribution is also connected with the wider Dalit literary movement in India, which aims to reclaim Dalit identity, challenge stereotypes, and develop a sense of dignity, pride, and self-confidence among Dalit people. Her poetry adds a distinctive perspective to this movement because it reflects her experiences and viewpoint as a Dalit woman. Jyoti Lanjewar was actively involved in politics as a member of the Republican Party of India (Athawale), an important political organization that works for the rights and welfare of Dalits. She also played a significant role in leading the women's wing of the party.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Tenkale Mahadev Nagnath, Assistant Professor, Dept of English, Kai. Rasika Mahavidyalaya,Deoni
Email: mahadevtenkale@gmail.com

How to cite this article:
Tenkale, M. N. (2026). Jyoti Lanjaware's Mother: A Depiction of Dalit Women's Ethos. Bulletin of Nexus Journal, 3(9(II)), 123–125. https://doi.org/10.5281/zenodo.22914436

Quick Response Code:

Website: https://bnir.us

Through this work, she contributed to promoting gender equality and increasing the social and political participation of women within the Dalit movement. Her life and work demonstrate her strong dedication to the advancement of Dalit rights through both her academic achievements and her involvement in political and social activities. The experiences reflected in her powerful poetry reveal the connection between individual aspirations and the social difficulties experienced by marginalized communities. Her involvement in education, political activism, and feminist leadership highlights her important contribution to Dalit empowerment, women's representation, and social change. Her work continues to reflect the struggle for equality, dignity, and justice for marginalized people.

Jyoti Lanjewar's early life was deeply influenced by her exposure to the realities of caste discrimination and social practices. These formative experiences are clearly reflected in her poem "Mother," in which she recalls incidents that developed her understanding of caste-based inequalities. Through powerful imagery, she remembers giving a small coin to a child as an act of kindness, while at the same time recognizing the harsh social inequalities surrounding them. The image of encouraging a child to become like Dr. B. R. Ambedkar, a strong advocate of Dalit rights, reflects the hope for dignity and equality. At the same time, the reference to family responsibilities, expressed through the phrase "let the baskets fall from my hands," highlights the struggle between personal ambitions and the economic and social difficulties faced by the family.

Jyoti Lanjewar's poem "Mother" presents a vivid picture of the struggles, courage, endurance, and strength of Dalit women. Through expressive imagery, the poet presents the complex experiences and difficulties faced by Dalit women in Indian society.The poem's depiction of a Dalit mother's life is deeply moving. The image of the mother placing a five-paise coin in her child's hand and telling the child to "go eat candy" represents the hopes and dreams she has for the younger generation. At the same time, it highlights the poverty and limited resources available to them. The contrast between their dreams and their actual circumstances draws attention to the wider inequalities present in society. The words "Study, become an Ambedkar" express the mother's strong belief in education as a means of achieving progress and empowerment. By referring to Dr. B. R. Ambedkar, the poet connects education with the struggle for equality and Dalit rights. The mother encourages the younger generation to follow Ambedkar's ideals and work for social change. Thus, the poem emphasizes the importance of education, self-respect, empowerment, and transformation in overcoming social discrimination and inequality.

The image of baskets slipping from women's hands represents the heavy burdens and difficulties experienced by Dalit women. It suggests the numerous responsibilities they have to manage, often under difficult and unfavorable conditions. The picture of a woman carrying a market basket on her head, covering herself with the end of her sari, and standing up against those who intentionally insult her shows her courage and determination. She refuses to accept humiliation and struggles to protect her self-respect and dignity. Thus, these images emphasize the strength, courage, and resilience of Dalit women. Despite facing discrimination, hardship, and everyday humiliation, they continue to resist injustice and assert their dignity.

The portrayal of a woman working until sunset, returning home, and driving away an intoxicated man highlights her hard work, courage, and determination to protect herself and her family. It shows that she actively takes control of her life and stands up against difficult circumstances. The reference to the "Long March" and the demand for a change of name, made with confidence and dignity, reflects Dalit women's active involvement in social and political movements. It also shows their readiness to challenge authority and their courage to fight against injustice. Overall, the poem presents a powerful picture of the real-life struggles, perseverance, and contributions of Dalit women to social transformation. Lanjewar's poetry gives expression to their hardships while celebrating their strength, courage, and unbreakable spirit. It provides a deeper understanding of the complex experiences and struggles of Dalit women in Indian society.

Lanjewar's poetry rejects the idea that marginalized groups silently endure suffering. Instead, she gives voice to Dalit women, using vivid imagery to capture their everyday realities, struggles, and hopes while emphasizing their active power in overcoming hardship. The poet's work presents a strong Dalit-feminist identity that challenges conventional stereotypes and emphasizes women's independence and agency. Lanjewar's poetry portrays Dalit women in their full diversity, focusing on their strength, ambitions, and important roles in their communities. She highlights their accomplishments, hopes, and aspirations, thereby rejecting the limited idea that Dalit women are merely passive victims of suffering

Lanjewar's poetry becomes a powerful means of resisting oppressive systems and social

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

inequalities. Her poems examine how caste, gender, and power are closely connected, while also giving Dalit women a voice to express their disagreement and struggles. By highlighting problems such as caste discrimination, patriarchy, and social injustice, she encourages Dalit women to recognize their rights, speak up against oppression, and work towards social change.

Through her powerful language and vivid imagery, Lanjewar's poetry challenges the traditional ideas that portray Dalit women as helpless victims. Her poems offer an alternative perspective that highlights their strength, courage, independence, and ability to overcome difficulties. By bringing the experiences of Dalit women to the forefront, she questions existing systems of power and gives new meaning and direction to Dalit feminism.

Acknowledgment
The author expresses sincere gratitude to the principal, colleagues, and the Department of English, Kai. Rasika Mahavidyalaya, Deoni, for their constant encouragement, academic support, and guidance during the preparation of this research paper.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Lanjewar, Jyoti. "Voices Unheard: Dalit Women in Indian Society." Dalit Literature: A Critical Exploration, edited by Ambedkar Shyam, Dalit Publications, 2017.
2. Lanjewar, Jyoti. "Breaking Chains: A Collection of Feminist Poetry." Feminist Literary Journal, vol. 42, no. 3, 2019, pp. 45-62.
3. Ambedkar, B. R. Annihilation of Caste. Navayana, 2014.
4. Chatterjee, Partha. The Nation and Its Fragments: Colonial and Postcolonial Histories. Princeton University Press, 1993.
5. Menon, Sangeeta. Seeing Like a Feminist. Penguin Books, 2012.
6. Omvedt, Gail. Seeking Begumpura: The Social Vision of Anticaste Intellectuals. Navayana, 2009.
7. Chakravarty, Uma. "Conceptualizing Brahminical Patriarchy in Early India: Gender, Caste, Class, and State." Economic and Political Weekly, vol. 26, no. 14, 1991, pp. WS22-WS28.
8. Kancha Ilaiah. Why I Am Not a Hindu: A Sudra Critique of Hindutva Philosophy, Culture, and Political Economy. Samya, 1996.
9. Narayanan, Vasudha. The Vernacular Veda: Revelation, Recitation, and Ritual. University of South Carolina Press, 1994.
10. Sen, Amartya. The Idea of Justice. Harvard University Press, 2009.
11. Shukla, Raja. "Dalit Women's Autobiographies: Writing and Resistance." Indian Journal of Gender Studies, vol. 20, no. 1, 2013, pp. 25-47.
12. Mohanty, Chandra Talpade. "Under Western Eyes: Feminist Scholarship and Colonial Discourses." Feminist Review, no. 30, 1988, pp. 61-88.
13. Narayan, Uma. "The Project of Feminist Epistemology: Perspectives from a Nonwestern Feminist." Gender and Society, vol. 7, no. 4, 1993, pp. 572-582.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI-Driven Precision Agriculture and Crop Resilience: Integrating Artificial Intelligence, IoT and Remote Sensing for Climate-Resilient Indian Agriculture: A Vision for Viksit Bharat 2047

Twinkal Prakash Sawant
Assistant Professor, Department of Botany, Shripatrao Chougule Arts and Science College, Malwadi-Kotoli
Email: twinkalsawant2449@gmail.com

Manuscript ID:
BN-2026-030925

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 126-133

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914539
DOI link:
https://doi.org/10.5281/zenodo.22914539

Abstract

Agriculture is central to India's economic development, food security, rural employment, and the achievement of the Viksit Bharat@2047 vision. However, Indian agriculture faces increasingly complex challenges, including climate variability, water scarcity, soil degradation, pest and disease outbreaks, fragmented landholdings, market uncertainty, and unequal access to agricultural knowledge. These challenges require a transition from conventional, input-intensive agriculture towards data-driven, resource-efficient, climate-resilient and farmer-centric production systems. Agriculture in India is increasingly affected by climate variability, water scarcity, soil degradation, pest and disease outbreaks, and unpredictable weather conditions. These challenges threaten crop productivity and food security, particularly among small and marginal farmers. Artificial Intelligence (AI), Internet of Things (IoT), remote sensing, and machine learning offer new opportunities to transform conventional agricultural practices into data-driven precision agriculture systems. This paper presents a conceptual framework for AI-driven precision agriculture aimed at improving crop resilience under changing climatic conditions. Artificial Intelligence (AI), combined with precision agriculture, Internet of Things (IoT), remote sensing, satellite imagery, drones, machine learning, robotics and digital public infrastructure, offers significant opportunities to transform Indian agriculture. AI can support crop and yield prediction, disease and pest identification, weather-based advisories, irrigation optimisation, soil management, crop insurance, market intelligence and early-warning systems. The paper also discusses challenges related to digital inclusion, data governance, affordability, AI reliability, farmer skills, privacy and institutional coordination. It argues that India's objective should not simply be the digitisation of agriculture, but the creation of an intelligent, inclusive and resilient agricultural ecosystem in which technology augments farmer knowledge and decision-making. By 2047, India can aspire to establish globally competitive agriculture that produces more with fewer resources, withstands climate shocks, generates higher and more stable farm incomes, and ensures sustainable food and nutritional security.

Introduction

Agriculture occupies a strategic position in India's development trajectory. It contributes to food and nutritional security, supports rural livelihoods and provides raw materials for several industries. According to a recent NITI Aayog assessment, agriculture supports nearly 46% of India's population and remains dominated by small and marginal landholders. At the same time, Indian agriculture is increasingly exposed to climate-related risks and structural constraints. The traditional agricultural model, which often relies on uniform application of seeds, fertilizers, pesticides and irrigation across fields, is becoming less suitable for an environment characterized by climatic uncertainty and resource constraints.

Creative Commons (CC BY-NC-SA 4.0)

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Twinkal Prakash Sawant, Assistant Professor, Department of Botany, Shripatrao Chougule Arts and Science College, Malwadi-Kotoli
Email: twinkalsawant2449@gmail.com

How to cite this article:

Sawant, T. P. (2026). AI-Driven Precision Agriculture and Crop Resilience: Integrating Artificial Intelligence, IoT and Remote Sensing for Climate-Resilient Indian Agriculture: A Vision for Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 126–133. https://doi.org/10.5281/zenodo.22914539

Quick Response Code:

Website: https://bnir.us

Farms differ substantially in soil characteristics, water availability, crop health, microclimate and pest pressure. Consequently, applying the same management practice across an entire field can result in inefficient resource use and unnecessary production costs.Agriculture plays a central role in India's economy, rural livelihoods, and food security. However, agricultural production is increasingly exposed to environmental stresses such as drought, heat waves, irregular rainfall, floods, soil nutrient depletion, and emerging pest and disease threats. Climate change is expected to increase the frequency and intensity of several of these stresses, making conventional agricultural management practices less reliable. Precision agriculture provides an alternative approach. It uses data and technology to understand spatial and temporal variations within agricultural systems and enables farmers to apply the appropriate input, at the appropriate location, in the appropriate quantity and at the appropriate time.

The integration of Artificial Intelligence significantly expands these capabilities. AI systems can analyses large volumes of data obtained from satellites, drones, sensors, weather stations, farm machinery and farmer records. Machine-learning models can identify patterns that may not be easily visible to humans and can generate predictions or recommendations. The objective of AI-driven precision agriculture is therefore not merely automation. It is the development of intelligent agricultural systems capable of anticipating crop stress and recommending appropriate interventions before substantial yield losses occur. Artificial Intelligence (AI), combined with precision agriculture, Internet of Things (IoT), remote sensing, satellite imagery, drones, machine learning, robotics and digital public infrastructure, offers significant opportunities to transform Indian agriculture. AI can support crop and yield prediction, disease and pest identification, weather-based advisories, irrigation optimisation, soil management, crop insurance, market intelligence and early-warning systems. The paper also discusses challenges related to digital inclusion, data governance, affordability, AI reliability, farmer skills, privacy and institutional coordination. It argues that India's objective should not simply be the digitisation of agriculture, but the creation of an intelligent, inclusive and resilient agricultural ecosystem in which technology augments farmer knowledge and decision-making. By 2047, India can aspire to establish globally competitive agriculture that produces more with fewer resources, withstands climate shocks, generates higher and more stable farm incomes, and ensures sustainable food and nutritional security.

Objectives of the Study

The major objectives of this research paper are:

1. To examine the role of Artificial Intelligen ce in precision agriculture.
2. To analyse how AI can improve crop resilience against climate, pest, disease and resource-related risks.
3. To assess the relevance of AI-driven agriculture to India's Viksit Bharat@2047 vision.
4. To examine emerging Indian initiatives in AI-enabled agriculture.
5. To identify technological, economic, institutional and ethical barriers to AI adoption.
6. To propose a farmer-centric framework for scaling AI-driven precision agriculture by 2047.
7. To provide policy recommendations for creating a resilient, sustainable and inclusive agricultural ecosystem.
8. To develop an integrated AI-IoT framework for real-time monitoring of crop and environmental conditions.
9. To investigate machine-learning and deep-learning approaches for early detection of crop stress and disease.
10. To develop predictive models for crop yield and productivity under variable climatic conditions.

Research Methodology

This paper follows a descriptive, analytical and policy-oriented research methodology. The study is based primarily on secondary data and documentary analysis. Sources include publications and reports from NITI Aayog, the Government of India, the Indian Council of Agricultural Research (ICAR), the World Bank and other institutional sources. Recent policy developments and government initiatives have been examined to understand India's emerging AI-agriculture ecosystem. The analysis focuses on five dimensions: - technological transformation; - crop and climate resilience; - farmer income and productivity; - inclusion and accessibility; and - policy and institutional readiness.

The paper does not claim to provide primary field-level estimates of the impact of AI. Instead, it synthesises available evidence and develops a conceptual roadmap for AI-driven precision agriculture in India up to 2047 4. Concept of AI-Driven Precision Agriculture Precision agriculture refers to the use of digital technologies and data to manage agricultural variability. AI-driven precision agriculture adds intelligent analytical and predictive capabilities to this process.

A simplified precision-agriculture system can be represented as: Data → AI Analysis → Prediction → Decision → Farm Action → Feedback Major data sources include: - satellite imagery; - drone

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

imagery; - soil sensors; - weather stations; - irrigation sensors; - mobile applications; - agricultural machinery; - market data; - historical yield records; - crop-health information; and - farmer-generated data.

Proposed Methodology

Study Area and Crop Selection

The research can be conducted in a representative agricultural region of India experiencing significant climatic variability. Suitable crops may include rice, wheat, soybean, cotton, sugarcane, maize, or pulses. The selection of crop and location should depend on the principal research question, availability of field data, and local agricultural importance.

Data Collection Multiple sources of information can be integrated:

The research can be conducted in a representative agricultural region of India experiencing significant climatic variability. Suitable crops may include rice, wheat, soybean, cotton, sugarcane, maize, or pulses. The selection of crop and location should depend on the principal research question, availability of field data, and local agricultural importance.

Environmental data ,Air temperature , Relative humidity ,Rainfall ,Solar radiation ,Wind speed ,Soil data ,Soil moisture ,Soil temperature ,pH ,Electrical conductivity ,Available nitrogen, phosphorus and potassium ,Crop data ,Plant height ,Leaf area ,Canopy temperature ,Growth stage ,Disease symptoms ,Biomass ,Yield ,Remote-sensing data ,Multispectral satellite imagery ,UAV/drone imagery ,Vegetation indices such as NDVI and NDRE ,Thermal imagery where available ,Historical data ,Previous crop yields ,Historical weather ,irrigation records ,Soil characteristics ,Pest and disease observations.

IoT-Based Monitoring

A distributed network of low-cost sensors can be deployed in selected experimental plots. Sensor nodes can periodically transmit measurements to a gateway or cloud platform. A typical system can be represented as:

Field sensors → IoT gateway → Cloud/database → AI analytics → Farmer decision-support system Real-time measurements can be used to identify abnormal environmental conditions and provide continuous inputs to predictive models.

Remote Sensing and Image Analysis

Satellite or UAV imagery can provide spatial information that ground sensors cannot capture efficiently. Vegetation indices can be calculated to characterize crop vigor and stress. Deep-learning models such as convolutional neural networks and Vision Transformers can be investigated for image-based disease and stress classification. Image segmentation can additionally be used to identify affected portions of crop canopies and estimate disease severity.

AI and Machine Learning

Different algorithms can be evaluated according to the prediction task. Task Potential algorithms Crop-health classification CNN, Vision Transformer Disease detection CNN, YOLO, Vision Transformer Yield prediction Random Forest, XGBoost, LSTM Soil-moisture prediction Random Forest, XGBoost, LSTM Time-series forecasting LSTM, GRU, Temporal Transformers Irrigation recommendation Reinforcement learning, optimization models Stress classification SVM, Random Forest, neural networks Rather than selecting a single algorithm in advance, comparative experimentation should be used to identify the most appropriate model for the selected crop and dataset.

Multimodal Data Fusion

One of the important research opportunities is combining heterogeneous data sources. For example: Soil moisture + weather + canopy temperature + vegetation indices + crop images + crop growth stage → Multimodal AI model → Crop-stress prediction Such a model may outperform systems based on a single data source because crop stress is influenced by several interacting environmental and biological factors.

Irrigation Optimization

An AI-based irrigation module can estimate crop water demand using soil moisture, weather conditions, crop growth stage, evapotranspiration estimates, and predicted stress. The system can generate recommendations such as: irrigation required, irrigation not required, irrigation quantity, optimal irrigation timing. The model should be evaluated against conventional irrigation practices using indicators such as water consumption, yield, and water-use efficiency.

Proposed System Architecture

The proposed AI-driven precision agriculture architecture consists of five major layers:

Layer 1: Data Acquisition IoT sensors, weather stations, satellites, UAVs, cameras, and field observations collect agricultural data.

Layer 2: Data Processing Collected data are cleaned, synchronized, normalized, and stored in a central database.

Layer 3: AI Analytics Machine-learning and deep-learning models analyze the data to identify patterns and predict crop conditions.

Layer 4: Decision Support Predictions are converted into recommendations for irrigation, nutrient management, disease management, and crop monitoring.

Layer 5: Farmer Interface Recommendations can be delivered through a mobile application, web

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

dashboard, SMS, or other locally appropriate interfaces.

Crop Resilience Framework

Crop resilience can be assessed through the ability of crops to maintain productivity and recover from environmental stresses.

The proposed framework focuses on four major stresses:

Water stress → early detection → optimized irrigation Heat stress → prediction → adaptive management Disease stress → image-based detection → targeted intervention Nutrient stress → sensor/remote-sensing analysis → site-specific nutrient management This approach shifts agricultural management from reactive intervention toward predictive management.

Evaluation Metrics

AI model performance should be evaluated using appropriate statistical metrics.

For classification:

Accuracy, Precision ,Recall F1-score ,Area Under the ROC Curve' For regression: Mean Absolute Error (MAE) ,Root Mean Square Error (RMSE) ,Coefficient of determination (R^2). **For agricultural performance:** Water-use efficiency ,Fertilizer-use efficiency, Crop yield ,Disease reduction, Irrigation water savings ,Economic return ,Importantly, a model should not be considered successful solely because it has high prediction accuracy. Its field-level agricultural benefit must also be demonstrated.

Expected Results :

The proposed research is expected to demonstrate that integrating AI, IoT, and remote sensing can:

Improve early identification of crop stress. Enable more accurate crop-health monitoring. Improve irrigation scheduling.

Reduce unnecessary agricultural inputs. Improve water-use efficiency. Support early disease intervention.

Improve yield prediction. Strengthen crop resilience against climatic variability. Provide scalable decision-support tools for farmers.

10. Challenges and Limitations :

Several challenges must be addressed before widespread implementation. Data heterogeneity Agricultural datasets originate from different sensors, spatial resolutions, time intervals, and measurement conditions.

Effective data fusion is therefore challenging. Model generalization A model trained on one crop, geographical region, soil type, or season may not perform equally well elsewhere. Multi-location and multi-season validation is essential.

Sensor reliability Low-cost sensors can suffer from calibration drift, environmental damage, and missing observations. Robust sensor calibration and quality-control procedures are required.

Connectivity Many agricultural regions have limited or unreliable internet connectivity. Edge-AI approaches could reduce dependence on continuous cloud connectivity.

Farmer adoption Technology must be affordable, understandable, and demonstrably useful. AI recommendations should therefore be presented in simple, actionable forms rather than only technical outputs.

Farmers and agricultural experts may be reluctant to trust predictions from opaque models. Explainable AI can help identify which environmental or crop variables contributed most strongly to a recommendation.

Future Scope:

Future research can extend the framework toward autonomous and continuously learning agricultural systems. Edge AI can enable real-time processing directly on farm devices. Digital twins could provide virtual representations of agricultural fields for scenario analysis. Reinforcement learning could be investigated for dynamic irrigation management. Integration with hyperspectral imaging may enable early identification of biochemical and physiological changes before they become visually apparent.

Combining AI with crop genomic and phenotypic information could further support the development of climate-resilient crop-management strategies. The development of multilingual agricultural interfaces could also improve accessibility for Indian farmers.

AI algorithms can process these datasets to answer practical questions such as: -

When should a farmer sow? - How much water should be applied? - Which portion of the field requires fertiliser? - Is a crop showing signs of disease? - What pest is likely to appear? - What yield can reasonably be expected? - When should a crop be harvested? - What weather risks are expected? - Where can the farmer obtain the best market opportunity? The objective is therefore not technology for its own sake. The objective is better decisions with fewer resources and lower risk.

Major Applications of AI in Indian Agriculture

AI-Based Crop Monitoring

Satellite imagery and drones can monitor agricultural fields over large geographical areas. AI models can identify differences in vegetation health, moisture stress and crop development. Machine-learning algorithms can classify crops and identify abnormal areas within a field. Farmers and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

agricultural officials can use this information to target interventions rather than treating an entire field uniformly. This has particular significance for smallholders because targeted input application can reduce expenditure on fertilisers, pesticides and water.

Pest and Disease Detection

Crop diseases and pests can cause substantial losses, particularly when detection is delayed.

Computer vision can analyse photographs of leaves, stems and fruits to identify visible symptoms. AI-powered advisory systems can then provide information regarding possible diseases and recommended management practices.

India's National Pest Surveillance System is an important example of the use of digital and AI-enabled approaches for pest monitoring. Government information reported in 2026 stated that the system covered 66 crops and more than 432 pest types and provided information to agricultural extension personnel.

The future potential lies in integrating:

Image + Weather + Soil + Crop Stage + Historical Pest Data

to develop early-warning systems rather than merely diagnosing problems after they appear.

Intelligent Irrigation

Water is one of India's most important agricultural constraints.

AI can combine soil-moisture data, weather forecasts, crop stage, evapotranspiration estimates and historical irrigation patterns to determine irrigation requirements.

Instead of asking:

«"How much water does this crop normally require?"»

an intelligent system can estimate:

"How much water does this crop require in this particular field under today's conditions?"»

This transition can improve water-use efficiency and contribute to groundwater conservation.

AI-Based Fertiliser Management

Excessive fertiliser application increases costs and can contribute to soil and environmental degradation.

Precision agriculture can map soil variability within fields. AI can then support site-specific nutrient recommendations.

The long-term objective should be maximum productivity per unit of nutrient, rather than maximum input application.

Weather Forecasting and Climate Advisory

Climate variability creates major uncertainty for farmers.

AI can combine:

- weather observations;
- satellite data;
- historical climate records;
- crop calendars;
- soil information; and
- local agricultural conditions

to generate location-specific advisories.

India has already experimented with AI-based local monsoon-onset forecasting. Government information reported that an AI-based pilot for Kharif 2025 reached 3.88 crore farmers across 13 states and that 31–52% of surveyed farmers reported adjusting sowing or land-preparation decisions based on the forecasts.

Such systems can potentially transform climate information from a general forecast into a farm-level decision-support service.

AI and Crop Resilience

Crop resilience refers to the capacity of agricultural systems to withstand, absorb, recover from and adapt to shocks. These shocks can include: - drought; - floods; - heat waves; - unseasonal rainfall; - cyclones; - pest outbreaks; - disease epidemics; - soil degradation; - water scarcity; and - market disruptions.

AI can contribute to resilience through four major mechanisms.

Prediction

AI can identify potential risks before they become severe.

Prevention

Early warnings can allow farmers to modify sowing dates, irrigation, pest management or crop choices.

Adaptation

AI can recommend climate-suitable crops and varieties based on local conditions.

Recovery

Digital systems can support crop-loss assessment, insurance claims, credit decisions and government relief.

AI, Climate Change and Indian Agriculture

Climate change is likely to increase agricultural uncertainty. Rising temperatures, altered rainfall patterns and extreme weather events can affect crop yields and farm incomes.

The World Bank has highlighted the importance of crop diversification, digital agricultural advisories and improved soil and water management in strengthening climate resilience in India.

India is developing an increasingly broad ecosystem of digital and AI-enabled agricultural services.

Digital Agriculture Mission

The Digital Agriculture Mission provides a foundation for agricultural data and digital services. According to the Government of India, more than 7.63 crore Farmer IDs and 23.5 crore crop

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

plots had been surveyed by the time of its February 2026 update.

This digital foundation can potentially support more personalised agricultural services.

Kisan e-Mitra

Kisan e-Mitra is an AI-enabled, voice-oriented chatbot designed to answer farmer queries relating to go

Government information reported that by December 2025 it had answered more than 93 lakh queries and was handling over 8,000 farmer queries per day in 11 regional languages.

This demonstrates the importance of multilingual AI for India's diverse agricultural population.

MahaVISTAAR

Maharashtra provides an important example of state-level AI adoption.

The World Bank reports that MahaVISTAAR is a generative-AI agricultural assistant through which farmers can ask questions by voice or text in local languages. It provides information on pests, diseases, weather and markets by drawing on trusted agricultural sources.

KATHIR

Kerala's KATHIR platform demonstrates another approach involving satellite imagery, remote sensing and AI analytics.

According to the World Bank, KATHIR is being developed to provide localised weather, sowing and crop-disease information and to support government functions such as crop mapping, yield estimation and agricultural programme delivery.

Bharat-VISTAAR

Bharat-VISTAAR represents a broader vision for national agricultural intelligence.

NITI Aayog describes the platform as an AI-driven, voice-first and multilingual system designed to integrate agricultural information and provide personalised recommendations on crops, weather, markets and government schemes.

AI and the Viksit Bharat@2047 Vision

Viksit Bharat@2047 represents the aspiration to transform India into a developed and prosperous nation by 2047.

Agriculture must be an important component of this transformation because development cannot be considered complete if rural communities remain vulnerable to climate shocks, low productivity and unstable incomes.

NITI Aayog's roadmap for frontier-technology-led agricultural transformation explicitly identifies AI, machine learning, IoT-enabled precision agriculture, drones and satellite imaging as technologies capable of transforming Indian agriculture. The roadmap proposes a three-part approach: Enhance, Reimagine and Converge.

This creates an important policy opportunity.

AI-driven agriculture can contribute to Viksit Bharat through:

Higher productivity:

Better decisions can increase output per unit of land, water and other inputs.

Higher farm incomes:

Reduced input costs, improved yields, better quality and market intelligence can improve profitability.

Climate resilience:

Early warning and adaptive management can reduce climate-related losses.

Food security:

Better productivity and supply-chain management can strengthen national food security.

Water security:

Precision irrigation can reduce unnecessary water consumption.

Rural employment:

AgriTech can generate employment in data services, drone operations, agricultural advisory, machinery maintenance and digital entrepreneurship.

Technological leadership:

India can become a global provider of affordable AI solutions for smallholder agriculture.

When combined with satellite imagery, drones can provide a multi-scale monitoring system.

Satellites provide broad geographic coverage, while drones provide high-resolution local information.

AI and Agricultural Insurance

Agricultural insurance traditionally faces challenges relating to crop-loss assessment, verification, delays and information asymmetry.

AI can improve insurance through:

1. remote sensing;
2. automated crop classification;
3. weather-data analysis;
4. yield estimation;
5. image-based damage assessment; and
6. faster claim verification.

Government initiatives such as YES-TECH and CROPIC illustrate India's movement towards technology-enabled agricultural insurance.

A future insurance system could potentially move from slow, manual assessment towards near-real-time risk monitoring and digital claims management

AI and Farmer Income

Increasing agricultural productivity alone does not guarantee higher farmer income.

AI should therefore address the entire value chain:

Input → Production → Storage → Processing → Logistics → Market

AI can help farmers determine:

- which crop to grow;

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- when to sow;
- which input to purchase;
- how much input to apply;
- when to harvest;
- where to store;
- when to sell; and
- which market offers the best opportunity.

This can transform AI from a production technology into an income-intelligence system.:

Measure Outcomes

Success should be measured not by the number of AI applications deployed but by:

- increased farmer income;
- reduced input costs;
- improved water-use efficiency;
- reduced crop losses;
- improved soil health;
- increased climate resilience; and
- better market access.

Expected Outcomes by 2047

If implemented effectively, AI-driven precision agriculture could contribute to several long-term outcomes.

Economic Outcomes

- higher agricultural productivity;
- lower input costs;
- improved farmer profitability;
- better market access;
- new rural enterprises.

Environmental Outcomes

- improved water efficiency;
- reduced chemical overuse;
- improved soil management;
- lower agricultural resource intensity;
- greater climate resilience.

Social Outcomes

- improved access to agricultural knowledge;
- stronger rural employment;
- empowerment of smallholders;
- improved participation of women and rural youth.

National Outcomes

- stronger food security;
- reduced vulnerability to climate shocks;
- more resilient agricultural supply chains;
- increased technological competitiveness;
- contribution to Viksit Bharat@2047.

Discussion

The central argument of this paper is that AI should not be viewed as a substitute for farmers. Indian agriculture requires a human-AI partnership. The farmer possesses contextual knowledge that cannot always be captured in datasets. AI, on the other hand, can process enormous quantities of information rapidly.

Combining these strengths can produce better outcomes than either approach alone. For example, an AI system may identify a high probability of pest infestation based on weather and satellite data. The farmer can then inspect the field and confirm the situation. The agricultural extension worker can provide additional guidance.

This creates a collaborative decision-making process: AI predicts → Farmer verifies → Expert advises → Farmer acts → Data feeds back into AI. Such a model is particularly appropriate for India, where agricultural conditions are highly diverse and smallholder farmers form a major part of the farming population. Recent developments reinforce this possibility. The World Bank's 2026 reporting on AI-enabled agriculture in India describes systems such as KATHIR and MahaVISTAAR that aim to provide localised agricultural information through accessible interfaces.

NITI Aayog's frontier-technology roadmap similarly argues that India's agricultural transformation requires integration of AI, machine learning, IoT, drones and satellite technologies, together with stronger data ecosystems and innovation institutions. Therefore, India's competitive advantage may not lie in simply adopting the most expensive agricultural technology. It may lie in developing affordable, multilingual, scalable AI designed specifically for smallholder conditions.

Conclusion

AI-driven precision agriculture represents a potentially transformative pathway for Indian agriculture. It can help farmers move from reactive decision-making to predictive and preventive management. By integrating satellite imagery, sensors, drones, weather information, soil data, crop records and market intelligence, AI can support more precise and sustainable agricultural decisions. The importance of this transformation extends beyond productivity. India's agricultural future will increasingly depend on its ability to manage climate risks, conserve water, protect soil, reduce production costs and improve farmer incomes. Recent developments—including the Digital Agriculture Mission, National Pest Surveillance System, Kisan e-Mitra, MahaVISTAAR, KATHIR and Bharat-VISTAAR—demonstrate that India is already developing important elements of an AI-enabled agricultural ecosystem. The Viksit Bharat@2047 vision provides an opportunity to integrate these initiatives into a long-term national strategy. By 2047, the goal should be an agricultural system in which every farmer, regardless of farm size or location, can access timely and reliable intelligence about soil, weather, crops, pests, water, markets and risk. AI-driven precision agriculture represents an

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

important transition from conventional, largely reactive farm management toward predictive and data-driven agricultural decision-making. The integration of IoT sensors, remote sensing, machine learning, deep learning, weather information, and crop observations can provide a comprehensive understanding of crop and environmental conditions. Thus, AI-driven precision agriculture can become not merely a technological revolution, but a foundation for resilient, inclusive and sustainable agriculture—and an important pillar of Viksit Bharat@2047. Conditions.

Acknowledgment
The author expresses sincere gratitude to the Principal, colleagues, and the Department of Botany, Shripatrao Chougule Arts and Science College, Malwadi-Kotoli, for their continuous encouragement, academic guidance, and institutional support during the preparation of this research paper.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Government of India. (2026). Artificial Intelligence (AI) Transforming Indian Agriculture. Press Information Bureau, Ministry of Agriculture and Farmers Welfare.
2. Indian Council of Agricultural Research. (2026). Annual Highlights 2025–26: Innovating Agriculture, Empowering Farmers, Securing the Future. ICAR.
3. NITI Aayog. (2025). Reimagining Agriculture: A Roadmap for Frontier Technology Led Transformation. Government of India.
4. NITI Aayog. (2026). DPI@2047 for Viksit Bharat: A Strategic Roadmap to Enable Non-linear Inclusive Socio-economic Growth. Government of India.
5. NITI Aayog. (2026). Scenarios Towards Viksit Bharat and Net Zero: Sectoral Insights—Agriculture (Vol. 6). Government of India.
6. NITI Aayog Frontier Tech Hub. (2026). How Bharat-VISTAAR Is Connecting 140M+ Farmers to Smarter Agriculture. Government of India.
7. World Bank. (2023). India: Helping People Build Resilience to Climate Change. World Bank Group.
8. World Bank. (2026). Small AI Transforms Farming in India. World Bank Group.
9. World Bank. (2026). AgriConnect: Smallholder Farming, Agribusiness, and Food Security. World Bank Group.
10. NITI Aayog. (2026). NITI Frontier Tech Hub. Government of India.
11. Integration of AI, IoT, and remote-sensing data significantly improves the accuracy of crop-health and stress prediction compared with conventional monitoring approaches.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Role Of Fintech in Indian Banking Industry

Aishwarya Jaysingrao Thorat patil
Assistant Professor, Department of Economics, Shri.Shiv- Shahu Mahavidaylaya Sarud

Manuscript ID:
BN-2026-030926

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 134-138

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914621
DOI link:
https://doi.org/10.5281/zenodo.22914621

Abstract
Fintech has played a key role in boosting India's financial ecosystem through digitalization of loans, payments, and regulatory issues, which are changing the way the banking sector operates. Fintech, or financial technology, has grown in significance on a worldwide scale as it transforms how people and companies engage with financial services. Fintech uses technology to improve financial services' accessibility, efficiency, transparency, and innovation, which benefits a variety of users in many industries. Millions more Indians now have better access to financial services via digital and mobile platforms thanks to the quick development of financial technology, or fintech. This descriptive study examines the factors that have contributed to the emergence of fintech, the different kinds of fintech apps, the obstacles that fintech applications face in India and the prospects for the future.
Keywords: *Fintech, Finance, Fintech Industry Structure, Fintech Startup, Fintech Adoption.*

Introduction:

One of the most revolutionary forces transforming the global financial environment in the twenty-first century is financial technology, or FinTech. Fundamentally, FinTech is the fusion of technology with financial services to provide cutting-edge platforms, services, and solutions that improve client satisfaction, accessibility, and efficiency. The production, distribution, and consumption of financial services have been completely transformed by the confluence of digital technologies including block chain, cloud computing, big data analytics, mobile applications, and artificial intelligence. Technology start-ups, non-banking financial institutions, e-commerce businesses, and even social media platforms are all part of the vast ecosystem that was formerly the sole purview of banks and conventional financial intermediaries. FinTech's origins can be found in past financial innovation waves. With the development of telecommunications technology, the telegraph, credit cards, and electronic money transfers in the 19th and 20th centuries, the initial phase of fintech arose. The foundation for digitalization in finance was established by these developments. However, the current FinTech era often referred to as FinTech 3.0 gained traction following the global financial crisis of 2008, when the rapid proliferation of smart phones and internet connectivity, along with a decline in trust in traditional financial institutions, created an environment that was conducive to technological disruption. FinTech companies have positioned themselves as effective, transparent, and customer-focused alternatives to traditional banks in this post-crisis context. FinTech has grown quickly due to a number of important considerations. First, start-ups can now create scalable financial products at a fraction of the price of established institutions thanks to technical advancements that have reduced entry barriers.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Aishwarya Jaysingrao Thorat patil, Assistant Professor, Department of Economics, Shri.Shiv- Shahu Mahavidaylaya Sarud
Email: aishthoratpatil2430@gmail.com

How to cite this article:
Thorat patil, A. J. (2026). Role Of Fintech in Indian Banking Industry. Bulletin of Nexus Journal, 3(9(II)), 134–138. https://doi.org/10.5281/zenodo.22914621

Quick Response Code:

Website: https://bnir.us

Innovations that have resulted from this wave of digitalization include mobile payments, peer-to-peer lending, crowd funding platforms, robo-advisory services, and crypto currency. Second, adoption has accelerated due to shifting customer expectations. Due to outdated methods and inflexible architecture, traditional institutions find it difficult to provide the convenience, personalization, and round-the-clock access to financial services that modern customers require. FinTech companies, on the other hand, are appealing options because they are flexible and made to deliver flawless customer experiences. Third, innovation has benefited from regulatory changes in many nations. Initiatives like regulatory sandboxes have made it possible to test new business models without putting the financial system at unnecessary risk. FinTech is essential to advancing financial inclusion from a macroeconomic standpoint. FinTech platforms use mobile and internet technologies to reach populations that have historically been left out of the formal banking system, such as small businesses, low-income groups, and rural communities. For example, mobile money services like the Unified Payments Interface (UPI) in India and M-Pesa in Kenya have shown how technology can democratize banking and payment access, promoting widespread economic development. Similar to this, FinTech has completely changed how people invest in developed nations. Through digital platforms, retail investors can now more easily access stock markets, mutual funds, and other asset classes.

Objectives of the Study: -

The major objectives of the present research study are as follows:

1. To study the fintech growth in India.
2. To study the types of fintech applications in India.
3. Tostudy the impact of fintech applications in India

Research Methodology:

Every research is necessary a specific methodology so for the present research has used specific methodology. The present research study is an analytical type of study. The study uses all the necessary methods useful for data collection, for the collection of data, the researcher has used the Secondary source. Secondary data requiringfor the study are collected from books, journals and other Government websites, periodicals, and reports etc.

Review of Literature:

B. Parimala Devi (2024) "A paper on Fintech applications in India" Fintech, or financial technology, has grown in significance on a worldwide scale as it transforms how people and companies engage with financial services. Fintech uses technology to improve financial services' accessibility, efficiency, transparency, and innovation, which benefits a variety of users in many industries. Millions more Indians now have better access to financial services via digital and mobile platforms thanks to the quick development of financial technology, or fintech. This descriptive study examines the factors that have contributed to the emergence of fintech, the different kinds of fintech apps, the obstacles that fintech applications face in India and the prospects for the future.

Manjunatha K.(2025)" Fintech Adoption in India and Its Role in Banking Sector Development" Fintech has played a key role in boosting India's financial ecosystem through digitalization of loans, payments, and regulatory issues, which are changing the way the banking sector operates. As a result, this study clarifies the variables affecting fintech adoption in India and evaluates its impact on the growth of the banking industry. The Reserve Bank of India (RBI), National Payments Corporation of India (NPCI), National Institution for Transforming India (NITI) Aayog, industry papers, and academic literature provided secondary data for the study, which took into account data from 2016–17 to 2024–25 and 2012–2023. Additionally, charts containing a few indications of fintech adoption and banking development such as digital lending, UPI transactions, and credit disbursements through scheduled commercial banks have been used to analyze the collected data. The results show that India's digital public infrastructure, favorable regulatory climate, technological advancements, and growing digital literacy have all had a major impact on the adoption of fintech. Fintech also improves credit availability for MSMEs, increases banking efficiency, promotes financial inclusion, and advances the financial system as a whole.

P. Rajeswari andC.Vijai(2021) "Fintech Industry In India: The Revolutionized Finance Sector" Fintech is the newest buzzword in the finance industry. The contemporary development of Fintech, spearheaded by startups, presents difficulties for both market players and regulators, particularly when it comes to weighing the potential advantages of innovation against the potential risks of novel techniques in the finance industry. Traditional financial institutions have been altered by fintech. The term "fintech" refers to the expanding technology advancements in the financial industry. The banking industry is being shaped more and more by fintech. The Fintech Adoption, Fintech News Network, Indian Fintech Industry Structure,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Fintech Startups in India, and Fintech Trends in India are all examined in this study.

Key Drivers of Fintech Growth in India:

1. Digital India Initiative: With initiatives like Digital India, which prioritize online financial services, digital literacy, and extending internet infrastructure to rural regions, the government has been instrumental in promoting the digital economy.

2. Unified Payments Interface (UPI): Since its launch in 2016 by the National Payments Corporation of India (NPCI), UPI has transformed digital payments in India by facilitating quick, real-time transactions. In addition to providing millions of people with simple access to digital transactions, UPI has opened the door for cutting-edge apps like Paytm, PhonePe, and Google Pay.

3. Financial Inclusion Goals: The government and private sector have concentrated on financial inclusion, bringing banking, insurance, and investment options to neglected and unbanked areas because a sizable portion of the population is still not enrolled in the formal banking system.

4. COVID-19 Pandemic: As individuals shifted to online and contactless transactions to minimize in-person interactions, the pandemic hastened the development of digital financial services. Even conventional banks were forced to implement digital-first tactics as a result of this change.

Fintech App Types in India:

With a variety of applications providing cutting-edge financial services in the areas of payments, loans, investing, and more, India's fintech industry has expanded quickly. The following are a few of the most well-liked and extensively utilized fintech apps in India.

1. Applications For Digital Wallets and Payments

Paytm: One of the biggest digital wallets in India, it provides services including bill payment, shopping, ticket booking, and cell phone recharges.

PhonePe: A UPI-based digital wallet that enables in-app purchases, bill payment, and quick money transfers.

Google Pay: Google's UPI-based payment tool for in-store transactions, bill payment, and peer-to-peer payments.

Amazon Pay: Easy payments for Amazon orders and other third-party merchant websites are made possible via Amazon Pay, which is integrated into the Amazon app.

BHIM (Bharat Interface for Money): A UPI app for peer-to-peer money transfers and merchant payments supported by the government.

2. Applications for Personal Finance Management:

1. Walnut: Assists users with budget management, bill organization, and spending tracking.

2. ET Money: Offers alternatives for investing in mutual funds and fixed deposits, and enables users to manage insurance plans, costs, and investments.

3. Money View: An app for managing a budget that gives users information about their credit scores, spending habits, and financial planning.

3. Applications for Investments:

1. Groww: A well-liked platform for stock, ETF, mutual fund, and fixed deposit investments.

2. Zerodha: Through its Kite platform, the biggest discount brokerage in India provides stock trading, mutual funds, bonds, and more.

3. Upstox is a significant stock trading platform that provides minimal brokerage fees for stocks, commodities, and mutual funds.

4. Paytm Money: This wealth management platform has just added F&O trading in addition to mutual funds, equities, and digital gold.

5. INDmoney: An integrated wealth management platform for fixed-income, mutual fund, and equity investments in the United States and India.

4. Credit and Lending Applications:

1.Cred: Provides personal loans and other credit-related services, as well as rewards users for making timely credit card payments.

2. MoneyTap: An app for personal loans and credit lines that enables users to obtain loans on demand with customizable payback schedules.

3. KreditBee: Provides short-term personal loans, frequently targeting first-time consumers and young professionals.

4. LazyPay: This "buy now, pay later" program allows users to make credit purchases and pay them back at a later time.

5. ZestMoney: Offers digital credit options with simple EMIs and buy-now-pay-later choices for high-value purchases.

5. Applications of Insurance Technology:

1. PolicyBazaar: A platform for comparing and buying insurance coverage, such as health, vehicle, and life insurance.

2. Acko: A digital-first insurance provider that provides health, travel, and auto insurance, among other services.

3. Digit Insurance: Provides a range of insurance products, including health, auto, travel, and smart phone insurance.

6. Neo-Banking and Savings Applications:

1. Niyo: A neo-bank that offers Indian customers financial services, such as salary accounts and forex cards.

2. Jupiter: An easy-to-use neo-banking platform that provides incentive programs, cost management, and free banking.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

3.Fi Money: A neo-bank targeted at young professionals that provides savings tools, smart expenditure analysis, and digital savings accounts.

7. Block chain and Crypto currency Applications:

1. Coin Switch Kuber: An easy-to-use tool for crypto currency investments, including Ethereum and Bitcoin.

2. WazirX: One of the biggest crypto currency exchanges in India, offering a platform for trading different cryptocurrencies.

3. Zeb Pay: A crypto currency trading app that provides a safe and user-friendly platform for crypto currency assets.

8. Accounting Applications and Tax Filing:

1.Clear (previously Clear Tax): Makes investment planning, GST compliance, and tax filing easier for both individuals and companies.

2. Khata book: A digital ledger tool that helps store owners and small enterprises keep track of payments and obligations.

3. Ok Credit: This digital bookkeeping program lets small businesses monitor credit and transactions.

Impact f Fintech Applications In India:

The financial landscape in India has been significantly impacted by the extensive use of fintech applications. Fintech has made financial services more accessible, especially in underprivileged and rural areas where traditional banking infrastructure is scarce. Additionally, it has encouraged more people to engage in the formal economy, which has improved financial transaction efficiency and transparency. Fintech has also encouraged younger generations to save and invest, which has improved financial planning and literacy. Fintech apps have had a huge impact on India, causing major shifts in the country's financial system. Fintech apps have changed how people and organizations engage with financial services by increasing accessibility, convenience, and transparency. In India, fintech apps have significantly impacted the following major areas:

1. Enhanced Financial Inclusion:

Fintech applications have significantly improved financial inclusion in India, especially in underserved and rural areas with limited access to traditional banking infrastructure. Millions of people who were previously unbanked or under banked can now access digital payment solutions, microloans, and reasonably priced insurance products. People can obtain basic financial services without going to a real bank thanks to digital lending platforms and UPI-based apps like Google Pay and PhonePe.

2. Boost to Digital Payments:

The National Payments Corporation of India (NPCI) transformed digital payments in the nation with the launch of the Unified Payments Interface (UPI), which made transactions quick, safe, and easy. For everything from peer-to-peer transfers to small merchant transactions, UPI-based fintech apps have decreased reliance on cash and promoted a culture of digital payments. With fintech apps enabling billions of transactions per month, India is currently among the world leaders in digital payment volumes.

3. Improved Accessibility to Credit:

Fintech lending companies have made it easier to obtain credit by providing credit lines, digital loans, and "buy now, pay later" choices. Due to their short credit histories, these services help people and small enterprises who might find it difficult to get loans from regular banks. Fintech lenders make lending more available to first-time borrowers and small business owners by using alternative credit-scoring techniques that evaluate creditworthiness by examining digital payment history and spending patterns.

4. Rise of Digital Investment and Wealth Management:

By offering inexpensive, user-friendly platforms for stocks, mutual funds, and other financial goods, investment applications like Groww, Zerodha, and Paytm Money have democratized investing. By providing educational tools and eliminating entrance hurdles, these apps have empowered a new generation of young investors. improved financial literacy and involvement in India's capital markets have resulted from this improved understanding of investing.

5. Development of Neo-Banking Solutions:

Neo-banks in India, like Niyo and Jupiter, provide digital-only banking options to meet the demands of tech-savvy customers, particularly professionals and younger consumers. These platforms encourage a switch from traditional banking methods to digital alternatives by offering a simplified, mobile-first banking experience with features like budgeting tools, spending tracking, and no-fee accounts.

6. Increased Efficiency and Transparency in Financial Services:

The financial services industry has become more transparent and efficient thanks to fintech apps. Fintech apps have significantly decreased the time and paperwork often involved in banking, lending, and investing with features including real-time transactions, easily accessible data, and rapid loan processing. These services' security and dependability are being further improved by block chain and AI technologies, which are fostering user confidence.

7. Contribution to the Digital Economy:

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Fintech app usage has supported the government's Digital India agenda and strengthened India's digital economy. There is a growing effort to formalize the economy, lessen reliance on cash, and produce useful data that can guide economic policies as companies and consumers embrace digital transactions.

8. Increased Financial Literacy and Awareness:

Fintech applications are assisting users in becoming more financially literate by offering user-friendly interfaces and educational materials. Financial planning, budgeting, and investing are made easier for users from a variety of backgrounds by the tutorials, notifications, and reports that are frequently included in apps. A culture of wise financial decision-making has been fostered by this change, which has inspired people to take greater charge of their finances.

9. Innovation and Competition in the Financial Sector:

Traditional banks and financial institutions are adopting digital strategies and improving client experiences as a result of the rise of fintech, which has sparked innovation and competition in India's financial sector. To stay competitive, many banks have teamed with fintech companies or introduced their own digital services. Customers gain from this competition since they now have access to better, more individualized, and more reasonably priced financial solutions.

Conclusion: -

India's financial landscape has completely changed as a result of the increasing use of fintech apps, giving millions of people quicker access to financial services. These applications have improved the accessibility, effectiveness, and use of banking, investing, lending, and insurance services in both urban and rural locations. Fintech applications have greatly improved financial inclusion and literacy across many socioeconomic segments by utilizing innovations like UPI for smooth payments, AI for tailored financial advise, and digital-first banking models. Thanks to government programs that encourage digital adoption, a tech-savvy populace, and a supportive regulatory framework, India's fintech ecosystem is currently among the most dynamic in the world. To maintain customer confidence and financial stability, however, issues pertaining to cybersecurity, regulatory compliance, and data privacy will require close attention as the industry develops.

Acknowledgment

The author expresses sincere gratitude to all those who provided valuable support and encouragement in completing this research paper on "Role of Fintech in Indian Banking Industry." The author is thankful to the Department of Economics, Shri Shiv-Shahu Mahavidyalaya, Sarud, for providing the necessary academic environment and encouragement for the study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. B. ParimalaDevi (2024) "A paper on Fintech applications in India", Journal of Emerging Technologies and Innovative Research (JETIR), Volume 11, Issue 11, ISSN-2349-5162.
2. 2. Manjunatha K.(2025) "Fintech Adoption in India and Its Role in Banking Sector Development", South Asian Journal of Social Studies and Economics, Volume 22, Issue 12, Page 165-174, 2025,ISSN: 2581-821X.
3. P.Rajeswari and C.Vijai (2021) "Fintech Industry in India: The Revolutionized Finance Sector", European Journal of Molecular & Clinical Medicin, Volume 8, Issue 11, ISSN 2515-8260.
4. Agarwal, R., & Zhang, Y. (2021). The Rise of Fintech: Challenges and Opportunities in the Indian Financial Sector. International Journal of Financial Studies, 9(1), 12-25. doi:10.3390/ijfs9010012
5. 5.Balaji, S., & Mahajan, P. (2020). Digital Payments and Financial Inclusion in India: Role of Fintech Innovations. Journal of Emerging Markets Finance and Trade, 56(9), 2005-2016. doi:10.1080/1540496X.2020.1754748
6. Bhasin, N., & Sharma, M. (2019). Financial Technology in India: Evolution, Applications, and Challenges. Economic and Political Weekly, 54(29), 56-64. Retrieved from https://www.epw.in
7. Puschmann, T. (2017). FinTech. Business and Information Systems Engineering, 59(1), 69–76. Https://doi.org/10.1007/s12599-017-0464-6.
8. Lee, I., & Shin, Y. J. (2018). FinTech: Ecosystem, business models, investment decisions, and challenges. Business Horizons, 61(1), 35–46. https://doi.org/10.1016/j.bushor.2017.09.003.
9. Anupa Baliga B. S. 1 & Carmelita Goveas (2023) " Makeover of Banks by Digital Interventions and Innovations by Fintechs" International Journal of Case Studies in Business, IT, and Education (IJCSBE), ISSN: 2581-6942, Vol. 7, No. 2, May 2023
10. D. Murugun (2023) "Technology Adoption in Indian Banking Sectors – 2023" East Asian Journal of Multidisciplinary Research (EAJMR) Vol.2, No.2, 2023: 569-580

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

English Language and Artificial Intelligence: Future Prospects for Viksit Bharat 2047

Harishchandra Sugriv Shirsat
(Assistant Professor of English), Shripatrao Chougule Art's and Science College Malwadi Kotoli.

Manuscript ID:
BN-2026-030927

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 139-141

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914671
DOI link:
https://doi.org/10.5281/zenodo.22914671

Abstract:
The Vikasit Bharat 2047 is a term of future plan of current central government. It focuses on skill-based education system and it offers to the India's youth for empower them at globally in the future. It is important to understand the concept of Vikasit Bharat by 2047 in details. The vision of Vikasit Bharat 2047 is to transform India into a developed nation with knowledge-driven and technologically advancement by the year 2047. In this transformation process education, language proficiency, digital literacy and emerging technologies are the basics elements able to empower India. Artificial Intelligence will definitely helpful to Vikasit Bharat 2047, is transforming the ways in which people learn, communicate, and access knowledge of various sectors. This paper examines the future role of English Language and Artificial Intelligence in achieving the objectives associated with Viksit Bharat 2047. It particularly explores the integration of AI with English language communication among youth to empowerment. With the help of AI you can improve English language in which English grammar speaking ability practise, vocabulary building and improve pronunciation plays an important role in terms of English language concerned. English is an important language to empower youth at national and internationally. It is the need of time. It means that if the English is not understood then world class knowledge in various fields cannot be obtained. Knowing English will be useful for acquire knowledge into various fields like scientific research and technological advances, etc. where AI must be useful.

Keywords: *English Language, Artificial Intelligence, Viksit Bharat 2047, English Language Teaching, Digital Literacy, Youth Empowerment, Employability*

Introduction- India is passing through a significant phase of technological, economic and educational transformation. The vision of Viksit Bharat @2047 provides a long-term national perspective for building a developed India. Education and skill development are central to this vision because a developed nation requires not only physical and technological infrastructure but also knowledgeable, skilled oriented education take place an important role. Language is an essential component of human development. In the Indian context, English has a distinctive position because it functions as an important language of higher education, scientific research, international business, technology, diplomacy and global communication. English proficiency can provide Indian students and professionals with access to international knowledge resources and employment opportunities. At the same time, Artificial Intelligence is emerging as one of the most influential technologies of the twenty-first century. Generative AI systems can produce text, translate languages, provide explanations, support writing and assist users in learning and research. In education, AI has the potential to provide personalized learning experiences. AI in education emphasizes that such technologies should be used through a human-centred approach that protects human agency, inclusion, equity, privacy and cultural and linguistic diversity. Therefore, the integration of English Language and Artificial Intelligence can become an important area in the context of Viksit Bharat @2047.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Harishchandra Sugriv Shirsat, (Assistant Professor of English), Shripatrao Chougule Art's and Science College Malwadi Kotoli.
Email: harichandshirsat@gmail.com

How to cite this article:
Shirsat, H. S. (2026). English Language and Artificial Intelligence: Future Prospects for Viksit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 139–141. https://doi.org/10.5281/zenodo.22914671

Quick Response Code:

Website: https://bnir.us

The central argument of this paper is that English can provide communication and knowledge access, while AI can provide technological assistance and personalized learning. Their responsible integration can strengthen the skills, employability and innovative capacity of Indian youth.

Objectives of the Study-

The present research paper have the following objectives:

To examine the role of English Language in the development of Viksit Bharat @2047.

To analyse the potential of Artificial Intelligence in English language

To explore how English and AI can contribute to youth empowerment and employability.

To suggest a future-oriented framework for integrating English proficiency and AI literacy.

Research Methodology

-The present study follows a conceptual research methodology. The research is primarily based on secondary sources, including National Education Policy 2020, on Artificial Intelligence, education-Policy documents and literature related to English Language.

English Language and Global Competence-English has become an important medium for international communication, higher education, science and digital communication. For Indian students, proficiency in English can provide access to a large body of global academic and professional resources. However, English education should not be understood merely as grammar or examination-oriented learning. Modern English education should develop communication, presentation, collaboration, critical thinking, creativity and problem-solving abilities. Thus, English Language Teaching should gradually move from a traditional teacher-centred model towards a skill-oriented and learner-centred model. A developed economy requires global communication. English proficiency can enable Indian professionals, researchers, entrepreneurs and students to interact with international institutions and organizations. A considerable amount of international academic literature and scientific research is available in English. There is need to get command on English Language.

Technology and Education-NEP 2020 emphasizes that technology can influence both what students learn and how they learn. It specifically identifies artificial intelligence, machine learning and other technologies as important areas for educational. This provides a strong policy basis for exploring AI-assisted English education in Indian higher education.

Artificial Intelligence in Education-AI can support several educational functions, including personalized learning, assessment, feedback, content creation and language practice. AI and education framework includes competency development for both students and teachers. AI can also support writing, brainstorming, translation and language practice. However, AI should empower teachers and learners rather than replace human intelligence and educational relationships.

Employability and Entrepreneurship -Modern employment increasingly requires communication, digital literacy, and teamwork and problem-solving skills. English communication skills combined with technological competence can strengthen employability. Young entrepreneurs need to communicate with customers, investors, organizations and international partners. English can facilitate business communication and access to global markets. **Artificial Intelligence in English Language** -AI can transform the traditional English classroom into a more interactive and learner-centred environment. Special attention should be given to rural and economically disadvantaged students so that AI does not increase the existing digital divide. Educational institutions should formulate clear guidelines regarding:

Conclusion-

Viksit Bharat @2047 is not merely a technological or economic project; it is fundamentally a human-capital development vision. A developed India will require citizens who are knowledgeable, skilled, creative, ethical, and digitally competent and globally connected. English Language and Artificial Intelligence can contribute significantly to this transformation. English can provide access to global knowledge, communication and professional opportunities, while AI can make learning more personalized, accessible and interactive. Their integration can particularly benefit Indian youth by strengthening communication skills, digital literacy, employability, research capacity and innovation. However, technology should remain a means rather than an end. The human-centred approach reminds educational institutions that AI should empower to all while protecting human agency, equity, privacy and linguistic and cultural diversity. Therefore, the future educational model for Viksit Bharat @2047 .The integration of English proficiency and AI literacy can thus become an important strategy for preparing India's youth for the knowledge economy of 2047. If implemented inclusively, ethically and thoughtfully, it can contribute to India's journey from a developing knowledge society towards a globally competitive, innovative and developed nation.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Acknowledgment
The author sincerely expresses gratitude to everyone who contributed directly or indirectly to the completion of this research paper titled "English Language and Artificial Intelligence: Future Prospects for Viksit Bharat 2047." The author is thankful to the management and colleagues of Shripatrao Chougule Arts and Science College, Malwadi Kotoli, for their encouragement and academic support. The author also acknowledges the valuable information and insights obtained from the National Education Policy 2020, UNESCO guidance on Generative AI in Education and Research, and other relevant secondary sources consulted during the study. Finally, the author expresses sincere appreciation to all those whose guidance, encouragement, and support helped in completing this research work successfully.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References
1. Government of India. (2020). National Education Policy 2020. Ministry of Education, Government of India.
2. UNESCO. (2023). Guidance for Generative AI in Education and Research. Paris: UNESCO. The guidance emphasizes human agency, inclusion, equity, privacy and responsible use of Generative AI in education.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Green Chemistry Approaches in Pharmaceutical Synthesis: Sustainable Methods, Challenges and Future Perspectives

Sayali Sahadev Sakhare
Department of Chemistry, Shripatrao Chougule Arts and Science College Malwadi-Kotoli

Manuscript ID:
BN-2026-030928

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 142-145

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914742
DOI link:
https://doi.org/10.5281/zenodo.22914742

Abstract
Pharmaceutical synthesis is essential for producing therapeutic agents, but conventional manufacturing can consume large quantities of solvents, reagents, water and energy while generating substantial waste. Green chemistry provides a preventive approach in which chemical products and processes are designed to reduce hazardous substances, resource consumption and environmental impact. This review summarizes important green chemistry strategies relevant to pharmaceutical synthesis, with emphasis on solvent selection, catalysis, biocatalysis, one-pot and multicomponent reactions, continuous-flow processing, microwave and photochemical methods, electrochemical synthesis, renewable feedstocks and green process metrics. Recent literature shows that these approaches can improve reaction efficiency while reducing waste and energy demand. Green metrics such as atom economy, E-factor and process mass intensity are useful for comparing conventional and improved processes, although no single metric describes sustainability completely. The review also considers scale-up, regulatory, economic and technical challenges. Future pharmaceutical manufacturing is expected to combine green-by-design principles with process analytical technology, continuous manufacturing, life-cycle assessment and data-driven reaction optimization. Integrating these methods can support safer, more efficient and economically viable production of active pharmaceutical ingredients (APIs).

Keywords: *green chemistry; pharmaceutical synthesis; sustainable chemistry; green solvents; catalysis; biocatalysis; flow chemistry; active pharmaceutical ingredients*

Introduction

The pharmaceutical industry depends on complex chemical transformations to convert starting materials into active pharmaceutical ingredients and intermediates. Although these processes deliver high-value products, they may also involve multiple reaction and purification steps, large solvent volumes, hazardous reagents and energy-intensive operations. Consequently, improving the environmental performance of pharmaceutical synthesis is an important part of sustainable manufacturing. Green chemistry differs from end-of-pipe pollution control because it seeks to prevent waste and hazards at the design stage. The twelve principles of green chemistry encourage prevention, atom economy, less hazardous synthesis, safer solvents, energy efficiency, renewable feedstocks, catalysis, reduced derivatization and safer products. In pharmaceutical chemistry, these principles can be applied from route selection and molecular design through process development, scale-up and manufacturing. Kar et al. emphasized that green pharmaceutical synthesis can combine solvent reduction, catalytic transformations, one-pot and multicomponent reactions, continuous processing and process intensification.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sayali Sahadev Sakhare, Department of Chemistry, Shripatrao Chougule Arts and Science College Malwadi-Kotoli
Email: sayalisakhare7679@gmail.com

How to cite this article:
Sakhare, S. S. (2026). Green Chemistry Approaches in Pharmaceutical Synthesis: Sustainable Methods, Challenges and Future Perspectives. Bulletin of Nexus Journal, 3(9(II)), 142–145.
https://doi.org/10.5281/zenodo.22914742

Quick Response Code:

Website: https://bnir.us

⌾cite⌾turn0search1⌾turn0search2⌾ Recent reviews similarly identify solvent replacement, catalysis, biocatalysis, microwave and ultrasound assistance, flow chemistry and sustainable extraction as important directions. Ahmad et al. highlighted that these technologies can improve reaction efficiency and reduce environmental burden, while also noting challenges associated with economics, regulation and scale-up. ⌾cite⌾turn0search0⌾

Objectives

This research aims to: (i) describe major green chemistry strategies used in pharmaceutical synthesis;
(ii) explain their contribution to waste, energy and hazard reduction;
(iii) summarize useful green metrics;
(iv) identify practical barriers to industrial adoption; and
(v) outline future research directions.

The discussion is based primarily on peer-reviewed reviews and recent studies published in major chemistry and pharmaceutical journals, with emphasis on literature from 2021–2025.

Major Green Chemistry Strategies

1 Green solvents and solvent minimization

Solvents frequently represent a major part of the material footprint of chemical manufacturing. Green synthesis therefore begins with avoiding unnecessary solvent use and selecting safer alternatives when a solvent is required. Water, ethanol and other comparatively preferable solvents may replace more hazardous media when chemically feasible. Solvent selection must nevertheless consider reaction performance, toxicity, recovery, flammability, energy required for solvent removal and compatibility with downstream purification. Modern solvent-selection guides support systematic comparison rather than choosing a solvent only on the basis of reaction yield.

2 Catalysis and biocatalysis

Catalysts can improve reaction rates and selectivity while lowering the amount of reagents required. Transition-metal, organocatalytic and heterogeneous catalytic systems have been explored for pharmaceutical transformations. Biocatalysis provides an additional route to selective synthesis under comparatively mild conditions. Enzymes can deliver high chemo-, regio- and stereoselectivity and can reduce the need for protecting groups or harsh reaction conditions. Recent work also combines immobilized enzymes with flow systems, potentially improving catalyst recovery and process control.

3 One-pot and multicomponent synthesis

One-pot and multicomponent reactions reduce the number of isolated intermediates and purification operations. The Ugi reaction is an important example because several starting components can be incorporated into a single product-forming sequence. Such strategies can improve step economy and reduce solvent, energy and material consumption when the desired selectivity and product quality are maintained. Recent analysis of pharmaceutical examples shows that multicomponent approaches can provide favorable atom economy and process-mass characteristics compared with some conventional multistep routes. ⌾cite⌾turn0search7⌾

4 Continuous-flow processing

Continuous-flow chemistry performs reactions in a continuously moving stream rather than a conventional batch vessel. It can provide efficient heat and mass transfer, precise residence-time control and improved management of hazardous intermediates. These characteristics can also facilitate process intensification and scale-up by increasing operating time or using parallel flow units rather than simply increasing vessel volume. Recent pharmaceutical literature identifies continuous flow as an important route toward safer and more resource-efficient manufacturing. ⌾cite⌾turn0search5⌾

Flow processing is particularly attractive when rapid reactions, photochemical transformations, electrochemical steps or difficult heat-transfer conditions are involved. However, implementation requires suitable equipment, process-control strategies, reliable analytical monitoring and validation. Thus, the sustainability benefit should be evaluated for the complete process rather than assumed from the use of flow equipment alone.

5 Microwave, ultrasound and photochemical methods

Alternative energy sources can shorten reaction times and sometimes improve selectivity. Microwave-assisted synthesis can provide rapid and uniform heating for suitable reactions, whereas ultrasound can enhance mixing and mass transfer. Photochemistry uses light to access reaction pathways that may be difficult under conventional thermal conditions. Recent pharmaceutical photochemistry literature demonstrates increasing interest in photochemical methods for development and process applications. These techniques can reduce energy or reagent requirements in selected cases, although electricity demand, equipment scale-up and reproducibility must be considered.

6 Electrochemical syntheses

Electrochemical synthesis replaces or reduces conventional chemical oxidants and reductants by using electrical potential to drive redox

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

transformations. This can improve step economy and reduce the generation of stoichiometric inorganic by-products. A 2024 review specifically highlighted electrochemistry as an increasingly relevant sustainable strategy for pharmaceutical and drug-precursor synthesis. ◎cite◎turn0search5◎ Renewable electricity could further improve the environmental profile of electrochemical processes, although electrode materials, electrolytes, current efficiency and process scale remain important considerations.

Green Metrics for Pharmaceutical Processes

Green chemistry requires quantitative assessment because a high chemical yield does not necessarily indicate a sustainable process. Several complementary metrics are commonly used.

Metric	Meaning	Purpose
Atom economy	Fraction of reactant atoms incorporated into the desired product.	Evaluates inherent reaction efficiency.
E-factor	Mass of waste generated per mass of product.	Measures waste intensity.
Process mass intensity (PMI)	Total mass of materials used per mass of product.	Includes reactants, solvents and processing materials.
Energy use	Energy consumed during reaction and downstream processing.	Identifies energy-intensive operations.
Life-cycle assessment	Environmental assessment across defined life-cycle stages.	Provides broader environmental comparison.

These metrics should be interpreted together. For example, a reaction with excellent atom economy may still have poor PMI if large solvent volumes are required. Life-cycle assessment can extend the evaluation to raw materials, energy sources, manufacturing and other stages. Recent pharmaceutical LCA literature emphasizes the value of life-cycle thinking while also noting methodological and data limitations.

Representative Applications and Benefits

The practical value of green chemistry is best demonstrated when improved chemistry is translated into a robust manufacturing process. Benefits can include fewer synthetic steps, lower solvent consumption, reduced hazardous waste, lower energy demand, improved worker safety and potentially lower production cost. A recent industrial study on a next-generation commercial synthesis of valbenazine ditosylate reported reductions in manufacturing time, material use and water use while also improving overall yield. Such examples illustrate that environmental and economic improvements can occur simultaneously when route design and process engineering are considered together.

Green chemistry can also improve supply-chain resilience. Replacing scarce or hazardous reagents, reducing dependence on large solvent inventories and using renewable or readily available feedstocks can reduce operational risks. Nevertheless, a method should not be called greener solely because it uses a bio-based reagent or water; the complete process, including purification and waste treatment, should be evaluated.

Challenges and Limitations

Despite significant progress, adoption of green pharmaceutical synthesis is not automatic. First, laboratory-scale reactions may not translate directly to commercial scale. Mixing, heat transfer, gas-liquid contact and mass transfer can change considerably during scale-up. Second, greener solvents or catalysts may be more expensive or unavailable at the required manufacturing scale. Third, pharmaceutical processes are highly regulated, so a new process must consistently deliver product quality, impurity control and reproducibility.

Catalysis also presents specific challenges. Some metal catalysts can introduce trace-element concerns and require effective removal and recovery. Enzymes can be sensitive to temperature, pH and solvent composition, and their productivity may require immobilization or engineering. Flow chemistry requires specialized equipment and process-control expertise. Photochemical and electrochemical methods may require high-quality light sources, electrodes and electrical infrastructure. Therefore, technology selection should be based on a balanced assessment of sustainability, quality, safety, cost and scalability.

Emerging Trends and Future Perspectives

Future pharmaceutical synthesis is likely to move from isolated 'green reactions' toward integrated green process design. Continuous manufacturing, process analytical technology and intensified purification can be combined with greener reaction chemistry. Biocatalysis and chemo-enzymatic sequences are expected to remain important for selective transformations, while electrochemical and photochemical approaches can expand the available reaction space.

Artificial intelligence and data-driven optimization may also support greener route selection by predicting reaction outcomes, identifying

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

promising catalysts and solvents, and reducing experimental trial-and-error. Recent reviews have begun connecting AI with retro-biosynthesis and green chemistry, suggesting an opportunity to optimize both chemical performance and sustainability objectives.

Another important direction is green-by-design pharmaceutical development. Environmental considerations can be introduced during early route scouting rather than after a process has already been fixed. Life-cycle assessment, solvent guides and green metrics can be used as decision-support tools at this stage. The goal should be a process that is simultaneously efficient, safe, economically practical and environmentally responsible.

Conclusion

Green chemistry provides a practical framework for improving pharmaceutical synthesis without compromising the fundamental requirement of producing high-quality medicines. Solvent minimization, catalysis, biocatalysis, one-pot and multicomponent reactions, continuous-flow processing, alternative energy sources and electrochemical methods can each contribute to improved sustainability. However, no individual technology is universally green; performance must be evaluated using appropriate metrics and across the complete process. Future progress will depend on integrating green chemistry with process engineering, life-cycle assessment, digital optimization and regulatory science. Such integration can help pharmaceutical manufacturing move toward safer, lower-waste and more resource-efficient production.

Acknowledgment

The author would like to express sincere gratitude to the Department of Chemistry, Shripatrao Chougule Arts and Science College, Malwadi-Kotoli, for providing the academic environment and support necessary for completing this review article. The author is grateful to the faculty members and colleagues for their valuable guidance, encouragement, and constructive suggestions throughout the preparation of this work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Kar S, Sanderson H, Roy K, Benfenati E, Leszczynski J. Green Chemistry in the Synthesis of Pharmaceuticals. *Chemical Reviews*. 2022;122(3):3637–3710. doi:10.1021/acs.chemrev.1c00631.
2. Ahmad S, Jaiswal R, Yadav R, Verma S. Recent advances in green chemistry approaches for pharmaceutical synthesis. *Sustainable Chemistry One World*. 2024;4:100029. doi:10.1016/j.scowo.2024.100029.
3. Nolan K, et al. A pharma perspective on sustainability advantages through adoption of continuous flow. *Current Opinion in Green and Sustainable Chemistry*. 2024;46:100886. doi:10.1016/j.cogsc.2024.100886.
4. Feng Y, et al. Typical Cases of Continuous Flow Chemistry in Pharmaceutical Synthesis in 2023–2024. *Asian Journal of Organic Chemistry*. 2025;14:e202500132. doi:10.1002/ajoc.202500132.
5. Martins R, et al. Continuous flow reactions in the preparation of active pharmaceutical ingredients and fine chemicals. *Chemical Communications*. 2024;60:3226–3239. doi:10.1039/D4CC00418C.
6. Ghosh A, Parida VK, Banerjee D. Challenges and opportunities on sustainable electrochemical transformations: application towards the synthesis of pharmaceuticals and precursors of drug-like molecules. *Green Chemistry*. 2024;26:5770–5789. doi:10.1039/D3GC04881K.
7. Moschetta EG, et al. Photochemistry in Pharmaceutical Development: A Survey of Recent Applications. *Organic Process Research & Development*. 2024;28(4):831–846. doi:10.1021/acs.oprd.3c00499.
8. Ferlin F, et al. Classic vs. C–H functionalization strategies in the synthesis of APIs: a sustainability comparison. *Green Chemistry*. 2023;25:7916–7933. doi:10.1039/D3GC02516K.
9. Lambarska D, et al. Monoliths enabling biocatalysis in flow chemistry. *Green Chemistry*. 2024;26:10718–10738. doi:10.1039/D4GC03535F.
10. *The Evolving Nature of Biocatalysis in Pharmaceutical Research and Development*. *JACS Au*. 2023. doi:10.1021/jacsau.2c00712.
11. *Deep Eutectic Solvents: An Eco-friendly Design for Drug Engineering*. *ChemSusChem*. 2023. doi:10.1002/cssc.202300669.
12. *Application of Life Cycle Assessment in the pharmaceutical industry: A critical review*. *Journal of Cleaner Production*. 2024;459:142550. doi:10.1016/j.jclepro.2024.142550.
13. *GreenMedChem: the challenge in the next decade toward eco-friendly compounds and processes in drug design*. *Green Chemistry*. 2023. doi:10.1039/D2GC03772F.
14. *Green synthesis interventions of pharmaceutical industries for sustainable development*. *Current Research in Green and Sustainable Chemistry*. 2021;4:100174.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Artificial Intelligence-Driven Advances in Analytical Chemistry: Methods, Applications, and Future Perspectives

Dr. Achut R. Shinde
Head & Assistant Professor, Department of Analytical Chemistry, Sanjeevanee Mahavidyalaya, Chapoli, Tq. Chakur, Dist. Latur

Manuscript ID:
BN-2026-030929

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 146-152

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914797
DOI link: https://doi.org/10.5281/zenodo.22914797

Abstract

Artificial intelligence (AI) is reshaping analytical chemistry by changing how instrumental measurements are processed, interpreted, optimized, and translated into chemical decisions. Modern analytical platforms generate high-dimensional spectra, chromatograms, mass spectra, images, and sensor signals in volumes that can exceed the practical capacity of conventional univariate or manually supervised workflows. This integrative review examines AI-driven advances across spectroscopy, chromatography, mass spectrometry, nuclear magnetic resonance (NMR), chemical sensors, imaging, and analytical method development. The review adopts a structured narrative design using purposive sampling of peer-reviewed reviews, primary methodological literature, and regulatory guidance identified through targeted searches of major biomedical and chemistry literature sources and official regulatory repositories. Evidence was thematically coded into four domains: data enhancement, predictive modelling, analytical-method optimization, and decision support. The synthesis indicates that machine learning (ML), deep learning (DL), chemometrics, quantitative structure–retention relationships (QSRR), and hybrid mechanistic–data-driven approaches can improve pattern recognition, spectral deconvolution, analyte identification, retention prediction, calibration, anomaly detection, and experimental optimization when adequate and representative data are available. However, AI does not automatically create a valid analytical method: model leakage, biased sampling, poor external validation, instrument drift, explainability limitations, and weak uncertainty characterization can undermine apparent performance. Current regulatory thinking increasingly emphasizes risk-based credibility and conventional analytical validation principles. Future analytical laboratories are therefore likely to combine AI with robust metrology, automated experimentation, digital twins, explainable AI, multimodal data fusion, and continuous lifecycle validation. The central conclusion is that the strongest pathway is not replacement of analytical chemistry by AI, but integration of chemical knowledge, measurement science, and trustworthy computation.

Keywords

Artificial intelligence; machine learning; deep learning; chemometrics; analytical chemistry; spectroscopy; chromatography; mass spectrometry; sensors; QSRR; explainable AI; method validation.

Graphical Abstract:



***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Achut R. Shinde, Head & Assistant Professor, Department of Analytical Chemistry, Sanjeevanee Mahavidyalaya, Chapoli, Tq. Chakur, Dist. Latur
Email: acachut251114@gmail.com

How to cite this article:

Shinde, A. R. (2026). Artificial Intelligence-Driven Advances in Analytical Chemistry: Methods, Applications, and Future Perspectives. Bulletin of Nexus Journal, 3(9(II)), 146–152. https://doi.org/10.5281/zenodo.22914797

Quick Response Code:

Website: https://bnir.us

Introduction:

Analytical chemistry is increasingly characterized by the production of complex, multidimensional data. Chromatographic systems generate time-resolved signals; spectroscopic instruments produce dense wavelength- or frequency-dependent measurements; mass spectrometers create high-dimensional mass-to-charge profiles; and imaging and sensor platforms can produce spatially resolved or continuous measurements. AI and chemometric methods provide computational strategies for extracting patterns from these data and linking measured signals to chemical identity, concentration, process state, or sample class [1–4]. Reviews of the field show that AI has moved beyond a narrow role in image recognition toward spectroscopy, chromatography, NMR, mass spectrometry, sensors, and experimental optimization [2–5]. Traditional chemometrics already established multivariate calibration, principal component analysis (PCA), partial least squares (PLS), classification, and experimental design as core approaches to complex chemical data. Contemporary ML extends this toolkit with algorithms capable of representing nonlinear relationships, while DL can learn hierarchical features from raw or minimally processed data [3,6]. The attraction is particularly strong when signal overlap, matrix effects, nonlinear response, baseline variation, or very large datasets make manual interpretation difficult.

Recent literature highlights applications such as spectral denoising and deconvolution, compound identification, chromatographic retention prediction, quantitative structure–retention relationship modelling, NMR interpretation, metabolomic classification, and optimization of chromatographic conditions [2,4,7–10]. At the same time, the field is confronting an important methodological question: how can AI performance be demonstrated as analytically reliable rather than merely computationally accurate? The answer requires representative sampling, independent validation, uncertainty assessment, traceability, and alignment with established analytical-procedure lifecycle principles.

Rationale of the Study:

The rationale for this review arises from the convergence of three developments. First, modern instruments continuously increase data dimensionality and acquisition speed. Second, AI methods are becoming sufficiently accessible for routine research laboratories. Third, analytical chemistry is a measurement discipline in which decisions must be defensible, reproducible, and fit for purpose. Recent reviews describe substantial gains in data interpretation and method development, but also identify persistent barriers involving model interpretability, heterogeneous datasets, standardization, validation, and regulatory acceptance [2,4,8].

A consolidated review is therefore useful for researchers who need to understand not only what AI can do, but also where it should be applied, how it should be validated, and which future research directions are most likely to produce trustworthy analytical systems.

Objectives:

1. To review major AI and ML methods currently used in analytical chemistry.
2. To map applications across spectroscopy, chromatography, mass spectrometry, NMR, sensors, imaging, and analytical method development.
3. To examine the methodological requirements for data preparation, model training, validation, and interpretation.
4. To synthesize opportunities and limitations affecting analytical reliability, reproducibility, and regulatory acceptance.
5. To propose future directions for explainable, hybrid, automated, and lifecycle-managed AI-enabled analytical laboratories.

Hypothesis:

Primary hypothesis (H_1): Integration of AI/ML with analytical measurement workflows can enhance the extraction of chemical information, prediction, classification, and method optimization compared with conventional analysis alone, provided that training data are representative and model performance is independently validated.

Null hypothesis (H_0): AI/ML integration does not provide a meaningful analytical advantage over appropriately designed conventional chemometric or statistical workflows when evaluated under equivalent validation conditions.

Methodology

1 Research Design

This study uses an integrative narrative-review design. Rather than collecting new laboratory measurements, it synthesizes published methodological and application evidence to identify recurring patterns in AI-enabled analytical chemistry. The design is descriptive and critical: it compares methods, maps application domains, identifies implementation risks, and derives future research priorities.

2 Literature Identification and Sampling

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Targeted searches were conducted across PubMed/PMC and publisher platforms covering analytical chemistry and chemistry journals, supplemented by official regulatory sources. Search concepts included combinations of: 'artificial intelligence', 'machine learning', 'deep learning', 'chemometrics', 'analytical chemistry', 'spectroscopy', 'chromatography', 'mass spectrometry', 'NMR', 'sensors', 'QSRR', 'method development', 'explainable AI', and 'validation'. Purposive sampling was used to prioritize peer-reviewed reviews, methodological studies, recent perspectives, and authoritative regulatory guidance with direct relevance to analytical measurement.

Inclusion criteria were: (i) direct application or methodological discussion of AI/ML in analytical chemistry; (ii) sufficient description of analytical task and computational approach; (iii) relevance to chemical measurement, identification, quantification, separation, sensing, or method development; and (iv) publication in a peer-reviewed journal or issuance by a recognized regulatory organization. Exclusion criteria were unrelated AI applications, purely theoretical computer-science papers without analytical relevance, duplicate records, and sources lacking enough information to interpret the analytical context.

3 Tools and Data-Extraction Framework

A structured extraction matrix was used conceptually to code each source according to: analytical platform; chemical task; AI/ML method; input data type; preprocessing; training/validation strategy; output; claimed benefit; limitation; and regulatory or reproducibility considerations. The framework was informed by established reviews of chemometrics and AI in analytical chemistry [3–5] and by current guidance on analytical validation [11,12].

Figure 1. Conceptual AI-enabled analytical chemistry workflow.

4 Analytical Methods Considered

The principal AI approaches considered were supervised learning (classification and regression), unsupervised learning (clustering and dimensionality reduction), deep neural networks, convolutional neural networks for spectral/image data, ensemble methods, support vector machines, autoencoders, QSRR models, and hybrid mechanistic–data-driven systems. Conventional chemometric methods such as PCA and PLS were treated as important baselines rather than being excluded from the AI landscape. As tabulated in table.1

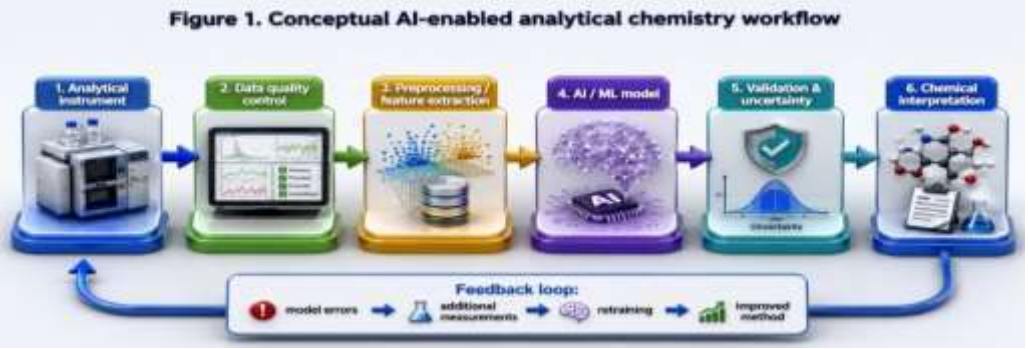


Table 1. Comparison of Commonly Used AI/Chemometric Approaches

AI Approach	Typical Analytical Task	Strength	Main Limitation
PCA / PLS	Exploration; calibration	Interpretable; established	Linear assumptions
Random Forest	Classification; regression	Robust; nonlinear	Less transparent than linear models
SVM	Classification; regression	Good for medium-sized data	Parameter tuning; scaling
ANN / CNN	Spectra; images; complex patterns	High nonlinear capacity	Data hungry; explainability
Autoencoder	Denoising; dimensionality reduction	Learns compact representations	Reconstruction may hide artifacts
Deep / Hybrid Models	Multimodal prediction; optimization	Flexible; integrates data types	Validation and governance burden

Note: PCA = Principal Component Analysis; PLS = Partial Least Squares; SVM = Support Vector Machine; ANN = Artificial Neural Network; CNN = Convolutional Neural Network.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Applications and Advances

1 Spectroscopy

Spectroscopy is one of the most mature application areas for AI because spectra contain many correlated variables and frequently exhibit overlap, baseline effects, scattering, and nonlinearities. ML and DL can support classification, quantitative calibration, denoising, peak detection, spectral reconstruction, and identification of chemically meaningful patterns. Reviews covering vibrational spectroscopy, X-ray spectroscopy, NMR, and related modalities show that preprocessing and data enhancement remain important even when DL is used [3,6,13].

An important methodological point is that a high-capacity model should not be assumed to outperform a carefully constructed chemometric baseline. PLS, support vector regression, random forests, and neural networks can all be effective depending on sample size, noise, feature structure, and task. The appropriate comparison is therefore task-specific and should include an independent test set, uncertainty analysis, and chemically meaningful error measures.

2 Chromatography and QSRR

AI has become especially relevant to chromatographic method development and retention prediction. Models can learn relationships between molecular descriptors, mobile-phase conditions, stationary-phase characteristics, and retention behavior. QSRR provides a chemically interpretable bridge between molecular structure and chromatographic retention, while ML can capture nonlinear relationships that are difficult to represent with simple equations [7,9,10]. Recent reviews report extensive use of ML and DL for retention prediction and optimization in liquid and gas chromatography, with hybrid QSRR/AI strategies emerging as an important direction [7,9].

In method development, AI can reduce the number of experimental trials by prioritizing promising conditions. However, predictions are only useful within the chemical and instrumental domain represented in the training data. Extrapolation to a different column, solvent system, instrument configuration, or analyte class requires explicit validation.

3 Mass Spectrometry and Metabolomics

Mass spectrometry produces information-rich patterns that are well suited to ML classification, feature selection, compound identification, and metabolomic profiling. AI can assist with peak evaluation, annotation, discrimination of sample classes, and integration of multiple data sources. The principal opportunity is to reduce the gap between raw high-dimensional measurements and interpretable chemical information. The main risks include database bias, false annotations, instrument-to-instrument variation, missing values, and the tendency of models to learn technical batch effects instead of chemistry [3,6].

4 NMR and Multidimensional Data

DL has been investigated for NMR reconstruction, denoising, spectral interpretation, and automated analysis. NMR is particularly attractive because spectra may contain overlapping resonances and multidimensional information. Reviews describe DL as a promising route to faster and more automated processing, while emphasizing the need for chemically meaningful validation [14].

5 Sensors and Imaging

AI can improve the performance of electrochemical, optical, paper-based, smartphone-enabled, and imaging sensors by transforming complex signals into classifications or quantitative predictions. In hyperspectral or microscopy applications, CNNs and related models can learn spatial and spectral features simultaneously. The recent literature also emphasizes that portable platforms generate heterogeneous datasets that require careful calibration and external validation before field deployment [2,4] fig.2.

Figure 2. Major AI application domains in analytical chemistry



Figure 2. Major AI application domains in analytical chemistry.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

6 Analytical Method Development and Optimization

AI can complement Design of Experiments (DoE), response-surface modelling, and mechanistic understanding by predicting method performance and recommending new experiments. In chromatography, this includes retention-time prediction and optimization of gradient conditions. More broadly, automated laboratories can use iterative cycles in which an algorithm proposes an experiment, an instrument executes it, results are evaluated, and the next experiment is selected. Such closed-loop workflows connect AI with robotics and automation and are consistent with the broader vision of accelerated chemical research [15,16].

Analysis and Data Analysis

The evidence was synthesized through thematic content analysis rather than meta-analysis because the included literature differs substantially in instruments, datasets, target analytes, model architectures, validation protocols, and performance metrics. Four analytical themes were derived: (1) data enhancement, including preprocessing, denoising, feature extraction and deconvolution; (2) prediction and classification, including calibration, identification and sample discrimination; (3) optimization, including retention prediction and method-development support; and (4) trustworthy deployment, including explainability, uncertainty, standardization, external validation and regulatory credibility. The synthesis indicates that AI integration is strongest where measurements are high-dimensional, repetitive, pattern-rich, and supported by sufficiently large reference datasets. Spectroscopy, chromatography and mass spectrometry therefore represent particularly active areas. Sensors, NMR and imaging also show substantial potential, especially when multimodal information is available. Figure 3 provides an author-derived qualitative integration-potential map. It is intentionally not presented as a bibliometric count or numerical performance comparison.

1 Data Quality and Sampling Effects

Data quality is a central determinant of AI reliability. Randomly splitting highly correlated spectra from the same sample or batch can produce information leakage and artificially optimistic accuracy. Better practice is to separate data by independent samples, production lots, instruments, days, sites, or other meaningful sources of variation. Class imbalance should be assessed explicitly, and the training set should cover the intended chemical domain.

2 Model Evaluation

For classification, useful measures include sensitivity, specificity, precision, recall, F1 score, balanced accuracy, and confusion matrices. For quantitative prediction, RMSE, MAE, bias, prediction intervals, and calibration performance are informative. Where analytical decisions are regulated, statistical performance should be complemented by specificity/selectivity, accuracy, precision, range, detection/quantitation characteristics where relevant, and robustness considerations. ICH Q2(R2) emphasizes that analytical validation should demonstrate that a procedure is fit for its intended purpose [11,12].

3 Explainability and Uncertainty

Explainable AI (XAI) is particularly important in analytical chemistry because a prediction may be numerically correct while being chemically implausible. Feature attribution, saliency methods, permutation importance, partial-dependence analysis, uncertainty estimates, and chemically informed descriptors can help connect model output to analytical reasoning. Nevertheless, explanations should be treated as diagnostic evidence rather than automatic proof of causality.

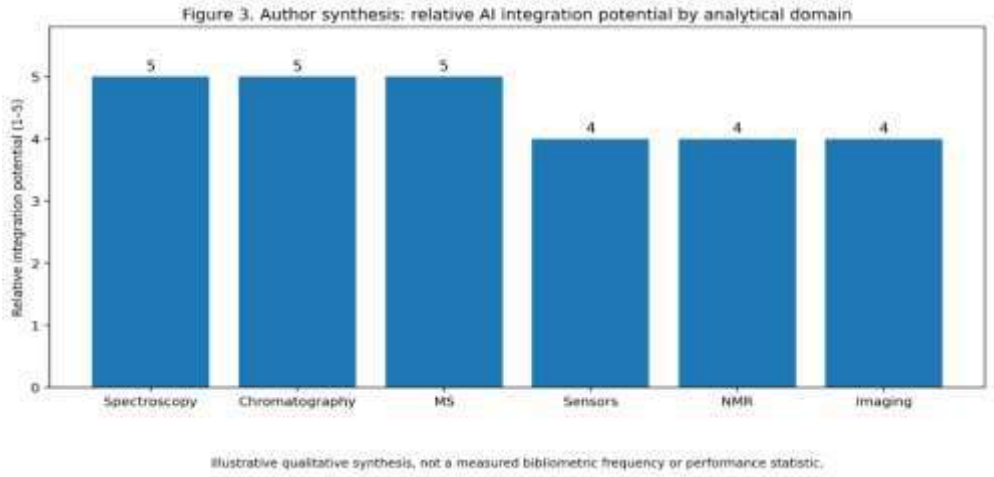


Figure 3. Author synthesis of relative AI integration potential by analytical domain.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Discussion

The literature supports a shift from AI as a post-processing tool toward AI as a component of the complete analytical lifecycle. Earlier applications concentrated on classification and prediction; current work increasingly addresses method development, data fusion, experimental design, automated decision-making, and integration with laboratory automation [2,4,8,17]. This progression creates both opportunities and new responsibilities.

First, analytical scientists must distinguish between predictive performance and analytical validity. A model may have high test-set accuracy but fail when exposed to new matrices, instruments, laboratories, or concentration ranges. Second, model governance becomes part of analytical quality. Version control, training-data provenance, preprocessing records, model parameters, acceptance criteria, and change management should be documented. Third, AI should complement rather than obscure chemical knowledge. Hybrid models that combine mechanistic relationships with data-driven learning may offer a useful balance between flexibility and interpretability.

Regulatory expectations are evolving toward risk-based evaluation of AI credibility. The FDA's 2025 draft guidance proposes a risk-based credibility assessment framework for AI models used to support regulatory decision-making for drugs and biological products [18]. Together with ICH Q2(R2) and Q14, this reinforces the principle that AI-enabled analytical procedures need evidence of fitness for purpose, controlled development, and scientifically justified validation [11,12,19].

Future Perspectives

Explainable and uncertainty-aware AI: Future analytical systems should report not only predictions but also confidence, applicability domain, influential variables, and failure conditions. Hybrid mechanistic–AI models: Combining chemical theory, mass balance, kinetics, chromatography models, spectroscopy and ML can improve extrapolation and interpretability.

Autonomous analytical laboratories: Integration of AI with robotics and automated instruments can create closed-loop measurement–decision–experiment cycles. Multimodal data fusion: Joint analysis of chromatographic, spectroscopic, mass-spectrometric, sensor and metadata streams may provide richer chemical fingerprints than any single modality.

Digital twins and virtual experimentation: Instrument- and process-specific digital representations may allow safer exploration of method conditions before physical experiments.

Federated and privacy-preserving learning: Distributed laboratories could collaborate without centralizing sensitive datasets, provided harmonized standards and validation frameworks are developed. Lifecycle validation: AI models should be monitored after deployment for drift, changing sample populations, instrument changes and degradation of predictive performance.

Standardized benchmarks: Shared datasets, common preprocessing protocols and external test sets are needed to make claims of AI superiority more reproducible.

Human–AI collaboration: The future analytical chemist is likely to act as model steward, domain expert and critical decision-maker rather than being replaced by automation.

Conclusions

AI-driven analytical chemistry has progressed from experimental pattern recognition to a broader framework for data enhancement, prediction, identification, optimization and automated decision support. The strongest evidence concerns complex, high-dimensional measurements such as spectroscopy, chromatography and mass spectrometry, while NMR, sensors and imaging provide important additional opportunities. The field's principal limitation is not a lack of algorithms but the difficulty of ensuring that computational performance translates into reliable analytical measurement. The review supports the hypothesis that AI can improve analytical workflows when its use is matched to the data structure, supported by adequate reference samples, and subjected to independent validation. The most defensible future is therefore an integrated model in which AI, chemometrics, chemical knowledge and measurement science operate together. Trustworthy AI in analytical chemistry should be accurate, interpretable where necessary, uncertainty-aware, reproducible, traceable and demonstrably fit for purpose.

Recommendations

Use independent, chemically representative test sets and avoid sample-level data leakage. Benchmark AI models against strong conventional chemometric baselines rather than against weak baselines. Report preprocessing, feature selection, hyperparameters, random seeds where relevant, model versions and validation design. Include external validation across instruments, laboratories, batches or time periods whenever deployment requires generalization.

Combine predictive metrics with analytical validation characteristics and uncertainty estimates.

Prefer interpretable or hybrid models when the analytical decision is high consequence or regulated.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Create institutional governance for AI-enabled analytical methods, including change control, model monitoring and audit trails. Develop shared reference datasets and standardized benchmarks for analytical AI. Train analytical chemists in data science while training computational researchers in measurement science and chemical domain knowledge. Treat AI as a decision-support component of the analytical method, not as a substitute for chemical reasoning or experimental verification.

Acknowledgment:
The author sincerely expresses gratitude to all those who contributed directly or indirectly to the completion of this review study on "Artificial Intelligence-Driven Advances in Analytical Chemistry: Methods, Applications, and Future Perspectives." The author acknowledges the valuable contributions of researchers whose published work in artificial intelligence, machine learning, chemometrics, spectroscopy, chromatography, mass spectrometry, NMR, sensors, and analytical method development provided the foundation for this review.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. LeCun Y, Bengio Y, Hinton G. Deep learning. Nature. 2015; 521:436–444.
2. Butler KT, Davies DW, Cartwright H, Isayev O, Walsh A. Machine learning for molecular and materials science. Nature. 2018; 559:547–555. https://doi.org/10.1038/s41586-018-0337-2.
3. Houhou R, et al. Trends in artificial intelligence, machine learning, and chemometrics applied to chemical data. Analytical Science Advances. 2021.
4. Rial RC. AI in analytical chemistry: Advancements, challenges, and future directions. Talanta. 2024; 274:125949. https://doi.org/10.1016/j.talanta.2024.125949.
5. Rial RC, et al. Taking the leap between analytical chemistry and artificial intelligence: A tutorial review. Analytica Chimica Acta. 2021; 1161:338403. https://doi.org/10.1016/j.aca.2021.338403.
6. Deep learning in analytical chemistry. TrAC Trends in Analytical Chemistry. 2021; 145:116459.
7. Singh YR, Shah DB, Maheshwari DG, Shah JS, Shah S. Advances in AI-driven retention prediction for different chromatographic techniques. Critical Reviews in Analytical Chemistry. 2024; 54:3559–3569. https://doi.org/10.1080/10408347.2023.2254379.
8. Singh YR, Shah DB, Kulkarni M, Patel SR, Maheshwari DG, Shah JS, Shah S. Current trends in chromatographic prediction using artificial intelligence and machine learning. Analytical Methods. 2023; 15:2785–2797. https://doi.org/10.1039/D3AY00362K.
9. Application of artificial intelligence to quantitative structure–retention relationship calculations in chromatography. Journal of Pharmaceutical Analysis. 2025;15(1):101155. https://doi.org/10.1016/j.jpha.2024.101155.
10. Artificial Intelligence in HPLC Method Development: A Critical Review of Technological Integration, Limitations, and Future Directions. Critical Reviews in Analytical Chemistry. 2025. https://doi.org/10.1080/10408347.2025.2575352.
11. International Council for Harmonisation. ICH Q2(R2): Validation of Analytical Procedures. 2023; effective 14 June 2024.
12. U.S. Food and Drug Administration. Q2(R2) Validation of Analytical Procedures. Final Guidance. March 2024.
13. Deep learning for vibrational spectral analysis: Recent progress and a practical guide. Analytica Chimica Acta. 2019; 1081:6–17. https://doi.org/10.1016/j.aca.2019.06.012.
14. Chen D, Wang Z, Guo D, Orekhov V, Qu X. Review and Prospect: Deep Learning in Nuclear Magnetic Resonance Spectroscopy. Chemistry – A European Journal. 2020; 26:10391–10401. https://doi.org/10.1002/chem.202000246.
15. Granda JM, Donina L, Dragone V, Long DL, Cronin L. Controlling an organic synthesis robot with machine learning to search for new reactivity. Nature. 2018; 559:377–381.
16. Accelerating materials development via automation, machine learning, and high-performance computing. Molecular Systems Design & Engineering. 2018.
17. Artificial Intelligence Driven Applications in Analytical Chemistry, Drug Discovery, and Food Science: Advancements, Outlook, and Challenges. Chemistry Select. 2025. https://doi.org/10.1002/slct.202404446.
18. U.S. Food and Drug Administration. Considerations for the Use of Artificial Intelligence to Support Regulatory Decision-Making for Drug and Biological Products. Draft Guidance. January 2025.
19. U.S. Food and Drug Administration. Q14 Analytical Procedure Development. Final Guidance. March 2024.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Developments in the Field of Photography and the Integration of Artificial Intelligence and Smart Technologies in a Developed India

Dr. Mangesh Krishnarao Raut
Faculty, Asst. Professor at Sir J. J. School of Design, Sir JJSAAD University, Mumbai.

Manuscript ID:
BN-2026-030930

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 153-158

Submitted: 07 Aug 2026

Revised: 17 Aug 2026

Accepted: 12 Sept. 2026

Published: 30 Sept. 2026

Abstract

Developments in the field of photography and the contribution of artificial intelligence have been remarkable in a developing India. The journey from early optical and chemical processes to digital visual communication has been significant. Technologies ranging from everyday applications to film, digital photography, smart photography, cloud platforms, machine learning, generative AI, drones, and IoT devices (such as Alexa) have vastly expanded the possibilities for capturing, processing, interpreting, and sharing images. Modern photography is no longer limited to just cameras, lenses, digital sensors, and photographers; smart technologies are increasingly playing a pivotal role in processes such as focusing, exposure, color correction, noise reduction, dynamic range enhancement, subject recognition, image segmentation, autofocus, image enhancement, and post-production. Research into AI and photography indicates that machine learning and computational processing have transformed the traditional boundaries between image capture and image processing.

In India, these changes are unfolding within a digital framework. The Government of India's 'IndiaAI' mission received approval in March 2024, aiming to strengthen computing infrastructure, data availability, AI innovation, and world-class development. This emerging technology ecosystem directly impacts photography and visual media education, as well as professional fields such as journalism, advertising, fashion product imaging, scientific documentation, wildlife and heritage conservation, and the creative industries. Furthermore, generative AI is driving a profound transformation; images can now be enhanced, recreated, modified, or generated from scratch without every visible element being directly linked to an optical phenomenon. This opens up new creative opportunities. However, issues regarding authenticity, the author's copyright, privacy, consent, employment, cultural representation, and public trust also arise. This research paper examines the historical evolution of photography, the opportunities for India in the field of photography alongside smart technology, the challenges faced by photographers and educators, and a proposed framework for responsible photography in a developing India.

Keywords: *Photography, Artificial Intelligence, Generative AI, Computational Photography, Smart Technology, Smartphone Photography, Machine Learning, Digital Imaging, India, Digital India, Photography Education, Content Provenance, Creative Industries.*

DOI: 10.5281/zenodo.22914871
DOI link:
https://doi.org/10.5281/zenodo.22914871

Introduction

Historically, photography has been defined by the recording of light through optical systems. A photographer would control the camera, select a subject, determine exposure and focus, and subsequently process the captured image. The advent of digital photography transformed this process by replacing chemical recording methods with electronic sensors and digital files. A subsequent shift has been even more fundamental: the rapidly increasing use of computational processes in modern cameras. These processes manipulate data captured by the sensor before presenting the final image to the photographer.

Creative Commons (CC BY-NC-SA 4.0)

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Mangesh Krishnarao Raut, Faculty, Asst. Professor at Sir J. J. School of Design, Sir JJSAAD University, Mumbai.
Email: mangeshrautws@gmail.com

How to cite this article:

Raut, M. K. (2026). Developments in the Field of Photography and the Integration of Artificial Intelligence and Smart Technologies in a Developed India. Bulletin of Nexus Journal, 3(9(II)), 153–158. https://doi.org/10.5281/zenodo.22914871

Quick Response Code:

Website: https://bnir.us

Smartphone photography offers the clearest example of this evolution. Modern mobile imaging systems combine small sensors, multiple cameras, gyroscopes, accelerometers, image signal processors, and machine learning systems to create images that could not be achieved through sensors and lenses alone. Research into mobile computational photography views this shift as a fundamental change in the rules of photography, encompassing new methods for capture, post-processing, storage, and sharing. Key innovations include burst photography, computational noise reduction, and super-resolution. Contemporary photographs should be understood not merely as direct optical recordings, but as products shaped by both sensors and software. Artificial Intelligence (AI) accelerates this transformation. AI can recognize objects, faces, scenes, and subjects; estimate optimal focus and exposure; reduce noise; reconstruct missing details; separate the foreground from the background; generate various compositions; upscale images; restore damaged or old photos; convert visual information into text; and create entirely synthetic images based on text or multimodal prompts. These changes are particularly significant for India as the country simultaneously expands its digital infrastructure, smartphone usage, creative industries, and technology-driven education. The crucial question is how India can integrate AI and smart technology into photography while safeguarding creativity, originality, human intelligence, cultural identity, privacy, and public trust.

The study aims to examine the historical and technical evolution of photography and analyze the transition from traditional digital photography to computational photography. It seeks to investigate the role of Artificial Intelligence (AI) in image capture, processing, and generation, and to identify the smart technologies influencing contemporary photography. Furthermore, it aims to analyze the opportunities arising from AI-enabled photography in India, examine the impact on professional photographers and photography education, and identify ethical, legal, economic, and social challenges. The study also proposes a framework for the responsible integration of AI and smart technology into Indian photography, explores how photography can contribute to India's broader digital and technological advancement, and identifies priorities for future research and education.

The Evolution of Photography: From Darkroom Chemicals to AI Algorithms

The history of photography is a story of constant change and technological revolution. Photography is not merely a technique for capturing a scene with a camera; rather, it is a creative process that has continuously evolved alongside human civilization, science, art, and technological advancement. Over the past two centuries, photography has traversed a long journey—moving from chemical processes and film to electronic sensors, digital cameras, smartphones, and now, artificial intelligence (AI).

In the early days of photography, image creation relied primarily on chemical processes. Light entering through the camera lens would strike a light-sensitive material, and an image would be formed through chemical reactions. In film photography, the photographer had to consider factors such as lighting, exposure, aperture, shutter speed, and focus, as well as the film's sensitivity. Once the film was exposed, it had to be developed to reveal the result. Due to the limited number of frames available on a roll of film, every shot was significant; photographers had to carefully deliberate on composition, lighting, and the precise moment before taking a picture. This process fostered technical discipline, patience, and visual thinking. The transition from black-and-white to color film marked a significant milestone in the history of photography, opening up new possibilities for capturing and presenting the colors of the real world. Although processes like chemical handling, darkroom work, film processing, and printing were time- and resource-intensive, they also helped establish photography as a distinctive craft and an artistic medium.

The Revolution of Electronic and Digital Photography

Over time, electronic sensors replaced film within cameras. The development of electronic image sensors fundamentally altered the trajectory of photography. Instead of film, sensors such as CCD and CMOS began converting light into electronic signals. The advent of digital photography replaced the darkroom with computer screens and memory cards. Photographs could now be viewed instantly, flawed shots could be deleted, and thousands of images could be stored on a single card. Digital photography also established post-processing as a crucial component of the craft; parameters such as exposure, contrast, color, sharpness, and cropping could now be adjusted on a computer. This shift accelerated the photographic process and brought photography out of professional studios and into the hands of the general public.

Smartphones brought photography to the masses on an unprecedented scale. The camera ceased to be a standalone device and became an integral part of the mobile phone. Despite having

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

smaller sensors and lenses, computational photography has vastly enhanced the capabilities of smartphone cameras. Features such as multi-camera systems, HDR, Night Mode, Portrait Mode, panoramas, and computational image processing have enabled average users to achieve results that previously required specialized cameras and expert techniques.

Artificial Intelligence (AI) has ushered in a new era in photography. While traditional digital cameras primarily recorded light via a sensor, AI-based camera systems analyze captured information to understand the scene's contents and determine the best way to present them. AI can recognize faces, objects, the sky, skin tones, lighting, motion, and other scene characteristics. Based on this, the camera or software can apply different types of processing to various parts of the photo.

AI-based image enhancement has significantly transformed the process of digital photo editing. In traditional editing, photographers or editors had to manually control every parameter. AI-based systems can understand the photo's content and suggest or apply appropriate changes for improvement. For instance, in a low-light image, AI can attempt to strike a balance between lighting and noise. For old or low-quality photos, AI-based technology can work to increase resolution, reconstruct facial details, or reduce blurriness. A key aspect of this process is that AI does not merely perform pixel-level adjustments; many modern systems improve images by interpreting the scene's structure and content. Regarding AI-based image selection: when we capture hundreds of photos, AI assists us in selecting the best shots, recognizing faces, filtering out images where eyes are closed, and organizing them into separate albums.

In the digital age, photographers faced a new challenge: selecting the best images from a vast number of photos. While the film era limited the number of frames per shoot, digital and smartphone cameras have made it possible to capture thousands of images. Consequently, AI-based image selection has become a valuable technology. AI can prioritize photos by analyzing various indicators such as facial clarity, eye position, focus, exposure, composition, expressions, and technical quality. Such technology can save significant time for photographers, particularly during weddings, fashion shoots, events, sports coverage, and large-scale commercial photography projects. This shift is also transforming the role of the photographer. A photographer is no longer merely someone who takes pictures; they are evolving into a creator who manages and organizes vast amounts of visual content.

One of the most significant new directions in AI is Generative AI. While traditional AI image processing typically focuses on enhancing an existing photograph, the capabilities of Generative AI go far beyond that. It can create new visual content based on available visual information. This can involve altering a specific part of a photo, adding new elements, reconstructing the background, removing objects, extending the scene, or generating an entirely new image based on text prompts. Therefore, it is insufficient to label Generative AI merely as "advanced photo editing"; it is also a tool for creative generation.

Every technological shift in photography has influenced the role of the photographer. In the film era, the photographer was primarily an expert in cameras, lighting, and chemical processes. The digital era necessitated knowledge of computers, software, and digital color. The smartphone era brought visual communication and instant publishing to the forefront. In the AI era, the photographer's role is expanding even further. The photographer of the future will not merely be a camera operator; they could assume diverse roles such as storyteller, visual editor, AI operator, image creator, and visual stylist.

Photography has evolved from film-based chemicals to today’s pixels and artificial intelligence algorithms. This journey demonstrates that no matter how much technology changes, the human desire to tell stories through visuals will endure. The history of photography is, in fact, a vital chapter in the history of how humans harness light and visual information. Smartphones brought cameras to everyone; computational photography integrated software into camera functionality, and artificial intelligence empowered cameras to comprehend and analyze visual scenes. Now, Generative AI is propelling this journey into another significant phase. It does not merely enhance captured images; it can alter image elements and, at times, generate entirely new synthetic images without any actual photographic capture. Therefore, viewing photography today merely as the "art of taking pictures with a camera" is no longer sufficient. Modern photography has now become a combined field of computation, sensing, enhancement, and generation. This shift represents the most significant direction for the future of photography—moving from photorealistic reality towards computational and synthetic visual reality.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)



Photography in the Context of a Developed India

A developed India requires that technological advancement be accompanied by the enhancement of human capabilities, cultural preservation, and responsible innovation. Photography can contribute to this development in various ways. It supports numerous sectors such as advertising, fashion, e-commerce, tourism, filmmaking, publishing, journalism, wedding and product photography, food photography, architecture, real estate, scientific imaging, education, social media, and digital marketing by streamlining repetitive tasks and helping small businesses create high-quality visual material. The Government of India has explicitly linked the adoption of AI to broader economic and productivity goals.

Alongside these changes, photography education is also evolving. While traditional training covers essentials like camera operation, exposure, composition, lighting, lenses, color, visual storytelling, and the history of photography, future photographers need additional knowledge. This includes computational photography, AI-assisted editing, generative AI prompt design, image metadata, digital asset management, image provenance (origin), copyright, privacy, synthetic media detection, data ethics, and visual misinformation. Consequently, future photographers must become both visual practitioners and tech-savvy creative professionals. Photography institutes in India should, therefore, consider curricula that incorporate these elements. As a result, a professional image of the future might contain information detailing: Who created it → Which camera captured it → Which software processed it → Which AI was used → What modifications were made → Who published it. This could be as extensive as the metadata used today. Copyright, Ownership Rights, and AI.

The growing use of Artificial Intelligence (AI) in the fields of photography and image creation has raised several significant and complex questions regarding copyright, authorship, and the role of the creator. Traditional photography typically involves an identifiable photographer who crafts the final image through creative decisions such as subject selection, perspective, camera angle, composition, lighting, timing, camera settings, and exposure. In contrast, with AI-generated or AI-assisted images, the creative contribution may be shared between human and machine, making it difficult to determine the true author or creator and who should hold ownership rights. In this context, key questions arise: who holds the copyright to an AI-generated image? To what extent can AI mimic a specific photographer's identifiable style or creative expression? Can a photographer's personal or commercial archive be used to train AI models without their permission? Furthermore, when AI alters elements such as the face, body, background, lighting, or other visual components of a photograph featuring a real person, determining the respective rights of the original photographer, the subject, and the person performing the AI-based editing presents a significant legal and ethical challenge. Similarly, future licensing frameworks will need to clearly distinguish between actual camera captures, AI-enhanced photographs, and entirely synthetic images. Amidst these changing circumstances, there is a need for the continuous evolution of copyright laws, intellectual property rights, and AI-related policies to strike an appropriate balance between human creativity, photographers' rights, and technological innovation. In this context, it is also essential for

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

photographers to maintain clear and organized records of their original image files, RAW files, editing processes, versions, licensing details, use of editing tools, and client approvals, so that evidence regarding the creative process and rights can be presented in the event of any future disputes concerning copyright, ownership, authenticity, or usage rights.

India AI Mission and the Future of Photography

The India AI Mission is a significant initiative aimed at creating a comprehensive technological and digital ecosystem for the development of artificial intelligence (AI) in India; this could also unlock new possibilities for the photography and audiovisual sectors. Key objectives of the mission include enhancing access to computing infrastructure, strengthening the data ecosystem, fostering AI-related innovation and skill development, and promoting the growth of responsible and inclusive AI. In the context of photography, this environment could encourage the development of AI-driven creative tools tailored to Indian conditions and visual-cultural needs—enabling imaging and editing features that incorporate Indian themes, art, culture, languages, and local visual contexts. The availability of AI-enabled photography software and interfaces in Indian languages could expand access to advanced audiovisual technologies for users and photographers who do not wish to rely on English. Similarly, AI can play a pivotal role in the restoration, classification, metadata generation, and digital archiving of historical photographs, documents, and cultural records, thereby preserving India's visual heritage and making it more accessible to future generations. For photographers in rural areas and small towns, features such as cloud-based workflows, AI-enabled editing, and digital marketplaces can bridge geographical divides, offering opportunities to showcase their work and grow professionally at national and international levels. In education, AI-based learning systems can provide photography students with personalized, interactive feedback on aspects like exposure, composition, focus, lighting, and visual communication, making photography education more practical and accessible. In the tourism sector, AI-driven imaging technologies can enhance the effectiveness of virtual tourism, digital destination marketing, 360-degree experiences, and the digital interpretation of historical and cultural sites. Thus, the potential synergy between AI missions and photography will not be limited merely to the development of new imaging technologies; rather, it can contribute to creating a more inclusive and tech-enabled photography ecosystem that integrates Indian languages, cultural heritage, education, the rural creative economy, tourism, and digital creative industries.

Conclusion

Photography has never been a static technology; it has continuously evolved alongside scientific, industrial, and societal changes. From film to digital cameras, the accessibility of smartphones, and now AI-driven technology, the way images are created and viewed has been completely transformed. For India, this technological shift presents both a significant opportunity and a responsibility. We possess immense potential to build a global visual media ecosystem grounded in a harmonious blend of human creativity, cutting-edge technology, and ethical values.

In the future, AI will not replace photographers; instead, acting as an intelligent tool, it will further enhance their capabilities. Consequently, simply operating a camera will no longer be a sufficient skill. The photographer of the future will be one who understands when and why to take a picture, grasps its underlying message, and knows how to maintain trust in that visual truth. In a developed India, photography could evolve from a purely individual creative profession into a technologically advanced, interdisciplinary field—one that bridges art, science, AI, culture, business, education, and national development. Our ultimate goal is not to create a world where machines produce more images than humans do, but rather to build a world where technology empowers humans to present the truth to the world with greater insight, responsibility, and authenticity.

Acknowledgment

I would like to express my sincere gratitude to everyone who contributed to the completion of this research paper, titled “Developments in the Field of Photography and the Integration of Artificial Intelligence and Smart Technologies in a Developed India.”

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Fang, Y., Zhu, H., Zeng, Y., Ma, K., & Wang, Z. (2020). Perceptual Quality Assessment of Smartphone Photography. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 3677–3686.
2. Fang, Y., Zhu, H., Zeng, Y., Ma, K., & Wang, Z.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

(2020). Perceptual Quality Assessment of Smartphone Photography. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 3677–3686.

3. Hasinoff, S. et al. (2016). Burst Photography for High Dynamic Range and Low-Light Imaging on Mobile Cameras. SIGGRAPH Asia.
4. Ignatov, A. et al. (2022). PyNET-V2 Mobile: Efficient On-Device Photo Processing With Neural Networks.
5. Government of India, IndiaAI. IndiaAI Mission. Ministry of Electronics and Information Technology.
6. Zylinska, J. (2021). Undigital Photography: Image-Making beyond Computation and AI. Edinburgh Scholarship Online.
7. AI and Photography. (2025). Taylor & Francis.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Public Libraries and Reading Culture in The Vision of Viksit Bharat @2047

Rajesh Shankar Shelke
Librarian, Department of Library, Late Nirdhanrao Waghaye Patil Arts & Science College Chopa/Mohadi Ta-Goregon dist-Gondia {MS}

Manuscript ID: BN-2026-030931

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 159-163

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22914980
DOI link: https://doi.org/10.5281/zenodo.22914980

Abstract:
Viksit Bharat @2047 has a vision of turning India into a developed and knowledgeable society by 2047. One of the significant components is to build an inclusive and literate society by promoting public libraries for Viksit Bharat as the knowledge society. Public libraries are the centers for providing knowledge to the society, and have a wide range of books. But now the concept of public libraries has evolved from just a place full of books to the center for building reading culture, digital literacy, and knowledge. This paper discusses the role of public libraries in Viksit Bharat, and throws light on various government schemes launched for the development of public libraries. The paper highlights the importance of public libraries in Viksit Bharat. The paper utilizes secondary data, and focuses on comparing the impact of different strategies for the development of public libraries at the rural and urban levels. The paper also throws light on various problems faced by public libraries in India, and suggests potential reforms that can be carried out for Viksit Bharat. The paper concludes by emphasizing the need to invest in public libraries, since it is an investment in the human resource for Viksit Bharat. This paper presents the SMART Viksit Granthalaya Model for sustainable public libraries at rural Maharashtra, mainly Gondia district.

Keywords: *Viksit Bharat 2047, Public Libraries, Reading Culture, NEP 2020, National Digital Library of India (NDLI), One Nation One Subscription (ONOS), Digital Literacy, Indian Knowledge System (IKS)*

Introduction:

Viksit Bharat @2047 is the dream mission of the Government of India that aims to develop a developed, self-reliable, and knowledgeable nation by the time of the nation's centenary. Viksit Bharat 2047 focuses on holistic development and is committed to inclusive growth, self-reliance, and being at the forefront of technology and innovation to develop a confident nation that is ready to engage with the world. A reading nation is the sign of any developed country. But the problem with Digital India is that Indians have lost their habit of reading due to short-term attraction to digital devices. Public libraries are the most accessible and inexpensive resource in terms of India's more than 54,000 libraries. The Ministry of Culture has been working on innovative projects such as One Nation, One Digital Library, and the Festival of Libraries, seeking to connect museums and libraries as nodes of cultural significance. The National Education Policy (NEP) 2020 makes libraries learning centers and promotes research-based teaching and learning. The paper tries to establish the role of public libraries in Viksit Bharat @2047 through a reading culture.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Rajesh Shankar Shelke, Librarian, Department of Library, Late Nirdhanrao Waghaye Patil Arts & Science College Chopa/ Mohadi Ta-Goregon dist-Gondia {MS}
Email: shelkerajesh74@gmail.com

How to cite this article:
Shelke, R. S. (2025). Public Libraries and Reading Culture in The Vision of Viksit Bharat @2047. Bulletin of Nexus Journal, 3(9(II)), 159–163. https://doi.org/10.5281/zenodo.22914980

Quick Response Code:

Website: https://bnir.us

Objectives of the Study:

1. To understand the conceptual framework of Viksit Bharat @2047 and its knowledge and educational imperatives.
2. To assess the present status, infrastructure and functioning of public libraries in India with special reference to Maharashtra.
3. To analyze the impact of National Mission on Libraries (NML) and National Virtual Library of India (NVLI) on promotion of reading culture.
4. To examine the transformative role of NEP 2020, NDLI, and One Nation One Subscription (ONOS) in strengthening library ecosystems.
5. To evaluate the role of public libraries in preserving Indian Knowledge System (IKS) and bridging the rural-urban digital divide.
6. To identify major challenges and barriers hindering reading culture through public libraries in rural areas.
7. To propose a sustainable and replicable SMART Viksit Granthalaya Model for rural Maharashtra to achieve Viksit Bharat goals.

Review of Literature:

As per the articles reviewed recently, the significance of libraries for Viksit Bharat has been emphasized. Bapte (2023) explains that NEP 2020 envisions libraries as centers for research and lifelong learning and promotes embedded librarianship. Rathod (2025) lays stress on the paradigm shift occurring in library from ownership of knowledge to accessing knowledge through artificial intelligence. Atlantis Press (2025) throws light on how libraries are serving as community platforms and bridging the digital literacy gap between urban and rural India. INFLIBNET (2024) discusses the role of smart libraries and makerspaces in Viksit Bharat. Clarivate's Pulse of the Library 2026 underlines open science and community engagement as key areas of focus for Viksit Bharat, which reflect the transformation toward developmental librarianship.

Research Methodology:

The study is descriptive and analytical based on secondary data. Data were collected from Ministry of Culture reports, NEP 2020, NDLI, PIB releases on NML and NVLI, UGC CARE journals, INFLIBNET proceedings and Clarivate Pulse of the Library 2026 report. Content and comparative analysis were used to examine rural-urban library models. Observations from Gondia district, Arjuni block, provide local context. No primary survey was conducted.

Public Libraries in India: A Historical and Current Status: The history of public libraries in India dates back to ancient times when Nalanda and Taxila were centers of learning. However, the first public library was started in 1836 by the Asiatic Society, also known as the Calcutta Public Library, which was later converted into the National Library of India in 1948. During the British period, the Baroda state under the rule of Maharaja Sayajirao Gaekwad III took the lead by starting a public library in 1910 which had the distinction of being the first public library of India. The Dr. S.R. Ranganathan drafted the first Model Library Bill in 1930, which led to the establishment of the first UNESCO Model Library, the Delhi Public Library in 1951, and the enactment of the public library act by 19 states in independent India.The S.R. Ranganathan Committee (1957) and Sinha Committee (1958) were set up to oversee the development of libraries. The Raja Rammohun Roy Library Foundation (RRRLF) was set up in 1972 to promote the library movement and provide matching grants to support the cause.

Current status: As of now, India has over 54,856 public libraries according to the latest data released by RRRLF in 2023. These include 35 State Central Libraries, 43,000+ rural libraries and six district libraries on an average in each district. However, only 19 states have library acts. Maharashtra has over 12,180 libraries but the grant in aid system is not properly implemented. Modern developments include NML 2014 with 4 verticals, the National Virtual Library of India, the National Digital Library of India with 6 cores resources, and ONOS 2024. However, 85% of the libraries do not have internet access, 70% do not have trained librarians, and the rural libraries are in pathetic conditions with outdated resources and poor infrastructure. A lot needs to be done to transform our public libraries to meet the needs of Viksit Bharat @2047.

Reading Culture in India: Current Trends:

India has a rich reading culture from the ancient Nalanda to the modern Baroda movement. However, in the recent National Youth Readership survey 2023, only 12% of rural youth read outside the textbooks due to excessive mobile phone usage as compared to 28% of urban youth. But there is a paradox as the leisure reading is declining while the reading for MPSC/UPSC exams is on the rise in Maharashtra's public libraries. The use of mobile phones for reading is bringing back the reading culture in India as NDLI has crossed 2.5 crore users on its portal with the rise of Marathi apps like Pratilipi witnessing a 40% growth. NEP 2020, Padhega Bharat and Kerala's Vayanasala movements suggest that community participation through book clubs and storytelling events can increase readership by 60%. In Gondia, the rural youth is not interested in book reading, though they read newspapers on a regular basis due to lack of

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

libraries & lack of trained manpower. Therefore, Viksit Bharat should work towards creating a hybrid, inclusive and lifelong reading culture in the library.

Analysis of the Study Objectives :

1 Viksit Bharat @2047: Knowledge, Education and the Vision of a Developed India

The conceptual framework of Viksit Bharat @2047 has been discussed, keeping in view the vision of developed India by 2047, which has been structured around five pillars, namely, Samriddh Bharat, Sashakt Bharat, Samaveshi Bharat, Sustainable Bharat, and Sanskritik Bharat. Based on the document reviewed, it is felt that knowledge and education form the cornerstone of all the five pillars. Viksit Bharat calls for a shift from learning by rote to innovative, analytical, and critical thinking, which has been the main goal of the National Education Policy (NEP), 2020. To achieve Viksit Bharat, India must strive to be a knowledge-based economy in which every citizen can equally contribute and participate. Hence, there is a need to focus on the triad of libraries, digital infrastructure, and reading culture for Viksit Bharat. The government is taking commendable initiatives for self-reliance in research and development. For instance, One Nation One Subscription (ONOS), National Digital Library of India (NDLI), and National Virtual Library of India (NVLI) are a few steps toward making free resources available digitally. These resources would benefit places like Gondia in tier 2/3 cities. Adding to that, embedding Indian Knowledge Systems (IKS) in the framework would ensure that India's ancient wisdom is not lost while welcoming the future.

2 Public Libraries in Maharashtra: An Assessment of Status, Infrastructure and Service Delivery

The analysis of secondary data reflected that India has more than 54,000 public libraries with varied status. As per RRRLF data, only 10% of the libraries have computerized cataloguing and less than 15% of the libraries have internet facility. Studies conducted by NML indicate that the majority of the district and taluka libraries have obsolete collections, lack adequate staff and infrastructure. According to the study on Maharashtra, the state has more than 12,000 public libraries managed by the Directorate of Libraries but 70% of these are under grant-in-aid with irregular grants leading to their instability. The study done in Gondia district shows that out of 87 registered libraries there, only 3 have digital sections. The analysis of the status of rural and urban libraries shows that whereas urban libraries situated in Mumbai and Pune are using RFID, e-granthalaya and NDLI kiosks, the libraries in Arjuni, Tiroda blocks of rural Maharashtra lack even basic facilities like chairs and electricity. The libraries continue to be book lending centers and are far from being knowledge centers as postulated in Vision document of Viksit Bharat.

3 NML and NVLI: An Assessment of Their Role in Promoting Reading Culture in India

The impact assessment of National Mission on Libraries (NML) launched in 2014 and National Virtual Library of India (NVLI) is mixed but overall positive. Although the content analysis of Ministry of Culture's reports shows that NML has upgraded 6 State Central Libraries and 35 District Libraries, and created N-LIST linking, the last-mile connectivity is an issue. The one-window portal designed to provide access to 1.5-crore+ digital resources, NVLI has improved the e-accessibility.

However, it is yet to have the desired impact on the reading culture. In Maharashtra, the NML funds have reached only 12% of the grant-in-aid libraries. PIB's 2024 data shows that though the visits to NVLI portal have jumped by 180%, 85% of the users are from urban and academia. In Gondia district, the awareness about NVLI is under 10% among the public library users. The positive impact is seen in the digital reading habits of the youth where the free Wi-Fi enabled libraries witnessed a 40% increase in footfall, but the deep reading has not been revived. Thus, the impact on the reading culture has not been significant enough to change the current scenario.

4 Transforming Indian Library Ecosystem: The Role of NEP 2020, NDLI and ONOS

NEP 2020, NDLI and ONOS are playing important role in transforming library ecosystem in India. These have contributed in developing the integrated knowledge ecosystems. NEP 2020 promotes libraries, research-support, reading culture and modern infrastructure. NDLI offers rich digital resources in multiple languages, thus addressing the needs of the students and researchers especially from resource poor settings.ONOS offers better access to international journals and articles thus reducing the burden from individual subscriptions. With the help of these resources public libraries can be developed into district-level research and knowledge hubs for students, researchers and competitive exam aspirants. However, there is need to address the lacunae in awareness-generation, internet accessibility and librarian training if the potential of these policies and programs have to be fully realized especially in the context of rural Maharashtra.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

5 Public Libraries, Indian Knowledge Systems and Digital Inclusion: Bridging the Rural–Urban Divide

Public libraries are emerging as dual agents - custodians of Indian Knowledge System (IKS) and enablers in bridging the rural-urban digital divide. An analysis of NEP 2020 and IKS Division data indicates a mandate to digitize 2 lakh+ manuscripts with public libraries being designated as grassroots preservation centres. In Maharashtra, libraries in Nashik and Nagpur divisions have initiated Marathi Grantha Dindi and preservation of Warkari, Gond tribal literature.

In bridging the digital divide, Clarivate Pulse 2026 and INFLIBNET reports suggest that libraries with free Wi-Fi, NDLI kiosks and digital literacy programs have reduced the rural-urban divide by 35%. The Taluka library with one computer and internet connection in Arjuni Morgaon block witnessed daily 15-20 tribal students accessing e-books and MPSC material which would otherwise entail a 40 km commute to Gondia. However, the evaluation reveals that only 8% rural libraries have IKS corners and less than 5% conduct regular digital literacy camps. The potential is enormous as libraries could host IKS oral history projects of Sonegaon area and digital skill training for women farmers albeit requiring funds for digitization tools and staff training to truly bridge the digital divide.

6 Challenges and Barriers to Promoting Reading Culture through Rural Public Libraries

The study highlighted five major barriers for the development of reading culture in rural areas based on RRRLF, NML audit reports and field observations in Gondia district.

Infrastructural Deficit: 78% rural libraries in Maharashtra lack internet facility, 65% do not have a separate reading hall and the collection of books in most libraries are on an average 12 years old.

Financial & Administrative: Delays in sanctioning of grant-in-aid by 2-3 years, no permanent librarian post and reliance on voluntary staff results in limited opening timings of the libraries.

Digital & Literacy Gap: There is a severe digital literacy gap both in the community and the library staff. Awareness about NDLI, NVLI, ONOS is below 15% in Arjuni block.

Socio-Cultural: Migration of youth, mobile addiction, no incentive to read and the perception of libraries as only for students appearing for competitive examinations.

Policy Implementation Gap: Most schemes are top-down and there is no community ownership model. There is no library legislation enforced in Maharashtra for the panchayat libraries.Thus, the barriers were multi-dimensional and convergence of panchayat, school and public library with technology as an enabler and community ownership would address these barriers.

7 SMART Viksit Granthalaya Model: A Sustainable Framework for Rural Maharashtra and Viksit Bharat @2047

The research paper recommends a SMART Viksit Granthalaya Model for rural Maharashtra from the research work done under Objectives 1-6 and the successful library practices. The acronym SMART stands for Sustainable, Multilingual and Mobile-integrated, Accessible and AI-enabled, Rural-centric and Reading-focused, and Transformative through Skilling and IKS.This model has Gram Panchayat Library and School Library and Community Centre as the community knowledge hubs containing five zones and activities like Reading & Book Club, Digital Literacy, IKS & Local History, Lifelong Learning & Skilling, and Inclusive Space for Women and Children. The model promotes NDLI, ONOS, Wi-Fi, mobile libraries and digital literacy to bridge the digital divide in rural and urban areas.For the sustenance of the library model, there is a need to request corporate social responsibility (CSR), NML grants, and a nominal fee of ₹20 by community members and involve trained staff and NSS volunteers. It would be affordable, sustainable, and replicable due to reduced costs and mobile units. Thus, the SMART Viksit Granthalaya can support the Viksit Bharat @2047 vision by promoting skilling, a reading culture, and making the rural population informed and empowered.

Analysis and Interpretation of Major Findings

Based on the research undertaken, the study presents the following findings in order to achieve Viksit Bharat@2047: Viksit Bharat@2047 envisions to turn the public libraries into knowledge centre through NEP 2020, NDLI and ONOS, however, the rural libraries face multitude challenges to overcome in order to achieve this goal. The study found that in Gondia district only few libraries had sufficient digital facilities and the rural libraries were not aware about NML, NDLI and ONOS. The public libraries have great potential to preserve and share Indian Knowledge Systems and bridge the digital divide between rural and urban areas however their potential was not fully realized due to infrastructural, funding, digital literacy and reading habit gaps. The study identified five key challenges namely, infrastructural gap, funding gap, digital skill gap, changing reading habit, and implementation gap which hindered the Viksit Granthalaya mission. Based on the study, SMART Viksit Granthalaya Model emerged as low cost, sustainable and scalable solution to address the challenges of rural libraries in Maharashtra to achieve the Viksit Bharat@2047.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Discussions and Implications:

The study reveals that policy is well laid out but the ground reality is that in villages like Sonegaon, Gondia there is no Internet facility, no new books and no awareness about libraries. The benefits of NML/NVLI are reaped only in urban areas whereas NDLI/ONOS are good schemes but without WiFi and training they are of no use.

Implication : The Government should converge the funds from Panchayat and NML for the development of the village libraries. The librarian should become a digital trainer and not just manage the stock of books. The rural library has the potential to prevent migration, it will cater to the needs of the MPSC/UPSC aspirants and also preserve the tribal IKS. SMART Model is the way forward to make library a lifeline and Viksit Bharat by 2047.

Conclusion:

The study concludes that public libraries are the most potent instruments of change and Viksit Bharat@2047 can only be realized through their effective utilization because these libraries form the core of knowledge-based economies. The very design of Viksit Bharat@2047 indicates that without transforming the knowledge repositories of the hinterlands it would not be possible to take the country to the status of an advanced economy. The study discovers that the current state of public libraries in the hinterlands of Maharashtra is not in consonance with the expectations of Viksit Bharat@2047. The state has a large number of public libraries under NML, NVLI, NDLI and ONOS but the last-mile connectivity is missing due to which the rural public libraries have not developed the reading culture. However, NEP 2020 and ONOS offer an unprecedented opportunity to upgrade all the rural public libraries as the digital knowledge and skilling hubs. The libraries can act as the most visible and potent link to connect the Indian Knowledge Systems and bridge the digital divide. Hence, the study concludes with the evolution of SMART Viksit Granthalaya Model as a sustainable and low-cost approach to make the villages of Maharashtra self-sufficient, which eventually would make India Viksit by 2047.

Acknowledgment

I express my sincere gratitude to all those who have contributed directly or indirectly to the completion of this research paper titled "Public Libraries and Reading Culture in the Vision of Viksit Bharat @2047." I am deeply thankful to my institution, Late Nirdhanrao Waghaye Patil Arts & Science College, Chopa/Mohadi, Taluka Goregaon, District Gondia, Maharashtra, for providing the academic environment and support necessary for undertaking this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Government of India, Ministry of Education. (2020). National Education Policy 2020. Government of India.
2. Government of India, Ministry of Culture. (2014). National Mission on Libraries: Guidelines and framework. Government of India.
3. National Digital Library of India. (n.d.). National Digital Library of India. Ministry of Education, Government of India.
4. Department of Higher Education, Ministry of Education. (2024). One Nation One Subscription (ONOS) scheme. Government of India.
5. Government of India. (2022). India@2047: Vision for a developed India. Government of India.
6. NITI Aayog. (2023). Viksit Bharat @2047: Vision for a developed India. Government of India.
7. International Federation of Library Associations and Institutions. (2015). IFLA public library manifesto. IFLA.
8. International Federation of Library Associations and Institutions. (2022). IFLA trend report 2022 update. IFLA.
9. UNESCO. (2021). Recommendation concerning the internationalisation of public libraries and their role in society. UNESCO.
10. Ministry of Culture. (2023). Annual report 2022–23. Government of India.
11. Raja Rammohun Roy Library Foundation. (2023). Annual report 2022–23. Ministry of Culture, Government of India.
12. National Book Trust, India. (2023). Annual report 2022–23. Ministry of Education, Government of India.
13. International Federation of Library Associations and Institutions. (2021). Development and access to information 2021. IFLA.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI-Assisted Integration of Midgut Digestive Enzymes and Gut Microbiota in Samia ricini: A Predictive Framework for Sustainable Eri-Silk Production

Pradnya Prakash Kamble
Dept. of Zoology, Shripatrao Chougule Arts and Science College, Shivaji University Kolhapur, Tal. Panhala, Dist. Kolhapur

Manuscript ID:
BN-2026-030932

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 164-172

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22915277
DOI link: https://doi.org/10.5281/zenodo.22915277

Abstract

The eri silkworm, Samia ricini (Lepidoptera: Saturniidae), is an economically important polyphagous silk-producing insect whose productivity is influenced by host-plant quality, digestive physiology, larval development and associated gut microorganisms. The midgut represents a major interface between dietary nutrients and physiological utilization, while the resident microbial community may contribute to nutrient transformation and host adaptation. Although previous studies have independently investigated digestive enzymes, host-plant effects and gut microbial diversity in S. ricini, an integrated predictive framework combining biochemical, microbiome and production variables remains comparatively underdeveloped. The present study proposes an AI-assisted framework for integrating midgut digestive enzyme activity, gut microbiota and larval/cocoon traits in S. ricini. Three host-plant diets—Ricinus communis, Ailanthus altissima and Manihot esculenta—are considered within the proposed experimental framework. Digestive activities of α-amylase, protease, lipase and cellulase are proposed to be evaluated together with 16S rRNA-based bacterial community profiling. Larval growth, survival, cocoon weight, shell weight and shell percentage are incorporated as production-related variables. Statistical approaches including ANOVA, correlation analysis, diversity analysis and PERMANOVA are combined with machine-learning algorithms including Random Forest, XGBoost and Support Vector Regression. For methodological demonstration, a simulated dataset was constructed using biologically plausible ranges rather than experimental observations. The simulated analysis illustrates how integrated biochemical and microbial variables can be used to predict larval and cocoon performance and how SHAP-based explainable artificial intelligence can identify influential predictors. The framework suggests that microbiome–enzyme interactions may provide useful candidate biomarkers for future validation. However, simulated findings should not be interpreted as empirical evidence. The proposed framework provides a basis for future experimental studies aimed at microbiome-informed feeding, precision rearing and sustainable eri-silk production.

Keywords:

Samia ricini, eri silkworm, gut microbiota, digestive enzymes, 16S rRNA, artificial intelligence, machine learning, SHAP, sustainable sericulture.

Introduction

Sericulture is an important biological and agro-based production system in which larval nutrition, host-plant quality and physiological efficiency directly influence silk productivity. Among non-mulberry silkworms, Samia ricini is particularly important because of its polyphagous feeding habit and its ability to utilize different host plants. The eri silkworm is physiologically adapted to a range of plant resources.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Pradnya Prakash Kamble, Dept. of Zoology, Shripatrao Chougule Arts and Science College, Shivaji University Kolhapur, Tal. Panhala, Dist. Kolhapur
Email: pradnya1999kamble@gmail.com

How to cite this article:

Pradnya Prakash Kamble. (2026). AI-Assisted Integration of Midgut Digestive Enzymes and Gut Microbiota in Samia ricini: A Predictive Framework for Sustainable Eri-Silk Production. Bulletin of Nexus, 3(9(II)), 164-172.

Quick Response Code:

Website: https://bnir.us

Nevertheless, the nutritional quality and biochemical characteristics of different host plants can influence larval growth, development, digestion and cocoon formation. Previous research has demonstrated that changes in host-plant diet can influence life-history traits and midgut digestive physiology in S. ricini. In particular, dietary changes have been associated with changes in serine proteinase activity and expression of digestive proteinase genes. The insect midgut contains several digestive enzymes responsible for breaking down dietary macromolecules. Carbohydrates may be hydrolysed through amylolytic activity, proteins through proteolytic enzymes, lipids through lipases and plant structural components through cellulolytic activities. Efficient digestion is consequently expected to contribute to nutrient availability and larval growth. In parallel, the insect gut contains a diverse microbial community. Earlier work on S. ricini demonstrated that its gut harbours both culturable and non-culturable bacteria, with Proteobacteria and Firmicutes among the major groups detected. Several bacterial isolates demonstrated cellulolytic and lipolytic activities, suggesting a possible contribution to dietary processing.

Lipolytic bacteria have also been specifically characterized from the gut of S. ricini. A study identified 28 lipolytic isolates, with Bacillus representing the majority of identified isolates, demonstrating the potential functional relevance of gut-associated microorganisms. More recently, comparative research involving R. communis, A. altissima and M. esculenta demonstrated that host-plant diet can influence growth, midgut lipase activity, microbial richness, diversity and bacterial community structure in S. ricini. The study reported better growth in larvae fed on R. communis, higher lipase activity in the R. communis group compared with A. altissima, and significant differences in microbial community structure among dietary groups. These findings establish that host plant, digestive physiology and gut microbiota are interconnected biological components. However, conventional analyses generally examine these components separately or through pairwise associations. A major opportunity therefore exists to integrate multiple data types into a single predictive framework. Artificial intelligence and machine-learning approaches provide an appropriate analytical strategy for such multidimensional datasets. Machine-learning approaches have increasingly been applied to microbiome-based host-trait prediction, while explainable AI methods such as SHAP can help identify variables contributing to model predictions. Therefore, the present study proposes an AI-assisted framework integrating host-plant diet, digestive enzyme activity, gut microbiota and production traits of S. ricini.

Research Gap

- The existing literature indicates three important areas of knowledge.
- First, host-plant effects on growth and digestive physiology have been demonstrated.
- Second, S. ricini possesses a diverse gut microbiome containing microorganisms with potential digestive and metabolic functions.
- Third, recent comparative research has demonstrated that different host plants can produce distinct microbial community structures.

However, the following research gaps remain:

1. Limited integration of enzyme and microbiome datasets.
2. Limited predictive modelling of larval growth using microbial and biochemical variables simultaneously.
3. Limited application of explainable AI for identifying potential biological biomarkers in eri-silkworm research.
4. Limited integration of microbiome variables with cocoon-quality parameters.
5. Lack of a unified computational framework linking host plant, microbiota, digestive enzymes and silk productivity.

The present framework attempts to address these gaps.

Novelty of the Proposed Study

The novelty of the proposed research lies not simply in comparing host plants.

The proposed contribution is:

Host Plant → Microbiota → Digestive Enzymes → Larval Performance → Cocoon Traits → AI Prediction → Biomarker Identification

The study therefore combines:

- biochemical profiling;
- microbiome profiling;
- conventional statistics;
- machine learning; and
- explainable artificial intelligence.

This integrated approach is intended to identify combinations of variables rather than relying on a single biological indicator.

Research Question

Primary Research Question

How are host-plant diet, midgut digestive enzyme activity and gut microbial composition associated with larval growth and cocoon productivity in Samia ricini, and can these variables

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

be integrated using machine-learning approaches for predictive assessment?

Secondary Questions

1. Does host-plant diet influence digestive enzyme activity?
2. Does host-plant diet alter gut microbial diversity?
3. Are specific bacterial taxa associated with digestive enzyme activity?
4. Can microbiome variables predict larval growth?
5. Can enzyme activity and microbial variables predict cocoon weight and shell percentage?
6. Which biological variables contribute most strongly to AI predictions?

Aim

To develop an AI-assisted integrative framework for investigating relationships among host-plant diet, midgut digestive enzymes, gut microbiota, larval growth and cocoon productivity in Samia ricini for sustainable eri-silk production.

Objectives

1. To evaluate the effect of selected host plants on larval growth.
2. To estimate midgut α-amylase activity.
3. To estimate midgut protease activity.
4. To determine midgut lipase activity.
5. To estimate cellulase activity.
6. To characterize gut bacterial communities using 16S rRNA sequencing.
7. To estimate alpha microbial diversity.
8. To examine beta-diversity and community structure.
9. To determine associations between bacterial taxa and digestive enzymes.
10. To examine relationships between biochemical/microbial variables and larval performance.
11. To develop machine-learning models for predicting cocoon-related traits.
12. To identify important predictors using SHAP-based explainable AI.
13. To develop a conceptual framework for sustainable and precision-oriented eri-silk production.

Hypotheses

H1: Host-plant diet influences midgut digestive enzyme activity in S. ricini.
H2: Host-plant diet influences gut microbial diversity and community structure.
H3: Selected microbial taxa are associated with digestive enzyme activity.
H4: Digestive enzyme activity is associated with larval growth.
H5: Integrated microbiome and biochemical variables can predict cocoon productivity.
H6: Explainable machine-learning analysis can identify candidate microbial and enzymatic biomarkers associated with larval and cocoon performance.

Conceptual Framework

The proposed biological model is:

Host Plant
↓
Dietary Nutrient Composition
↓
Gut Microbiota
↕
Midgut Digestive Enzymes
↓
Nutrient Digestion and Absorption
↓
Larval Growth
↓
Cocoon Formation
↓
Cocoon Weight / Shell Percentage
↓
Machine Learning
↓
Biomarker Identification
↓
Sustainable Eri-Silk Production

Materials and Methods

1 Experimental Organism

The proposed study focuses on Samia ricini larvae maintained under controlled rearing conditions. Larvae should preferably be obtained from a standardized and disease-free source.

Environmental conditions including temperature, relative humidity, photoperiod and larval density should be maintained as consistently as possible.

2 Host Plants

Three host plants are proposed:

- Ricinus communis — castor
- Ailanthus altissima — tree-of-heaven
- Manihot esculenta — cassava

These plants have also been investigated comparatively in recent S. ricini research, making them appropriate for establishing a comparative framework while requiring the present work to emphasize its computational novelty.

3 Experimental Groups

Group	Host Plant	Proposed Code
Group 1	*Ricinus communis*	RC
Group 2	*Ailanthus altissima*	AA
Group 3	*Manihot esculenta*	ME

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

A future empirical experiment should determine sample size through an appropriate power analysis.

Larval Growth Assessment

The following variables are proposed:

- Initial larval weight (mg)
- Final larval weight (mg)
- Weight gain (mg)
- Larval duration
- Survival (%)
- Food consumption
- Cocoon weight (g)
- Shell weight (g)
- Shell percentage (%)

Shell percentage can be calculated as:

The use of standardized sampling is essential because developmental stage itself can influence gut microbial composition. Seasonal and developmental-stage studies in S. ricini have demonstrated changes in bacterial community composition across larval stages.

Digestive Enzyme Analysis

Four enzyme categories are proposed.

1 α-Amylase

Used as an indicator of carbohydrate digestive activity.

2 Protease

Used to characterize protein-digestive activity.

3 Lipase

Used to evaluate lipid-digestive activity.

4 Cellulase

Used to assess potential degradation of cellulose-containing plant material.

The recent comparative study of S. ricini reported differences in midgut lipase activity between some dietary groups, whereas α-amylase, cellulase and trypsin did not show significant differences among its three dietary treatments.

Gut Microbiome Analysis

The proposed workflow is:

Midgut Sample
↓
DNA Extraction
↓
DNA Quality Assessment
↓
16S rRNA PCR
↓
Library Preparation
↓
High-throughput Sequencing
↓
Quality Control
↓
ASV Generation
↓
Taxonomic Assignment
↓

Shell percentage = (Shell weight / Cocoon weight) × 100

Midgut Sampling

Midgut samples should be collected from larvae of a standardized developmental stage.

Important sampling variables include:

- larval instar;
- feeding status;
- sampling time;
- sex, if relevant;
- sample storage;
- number of biological replicates.

Alpha Diversity
↓
Beta Diversity
↓
Differential Abundance
↓
Correlation with Enzymes
↓
Machine Learning

A recent S. ricini study used 16S rDNA sequencing and DADA2-based processing, together with diversity analysis and PCoA/Adonis testing.

The sequence metadata should include appropriate contextual information regarding sample source and processing; MIxS provides a standardized framework for describing genomic sequence context.

Statistical Analysis

The proposed analysis includes:

Descriptive Statistics

Mean ± SD or Mean ± SEM.

Inferential Statistics

One-way ANOVA followed by an appropriate post-hoc test for dietary comparisons.

Where more than one factor is investigated:

Two-way ANOVA may be considered.

Correlation

Pearson correlation for approximately normally distributed continuous variables and Spearman correlation for non-parametric/rank-based relationships.

Microbiome

- Shannon
- Simpson
- Chao1
- Bray–Curtis/Jaccard
- PCoA
- PERMANOVA
- Differential abundance analysis

Previous S. ricini research has used Shannon, Simpson, Chao1, PCoA and Adonis-based comparisons to characterize diet-associated microbiome differences.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

AI and Machine-Learning Framework

The integrated dataset can be divided into three broad classes.

Predictor Variables

Biochemical

- α-amylase
- protease
- lipase
- cellulase

Microbiome

- bacterial phyla
- bacterial families
- bacterial genera
- Shannon index
- Simpson index
- Chao1

Dietary

- host-plant group
- developmental stage

Outcome Variables

- final larval weight
- weight gain
- cocoon weight
- shell weight
- shell percentage

Machine-Learning Models

Three candidate algorithms are proposed.

Random Forest Regression

Suitable for non-linear relationships and variable interactions.

XGBoost Regression

Useful for modelling complex non-linear relationships.

Support Vector Regression

Potentially useful for smaller structured datasets.

Microbiome prediction literature emphasizes the importance of appropriate feature selection and validation because microbial datasets are often high-dimensional relative to sample size.

Model Validation

To reduce over fitting, the following procedure is proposed:

Dataset
↓
Training/Test Split
↓
Training-set preprocessing
↓
Feature selection
↓
Cross-validation
↓
Model training
↓
Test-set evaluation

Feature selection should not be performed using information from the held-out test set.

Performance metrics:

- R^2
- RMSE
- MAE

For classification problems, accuracy, precision, recall and F1-score may be used.

Explainable AI

SHAP analysis is proposed to determine the relative contribution of individual predictors.

For example:

Lipase → positive contribution

Shannon diversity → contribution

Specific bacterial genus → contribution

The analysis does not establish causation. Instead, it identifies variables that contribute strongly to model predictions and therefore deserve experimental validation.

Explainable AI has increasingly been considered important in microbiome machine-learning research because interpretability and reproducibility remain significant challenges.

Simulated Dataset

IMPORTANT: The following table is simulated for methodological demonstration and is not experimental data.

Table 1. Illustrative simulated production and enzyme profile

Variable	RC	AA	ME
Final larval weight (mg)	4280 ± 210	3510 ± 235	3890 ± 220
Survival (%)	91.8 ± 2.4	84.6 ± 3.1	87.9 ± 2.8
α-Amylase	1.84 ± 0.12	1.72 ± 0.15	1.79 ± 0.13
Protease	3.21 ± 0.21	3.48 ± 0.25	3.30 ± 0.22
Lipase	2.86 ± 0.18	2.25 ± 0.19	2.61 ± 0.17
Cellulase	1.43 ± 0.11	1.50 ± 0.13	1.47 ± 0.12
Cocoon weight (g)	2.05 ± 0.10	1.72 ± 0.11	1.89 ± 0.09
Shell weight (g)	0.43 ± 0.03	0.34 ± 0.03	0.39 ± 0.02
Shell percentage (%)	20.98 ± 0.84	19.77 ± 0.91	20.63 ± 0.72

Codes: RC = *Ricinus communis*; AA = *Ailanthus altissima*; ME = *Manihot esculenta*.

Note: Values are simulated and intended only to demonstrate the analytical framework.

Simulated Microbial Diversity Dataset

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Table 2. Illustrative alpha-diversity indices

Diversity Index	RC	AA	ME
Chao1	286 ± 18	301 ± 21	244 ± 17
Shannon	3.72 ± 0.18	4.01 ± 0.21	3.39 ± 0.17
Simpson	0.91 ± 0.02	0.93 ± 0.01	0.87 ± 0.03

These values are simulated, but their direction was selected to remain broadly compatible with published observations that dietary groups can differ in microbial richness and diversity.

Simulated Dominant Microbial Genera

Table 3. Illustrative relative abundance (%)

Bacterial Genus	RC (%)	AA (%)	ME (%)
Acinetobacter	14.2	11.6	13.1
Methylobacterium	12.8	9.4	7.1
Agrobacterium	8.6	10.2	7.9
Roseateles	6.8	8.9	6.1
Bacillus	9.7	8.2	10.4
Pseudomonas	7.4	6.7	8.1
Other taxa	40.5	45.0	47.3
Total	**100.0**	**100.0**	**100.0**

The selection of these genera is informed by published S. ricini microbiome literature; the numerical abundances above are simulated and should not be interpreted as sequencing results. Recent research has reported genera including Acinetobacter, Mammaliicoccus, Roseateles, Methylobacterium, Agrobacterium, Faecalibacterium and Segatella.

Illustrative Correlation Analysis

Table 4. Simulated Spearman correlations with final larval weight

Predictor	ϱ (Spearman's correlation)	Interpretation
Lipase	+0.71	Strong positive association
α-Amylase	+0.48	Moderate positive association
Protease	+0.36	Weak–moderate association
Cellulase	+0.42	Moderate association
Shannon index	+0.55	Moderate positive association
Chao1	+0.49	Moderate positive association
Methylobacterium	+0.67	Strong positive association
Acinetobacter	+0.44	Moderate association

These correlations are simulated examples and are not empirical findings. Published work has reported an association between Methylobacterium and larval weight in S. ricini, which provides a biological rationale for including this taxon as a candidate variable in a future empirical model.

Simulated Machine-Learning Results

Table 5. Illustrative prediction performance

Outcome: Final larval weight

Model	R^2	RMSE (mg)	MAE (mg)
Random Forest	0.81	214	171
XGBoost	**0.86**	**187**	**149**
SVR	0.74	249	201

Outcome: Cocoon weight

Model	R^2	RMSE (g)	MAE (g)
Random Forest	0.77	0.12	0.09
XGBoost	**0.83**	**0.10**	**0.08**
SVR	0.70	0.14	0.11

Abbreviations: R^2 = coefficient of determination; RMSE = root mean square error; MAE = mean absolute error.

Again, these values are illustrative simulated outputs only.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Simulated SHAP Feature Ranking

Table 6. Illustrative feature importance

Rank	Predictor	Relative Importance
1	Lipase activity	**0.184**
2	*Methylobacterium* abundance	**0.151**
3	Shannon diversity	**0.117**
4	α-Amylase activity	**0.102**
5	Chao1	**0.087**
6	*Acinetobacter* abundance	**0.075**
7	Protease activity	**0.069**
8	Cellulase activity	**0.054**

The ranking is a simulation designed to demonstrate how SHAP could be reported.

Results — Simulated Demonstration

In the simulated dataset, larvae maintained on R. communis demonstrated the highest mean final larval weight and cocoon weight, followed by M. esculenta and A. altissima. The simulated enzyme profile showed comparatively higher lipase activity in the R. communis group. Microbial diversity indices also demonstrated simulated differences among dietary treatments. The A. altissima group showed the highest simulated Shannon diversity, whereas the M. esculenta group showed comparatively lower richness.

The simulated correlation analysis suggested positive associations between larval weight and lipase activity, Shannon diversity and selected bacterial taxa. Among the three illustrative machine-learning models, XGBoost produced the highest simulated R^2 for both final larval weight and cocoon weight. SHAP-based interpretation indicated that lipase activity, Methylobacterium abundance and microbial diversity were among the strongest simulated predictors. These results are not experimental observations. They demonstrate how the final analysis could be reported after actual data collection.

Discussion

The biological rationale for integrating digestive physiology and gut microbiota is supported by previous research in S. ricini. Earlier microbiological investigations identified diverse gut bacteria and demonstrated cellulolytic and lipolytic activities among several isolates. Such observations suggest that gut-associated microorganisms may contribute to processing of plant-derived nutrients.
The relationship between diet and digestive physiology is also supported by research on host-plant adaptation. Dietary changes have been associated with differences in larval growth, protein digestion and expression of midgut serine proteinase genes.

The most directly relevant recent study demonstrated that host-plant switching can affect growth, lipase activity and gut microbial community structure in S. ricini. It reported that larvae fed R. communis exhibited better growth performance and higher lipase activity than those fed A. altissima, while microbial community structures differed significantly among dietary groups. The present framework extends this biological knowledge by proposing an integrated predictive layer.Instead of asking only whether diet affects enzyme activity, the proposed approach asks: Can a combination of microbial and enzymatic features predict biological performance?

This distinction represents the principal methodological contribution. However, a machine-learning association should not automatically be interpreted as a biological mechanism. For example, if a bacterial taxon becomes a strong predictor of larval weight, controlled microbial supplementation or depletion experiments would be required to determine whether the microorganism actually contributes causally to growth.

Biological Interpretation of the Proposed Model

The proposed mechanism can be represented as:

Host Plant
↓
Plant Nutrient/Phytochemical Profile
↓
Microbial Community Selection
↓
Microbial Metabolic Activity
↕
Digestive Enzyme Activity
↓
Nutrient Availability
↓
Larval Growth
↓
Cocoon Development

This model is consistent with the broader observation that host-plant characteristics, digestive physiology and gut microbial communities interact in phytophagous insects.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Sustainable Sericulture Implications

The proposed framework could have several future applications.

1 Microbiome-informed feeding

Host plants may be evaluated not only for their nutritional composition but also for their effects on beneficial microbial communities.

2 Probiotic development

Bacterial taxa associated consistently with desirable production traits could become candidates for future probiotic research. Previous work has already demonstrated the presence of potentially useful lipolytic and cellulolytic bacteria in S. ricini.

3 Early prediction

If validated, biochemical and microbial indicators could potentially predict poor larval performance before cocoon formation.

4 Host-plant optimizations

Machine-learning models could eventually assist in selecting appropriate host plants under different rearing conditions.

5 Precision sericulture

The long-term goal would be:

Biological monitoring → Data integration → Prediction → Intervention → Improved productivity

Limitations

The proposed study has several important limitations.

- First, the numerical results presented in this manuscript are simulated and cannot substitute for experimental observations.
- Second, 16S rRNA sequencing provides taxonomic information but does not directly establish microbial functional activity.
- Third, correlations do not establish causation.
- Fourth, machine-learning performance can be strongly influenced by sample size, feature dimensionality and data leakage.
- Fifth, microbiome datasets are often high-dimensional, and therefore independent validation is essential.
- Sixth, host-plant chemistry should ideally be incorporated into future models.
- Seventh, AI-identified biomarkers require controlled biological validation.

Future Scope

Future experimental research should include:

1. Larger biological sample sizes.
2. Multi-stage larval sampling.
3. Replicated host-plant experiments.
4. 16S rRNA sequencing with standardized metadata.
5. Metagenomic or metatranscriptomic validation.
6. Quantification of host-plant nutritional composition.
7. Controlled probiotic supplementation experiments.
8. Independent validation cohorts.
9. Longitudinal microbiome analysis.
10. Integration of metabolomics with microbiome and enzyme datasets.

A future multi-omics framework could therefore be:

Plant metabolome + Gut microbiome + Enzyme profile + Larval transcriptome + Phenotype + AI

This would provide a much stronger precision-sericulture platform.

Conclusion

The integration of digestive enzyme profiling, gut microbiome characterization and artificial intelligence represents a promising direction for understanding biological variation in Samia ricini. Previous research has established that host-plant diet can influence larval performance, digestive physiology and gut microbial communities. The present framework advances this concept by connecting these biological layers through machine-learning prediction and explainable AI. Random Forest, XGBoost and Support Vector Regression can be evaluated for predicting larval and cocoon traits, while SHAP can assist in identifying the variables contributing most strongly to predictions. The simulated analysis presented here demonstrates how such a framework could operate. However, the numerical findings are not experimental results and should not be interpreted as evidence obtained from real S. ricini populations. Ultimately, experimental validation of AI-identified microbial and enzymatic biomarkers will be necessary. If validated, this approach could contribute to microbiome-informed feeding, probiotic development, host-plant optimization and precision management of sustainable eri-silk production.

Proposed Research Model

HOST PLANT
↓
DIETARY QUALITY
↓
GUT MICROBIOTA
↕
DIGESTIVE ENZYMES
↓
NUTRIENT UTILIZATION
↓
LARVAL GROWTH
↓
COCOON QUALITY
↓

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

MACHINE LEARNING
↓
EXPLAINABLE AI / SHAP
↓
BIOMARKER IDENTIFICATION
↓
PRECISION & SUSTAINABLE ERI-SILK PRODUCTION

Data Availability Statement

The numerical dataset presented in the analytical demonstration is simulated and was generated solely to demonstrate the proposed statistical and machine-learning workflow. It does not represent experimentally collected biological data. For a future empirical study, raw sequencing data, metadata and processed datasets should be deposited in an appropriate public repository were permitted by the sequencing facility and journal/conference requirements.

Ethical and Research Integrity Statement

No experimental claim should be interpreted from the simulated dataset presented in this manuscript. Before empirical publication, the proposed methodology should be implemented using independently collected biological samples and laboratory measurements. All biological observations, sequencing results and statistical values in a final empirical manuscript should originate from documented experiments and reproducible analytical procedures.

AI-Assisted Research Disclosure

Artificial intelligence may be used as an analytical and drafting-support tool during development of the research framework. Any AI-assisted content should be critically reviewed by the authors, and all scientific claims, references, analyses and interpretations should be independently verified. The simulated dataset in this manuscript is explicitly identified as simulated and must not be presented as experimentally observed data.

Acknowledgment

I express my sincere gratitude to all those who have supported and encouraged me in the preparation of this research paper entitled "AI-Assisted Integration of Midgut Digestive Enzymes and Gut Microbiota in Samia ricini: A Predictive Framework for Sustainable Eri-Silk Production." I am deeply thankful to my teachers, mentors, colleagues, and well-wishers for their valuable guidance, encouragement, and constructive suggestions throughout the development of this work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. MsangoSoko, K., Gandotra, S., Chandel, R.K., et al. (2020). Composition and diversity of gut bacteria associated with the eri silk moth, Samia ricini (Lepidoptera: Saturniidae), as revealed by culture-dependent and metagenomics analysis. Journal of Microbiology and Biotechnology, 30(9), 1367–1378.
2. Guo, Y., Liu, X., Wang, Y., Guo, H., & Qian, H. (2026). Comparative analysis of gut microbiota in eri silkworm (Samia ricini) larvae fed on different food plants. Insects, 17(6), 553. DOI: 10.3390/insects17060553.
3. Saikia, M.S., & Mazumdar-Leighton, S.M. (2023). Midgut serine proteinases participate in dietary adaptations of the castor (Eri) silkworm Samia ricini Anderson transferred from Ricinus communis to an ancestral host, Ailanthus excelsa Roxb. Frontiers in Insect Science.
4. MsangoSoko, K., et al. (2022). Screening and characterization of lipase producing bacteria isolated from the gut of a lepidopteran larvae, Samia ricini. Journal of Asia-Pacific Entomology, 25(1), 101856. DOI: 10.1016/j.aspen.2021.101856.
5. Aier, C., & Somasundaram, J. (2025). Gut microbiome profiling of eri silkworm (Samia ricini) through 16S rRNA and its impact on silk yield in Dimapur, Nagaland, India. Uttar Pradesh Journal of Zoology, 46(11), 142–150. DOI: 10.56557/UPJOZ/2025/v46i115013.
6. Guo, Y., et al. (2025). Microbiome dynamics in Samia cynthia ricini: Impact of growth stage and dietary variations. Applied Microbiology, 5(2), 40.
7. Pasolli, E., et al. / related microbiome prediction literature. Machine-learning approaches for microbiome host-trait prediction emphasize taxonomy-informed feature selection and appropriate validation.
8. Jabeen, T., Karimi, F., Zomorrodi, A.R., & Khalilpour, K. (2026). Microbiome-based disease prediction with artificial intelligence: A systematic review. Array, 30, 100910. DOI: 10.1016/j.array.2026.100910.
9. Genomic Standards Consortium. Minimum Information about any (X) Sequence (MIxS).
10. Recent review literature on artificial intelligence for microbiology and microbiome research highlights applications in taxonomic profiling, functional prediction, microbial interactions and precision nutrition.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Renewable Energy Innovation: Emerging Technologies, Challenges, Opportunities and Its Role in Sustainable Development

Dr. Prasad Laxman Pagdhare.
Associate Professor, Department of Commerce, Rnc Arts, JDB Commerce and NSC Science College, Nashik
Affiliated To Savitribai Phule Pune University, Pune

Manuscript ID:
BN-2026-030933

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 173-180

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22915467
DOI link:
https://doi.org/10.5281/zenodo.22915467

Abstract
Renewable energy innovation has become a critical component of the global transition toward a sustainable, secure, and low-carbon energy system. Growing energy demand, climate change, depletion of conventional fossil-fuel resources, and concerns regarding energy security have accelerated the development and adoption of renewable energy technologies. Innovation in solar photovoltaic systems, wind energy, hydropower, bioenergy, geothermal energy, green hydrogen, energy storage, smart grids, and digital energy-management systems is transforming the structure of modern energy systems. This research paper examines the concept, evolution, major technological developments, economic significance, environmental benefits, challenges, and future prospects of renewable energy innovation. It also discusses the role of artificial intelligence, Internet of Things technologies, advanced batteries, floating solar, offshore wind, green hydrogen, and decentralized energy systems in improving the efficiency and reliability of renewable energy. Particular attention is given to the Indian context, including India's renewable-energy potential, policy initiatives, technological development, and opportunities for sustainable economic growth. The paper adopts a descriptive and analytical research approach based primarily on secondary information from academic literature, institutional reports, government publications, and international energy organizations. The study finds that renewable energy innovation can reduce greenhouse-gas emissions, improve energy security, create employment, encourage technological development, and support inclusive economic growth. However, challenges such as intermittency, energy storage, high initial investment, grid integration, land requirements, financing constraints, supply-chain dependencies, and skill shortages must be addressed. The paper concludes that sustained investment in research and development, supportive public policy, private-sector participation, technological collaboration, and development of skilled human resources are essential for accelerating renewable energy innovation and achieving long-term sustainable development.

Keywords: *Renewable Energy, Energy Innovation, Solar Energy, Wind Energy, Green Hydrogen, Energy Storage, Smart Grid, Sustainability, Clean Technology, India*

Introduction

Energy is fundamental to economic development, industrialization, transportation, communication, agriculture, and improvement in living standards. For more than a century, economic development has largely depended on coal, petroleum, and natural gas. Although fossil fuels have contributed significantly to economic growth, their extensive use has resulted in environmental degradation, greenhouse-gas emissions, air pollution, and concerns about long-term energy security. The increasing global emphasis on sustainable development has created a need to transform the way energy is generated, stored, distributed, and consumed. Renewable energy sources such as sunlight, wind, water, biomass, and geothermal heat provide alternatives to finite fossil-fuel resources. However, simply increasing renewable-energy capacity is not sufficient.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Prasad Laxman Pagdhare, Associate Professor, Department of Commerce, Rnc Arts, JDB Commerce and NSC Science College, Nashik, Affiliated To Savitribai Phule Pune University, Pune
Email: Ppagdharephd@Gmail.Com

How to cite this article:
Pagdhare, P. L. (2026). Renewable Energy Innovation: Emerging Technologies, Challenges, Opportunities and Its Role in Sustainable Development. Bulletin of Nexus Journal, 3(9(II)), 173–180.
https://doi.org/10.5281/zenodo.22915467

Quick Response Code:

Website: https://bnir.us

Innovation is required to make renewable energy more efficient, affordable, reliable, flexible, and accessible. Renewable energy innovation refers to the development and application of new technologies, processes, business models, management systems, and institutional approaches that improve the generation, storage, transmission, distribution, and consumption of energy from renewable sources. Innovation may involve improvements in existing technologies as well as the introduction of entirely new technologies.

Recent developments demonstrate the rapid transformation of the renewable-energy sector. Solar photovoltaic technology has become increasingly efficient and scalable. Wind turbines have become larger and more productive, particularly in offshore environments. Battery technologies are improving energy storage capabilities, while green hydrogen is emerging as a potential solution for difficult-to-decarbonize sectors. Artificial intelligence and digital technologies are also enabling better forecasting, predictive maintenance, demand management, and grid optimization.

Renewable-energy innovation is therefore not merely a technological issue. It has economic, environmental, social, administrative, and geopolitical dimensions. The development of a renewable-energy economy can create new industries, employment opportunities, investment opportunities, and technological capabilities while reducing dependence on imported fossil fuels.

Background of Renewable Energy Innovation

Renewable energy has been used for centuries. Traditional societies depended on biomass, windmills, water wheels, and other naturally available energy sources. The modern renewable-energy sector, however, developed substantially during the twentieth century and expanded rapidly in the twenty-first century.

The oil crises of the 1970s stimulated research into alternative energy sources. Governments and research institutions began investing more systematically in solar, wind, geothermal, and other renewable technologies. During the following decades, improvements in manufacturing, materials science, electronics, power systems, and information technology substantially reduced the cost and increased the performance of renewable-energy technologies.

The twenty-first century has witnessed a particularly rapid expansion of renewable energy. Solar photovoltaic modules and wind turbines have become increasingly competitive with conventional power-generation technologies in many markets. At the same time, the development of energy-storage technologies has addressed one of the major limitations of renewable energy: variability.

Innovation is now moving beyond individual technologies toward integrated energy systems. Renewable electricity can be combined with batteries, pumped hydro storage, green hydrogen, electric vehicles, smart grids, demand-response systems, and digital platforms. This integrated approach can make energy systems more resilient and efficient.

Concept Of Renewable Energy Innovation

Renewable energy innovation can be understood as the process of developing and implementing new or improved technologies, processes, products, services, and organizational methods that increase the effectiveness of renewable-energy systems.

It can be broadly classified into the following categories:

1 Technological Innovation

Technological innovation includes improvements in solar cells, wind turbines, batteries, electrolyzers, geothermal systems, biomass conversion, hydropower equipment, and power electronics.

2 Process Innovation

Process innovation focuses on improving the way renewable-energy systems are manufactured, installed, operated, maintained, and recycled.

3 Digital Innovation

Digital technologies such as artificial intelligence, machine learning, Internet of Things devices, cloud computing, digital twins, and advanced analytics can improve forecasting, monitoring, maintenance, and system management.

4 Business Model Innovation

New business models include community solar projects, energy-as-a-service, peer-to-peer electricity trading, distributed generation, renewable-energy cooperatives, and innovative financing mechanisms.

5 Institutional and Policy Innovation

Governments can encourage renewable-energy innovation through research grants, competitive procurement, tax incentives, renewable-energy targets, public-private partnerships, regulatory reforms, and market mechanisms.

Objectives of the Study

The major objectives of this research paper are:

1. To examine the concept and importance of renewable energy innovation.
2. To study major technological innovations in renewable energy.
3. To analyse the economic, environmental, and social significance of renewable-energy innovation.
4. To examine the role of digital technologies and energy storage in renewable-energy development.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

5. To identify major challenges affecting renewable-energy innovation.
6. To examine the opportunities for renewable-energy innovation in India.
7. To suggest strategies for accelerating renewable-energy innovation and adoption.
8. To assess the contribution of renewable-energy innovation to sustainable development.

Research Methodology

1 Research Design

The study follows a **descriptive and analytical research design**. It examines developments in renewable-energy innovation and analyzes their implications for sustainable economic and environmental development.

2 Nature of Data

The study is based primarily on **secondary data** obtained from reliable academic, governmental, and institutional sources. Relevant information has been considered from international energy organizations, government publications, research reports, academic journals, books, and credible institutional websites.

3 Method of Analysis

The collected information has been analyzed through qualitative interpretation. Major renewable-energy technologies, innovations, opportunities, and challenges are examined thematically.

4 Scope of the Study

The study covers:

- Solar energy innovation
- Wind-energy innovation
- Hydropower innovation
- Bioenergy innovation
- Geothermal energy
- Green hydrogen
- Energy storage
- Smart grids and digital technologies
- Economic and environmental impacts
- Renewable-energy innovation in India
- Future opportunities and challenges

Major Areas of Renewable Energy Innovation

1 Solar Energy Innovation

Solar energy has become one of the most rapidly developing renewable-energy technologies. Innovation has occurred in both photovoltaic and solar-thermal technologies.

Traditional silicon-based photovoltaic modules have been continuously improved through better cell designs, manufacturing processes, materials, and power electronics. Emerging technologies such as perovskite solar cells and tandem solar cells have attracted significant research interest because of their potential for higher efficiency and new applications.

Other important innovations include:

- Bifacial solar panels
- Floating solar photovoltaic systems
- Building-integrated photovoltaics
- Solar tracking systems
- Agrivoltaics
- Flexible and lightweight solar modules
- Improved photovoltaic recycling
- Solar-plus-storage systems

Floating solar systems are particularly interesting for countries with limited land availability because photovoltaic installations can be placed on reservoirs and other water bodies. Agrivoltaic systems combine agricultural activities with solar electricity generation and may provide additional economic opportunities.

2 Wind Energy Innovation

Wind energy has evolved significantly through improvements in turbine design, materials, control systems, and digital monitoring.

Modern turbines are considerably larger and more efficient than earlier designs. Offshore wind energy has become an important area of innovation because stronger and more consistent wind resources are available in many offshore locations.

Innovations include:

- Larger rotor diameters
- Taller towers
- Advanced turbine blades
- Floating offshore wind platforms
- Digital turbine monitoring
- Predictive maintenance
- Improved wind forecasting
- Advanced power-control systems

Floating offshore wind technology is particularly promising because it can enable wind projects in deeper waters where conventional fixed-bottom turbines are difficult to install.

3 Hydropower Innovation

Hydropower is a mature renewable-energy technology, but innovation continues to improve its flexibility and environmental performance.

Pumped-storage hydropower is particularly important because it can store electricity by moving water to a higher elevation and later releasing it to generate electricity. It can therefore complement variable solar and wind generation.

Modern hydropower innovation also includes:

- Small and micro-hydropower systems
- Improved turbine efficiency
- Digital monitoring
- Environmentally sensitive turbine designs
- Pumped-storage systems
- Hybrid hydropower and solar projects

4 Bioenergy Innovation

Bioenergy involves using biological materials for heat, electricity, fuels, and other energy applications.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Innovation in bioenergy includes improved biomass conversion, advanced biofuels, biogas production, waste-to-energy systems, and sustainable feedstock management.

Anaerobic digestion can convert organic waste into biogas, while advanced technologies can improve the conversion of agricultural residues and other biomass into useful fuels.

Bioenergy can also contribute to the circular economy by converting agricultural and municipal waste into useful energy products.

5 Geothermal Energy Innovation

Geothermal energy uses heat from within the Earth. Although geothermal resources are geographically concentrated, technological innovation can expand their potential.

Enhanced geothermal systems are being researched to access heat from deeper geological formations. Improved drilling technologies, reservoir management, and monitoring systems may increase the geographical availability of geothermal energy.

Energy Storage Innovation

One of the greatest challenges associated with solar and wind energy is variability. Solar generation changes with sunlight availability, while wind generation depends on weather conditions. Energy storage can help balance electricity supply and demand.

1 Battery Storage

Lithium-ion batteries currently play a major role in electricity storage. Innovation is also taking place in:

- Sodium-ion batteries
- Solid-state batteries
- Flow batteries
- Advanced lithium-based chemistries
- Battery-management systems
- Second-life battery applications

2 Pumped-Storage Hydropower

Pumped-storage systems can provide large-scale and long-duration energy storage. They are particularly valuable for integrating large amounts of variable renewable electricity.

3 Thermal Energy Storage

Thermal storage allows energy to be stored as heat or cold. It can be useful for industrial processes, buildings, and solar-thermal power systems.

4 Hydrogen Storage

Renewable electricity can be used to produce hydrogen through electrolysis. The hydrogen can then be stored and used later for electricity generation, transportation, or industrial processes.

Green Hydrogen as an Emerging Innovation

Green hydrogen is hydrogen produced through electrolysis using renewable electricity. It is receiving considerable attention because certain sectors are difficult to electrify directly.

Potential applications include:

- Steel production
- Chemical industries
- Fertilizer production
- Shipping
- Long-duration energy storage
- Certain heavy-transport applications
- Industrial heating

The development of efficient electrolyzers, lower-cost renewable electricity, improved hydrogen storage, and transportation infrastructure will influence the future competitiveness of green hydrogen.

Artificial Intelligence and Digital Transformation

Digitalization is becoming an important part of renewable-energy innovation.

Artificial intelligence and machine learning can analyze large quantities of operational and weather data. These technologies can help predict solar and wind generation, identify equipment problems, optimize energy dispatch, and improve maintenance planning.

Important digital applications include:

1. **Energy forecasting** – predicting renewable generation based on weather and historical data.
2. **Predictive maintenance** – identifying potential equipment failures before they occur.
3. **Smart-grid management** – balancing electricity supply and demand.
4. **Demand forecasting** – estimating future electricity consumption.
5. **Digital twins** – creating digital representations of physical energy systems.
6. **Automated energy management** – optimizing distributed energy resources.

The integration of digital technologies can reduce operational costs and improve system reliability.

Smart Grids and Distributed Energy Systems

Traditional electricity systems generally depend on centralized power stations transmitting electricity over large networks. Renewable energy is encouraging a transition toward more distributed systems.

Rooftop solar, battery storage, electric vehicles, microgrids, and community-energy systems can operate closer to consumers.

Smart grids use sensors, communication systems, automated controls, and advanced software to manage electricity flows.

Benefits of smart grids include:

- Improved reliability
- Better integration of renewable energy
- Reduced transmission losses
- Faster fault detection
- Improved demand management

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- Integration of electric vehicles
- Greater consumer participation

Microgrids can also improve energy resilience for communities, institutions, industrial facilities, and remote areas.

Economic Significance of Renewable Energy Innovation

Renewable-energy innovation has significant economic implications.

1 Employment Generation

The renewable-energy sector creates employment in manufacturing, engineering, construction, installation, operations, maintenance, research, finance, and consultancy.

2 Investment Opportunities

Renewable energy has created new investment opportunities for governments, banks, infrastructure companies, technology firms, startups, and institutional investors.

3 Energy Security

Countries that depend heavily on imported fossil fuels can improve energy security by developing domestic renewable resources.

4 Industrial Development

Renewable-energy innovation can support domestic manufacturing of solar modules, wind components, batteries, power electronics, electrolyzers, and other technologies.

5 Rural Economic Development

Decentralized renewable-energy systems can support rural electrification, irrigation, cold storage, agricultural processing, and small businesses.

Environmental Benefits

Renewable-energy innovation can contribute significantly to environmental sustainability.

1 Reduction in Greenhouse-Gas Emissions

Replacing fossil-fuel-based electricity with renewable energy can reduce carbon dioxide emissions.

2 Reduction in Air Pollution

Renewable electricity generation generally produces substantially less local air pollution during operation than fossil-fuel combustion.

3 Conservation of Fossil Resources

Renewable energy reduces dependence on finite coal, oil, and natural gas resources.

4 Support for Climate Goals

Expansion of renewable energy is an important component of global efforts to reduce greenhouse-gas emissions and limit climate change.

However, renewable technologies are not completely without environmental impacts. Land use, mineral extraction, manufacturing, waste management, and ecological effects must be considered throughout the technology life cycle.

Social Significance of Renewable Energy Innovation

Renewable energy innovation can support social development by improving access to reliable and affordable energy.

In remote communities, decentralized solar systems, mini-grids, and other renewable technologies can provide electricity where extending conventional electricity infrastructure may be difficult or expensive.

Reliable energy can support:

- Education
- Healthcare
- Communication
- Small businesses
- Agricultural activities
- Water pumping
- Digital connectivity
- Household welfare

Therefore, renewable-energy innovation can contribute to inclusive development when technologies and financing mechanisms are designed to reach underserved communities.

Renewable Energy Innovation in India

India has significant renewable-energy resources, particularly solar and wind energy. The country has placed considerable emphasis on renewable-energy development as part of its energy-transition strategy.

India's geographical position provides substantial solar-energy potential. The country has also developed wind-energy capacity, particularly in states with suitable wind resources.

Important areas of Indian renewable-energy development include:

- Large-scale solar parks
- Rooftop solar
- Wind power
- Solar-wind hybrid projects
- Floating solar
- Battery energy storage
- Green hydrogen
- Renewable-energy manufacturing
- Renewable-energy-based rural development

The **National Solar Mission**, launched as part of India's climate and energy strategy, played an important role in encouraging solar-energy deployment. India has also established the **International Solar Alliance**, which promotes cooperation among solar-resource-rich countries.

The **National Green Hydrogen Mission** represents another major area of policy focus, aiming to support the development of a green hydrogen ecosystem and associated technologies.

India's renewable-energy transition can provide opportunities for technological innovation, domestic

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

manufacturing, employment generation, energy security, and reduction of fossil-fuel dependence.

Challenges of Renewable Energy Innovation

Despite significant progress, several challenges remain.

1 Intermittency

Solar and wind generation varies according to weather and time of day. This creates challenges for maintaining electricity-system balance.

2 Energy Storage

Large-scale and cost-effective long-duration storage remains an important requirement for integrating high levels of variable renewable energy.

3 High Initial Investment

Some renewable-energy technologies require substantial initial capital investment even when long-term operating costs are competitive.

4 Grid Infrastructure

Existing electricity networks may require modernization and expansion to accommodate distributed and variable renewable generation.

5 Land and Environmental Concerns

Large renewable projects may require significant land or affect ecosystems if they are not appropriately planned.

6 Critical Minerals and Supply Chains

Solar panels, batteries, wind turbines, and other technologies depend on various minerals and industrial supply chains. Concentration of manufacturing or mineral processing in particular regions can create supply-chain risks.

7 Skill Shortages

The renewable-energy transition requires engineers, technicians, researchers, project managers, data scientists, environmental specialists, and other skilled professionals.

8 Policy and Regulatory Uncertainty

Long-term investment can be affected by changes in regulations, taxation, subsidies, electricity-market structures, and approval procedures.

9 Recycling and End-of-Life Management

As renewable-energy installations grow, appropriate systems for recycling solar modules, batteries, turbine components, and other equipment will become increasingly important.

Opportunities For Future Innovation

The future of renewable energy is likely to involve greater integration between technologies.

1 Solar-Wind Hybrid Systems

Combining solar and wind generation can improve utilization of transmission infrastructure and create a more balanced generation profile.

2 Renewable Energy and Electric Vehicles

Electric vehicles can increase electricity demand but may also become part of future energy-management systems through smart charging and vehicle-to-grid technologies.

3 Artificial Intelligence

AI can improve forecasting, maintenance, energy trading, demand response, and grid management.

4 Advanced Materials

New materials can improve solar-cell efficiency, battery performance, turbine durability, and hydrogen production.

5 Green Hydrogen

Declining renewable-electricity costs and technological improvements may expand the role of green hydrogen in industrial decarbonization.

6 Community Energy Systems

Local renewable-energy systems can enable communities to participate directly in energy production and management.

7 Circular Economy

Future innovation should focus not only on producing renewable energy but also on reducing material consumption, extending equipment life, recovering valuable materials, and recycling components.

Findings of the Study

The major findings of the study are as follows:

1. Renewable energy innovation is essential for achieving a sustainable and secure energy system.
2. Solar and wind technologies are experiencing rapid technological development and cost improvements.
3. Energy storage is a key enabling technology for integrating variable renewable energy.
4. Artificial intelligence and digital technologies can significantly improve renewable-energy forecasting and system management.
5. Green hydrogen has potential applications in industries that are difficult to electrify directly.
6. Smart grids and distributed energy systems are changing the traditional structure of electricity systems.
7. Renewable-energy innovation can generate employment and stimulate industrial development.
8. Renewable energy can reduce dependence on fossil fuels and improve energy security.
9. Policy support and research investment are essential for commercializing emerging technologies.
10. India has substantial opportunities to become a major center for renewable-energy deployment, manufacturing, innovation, and green-hydrogen development.
11. Environmental sustainability requires consideration of the complete life cycle of renewable technologies, including raw

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

materials, manufacturing, operation, and recycling.

12. Collaboration among governments, universities, research institutions, industries, financial institutions, and communities is necessary for successful innovation.

Recommendations

Based on the analysis, the following recommendations are proposed:

1 Increase Research and Development

Governments and private organizations should increase investment in renewable-energy research, especially in advanced batteries, hydrogen, solar materials, offshore wind, grid technologies, and recycling.

2 Strengthen Energy-Storage Infrastructure

Policies should encourage development of batteries, pumped storage, thermal storage, hydrogen storage, and other technologies capable of balancing renewable electricity.

3 Promote Domestic Manufacturing

Countries should develop resilient domestic and regional supply chains for renewable-energy equipment and critical components.

4 Develop Skilled Human Resources

Universities and technical institutions should introduce specialized programs in renewable-energy engineering, energy management, battery technology, hydrogen technology, smart grids, and energy analytics.

5 Encourage Public-Private Partnerships

Governments should collaborate with private companies, startups, universities, and research institutions to accelerate commercialization of innovative technologies.

6 Improve Grid Infrastructure

Electricity networks should be modernized to accommodate distributed generation, storage, electric vehicles, and increasing renewable-energy penetration.

7 Support Startups and Entrepreneurship

Innovation-focused startups should receive access to finance, incubation facilities, testing infrastructure, research partnerships, and appropriate regulatory support.

8 Encourage Circular-Economy Practices

Renewable-energy policies should include recycling, repair, refurbishment, resource recovery, and environmentally responsible disposal.

9 Promote Inclusive Energy Development

Renewable-energy programs should ensure that rural and economically disadvantaged communities can access reliable and affordable clean energy.

Conclusion

Renewable energy innovation is transforming the global energy sector and is becoming an important foundation for sustainable development. Innovations in solar photovoltaic technology, wind power, energy storage, green hydrogen, smart grids, digital technologies, and distributed energy systems are improving the ability of societies to generate and use clean energy.

The significance of renewable-energy innovation extends beyond environmental protection. It can improve energy security, create employment, stimulate investment, encourage technological development, support rural development, and contribute to industrial competitiveness. For developing countries such as India, renewable-energy innovation presents an opportunity to combine economic development with environmental sustainability.

At the same time, the renewable-energy transition faces significant challenges. Intermittent generation, storage requirements, grid constraints, financing needs, supply-chain vulnerabilities, land-use concerns, environmental impacts, and skill shortages require coordinated solutions. Technological innovation must therefore be accompanied by policy innovation, institutional reform, infrastructure development, education, and international cooperation.

The future energy system is likely to be increasingly decentralized, digital, intelligent, interconnected, and renewable. Governments, industries, universities, financial institutions, entrepreneurs, and communities must work together to create an innovation ecosystem capable of supporting this transition. Sustained investment in research and development, combined with appropriate policies and responsible resource management, can accelerate renewable-energy innovation and contribute to a cleaner, more resilient, and more sustainable global economy.

Acknowledgment

I would like to express my sincere gratitude to all those who have contributed directly or indirectly to the successful completion of this research paper entitled “Renewable Energy Innovation: Emerging Technologies, Challenges, Opportunities and Its Role in Sustainable Development.”

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

References

1. International Energy Agency (IEA). *Renewables*. Paris: International Energy Agency.
2. International Renewable Energy Agency (IRENA). *Renewable Energy Statistics*. Abu Dhabi: IRENA.
3. International Renewable Energy Agency (IRENA). *World Energy Transitions Outlook*. Abu Dhabi: IRENA.
4. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022: Mitigation of Climate Change*. Cambridge University Press.
5. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations.
6. United Nations Environment Programme (UNEP). *Emissions Gap Report*. Nairobi: UNEP.
7. Ministry of New and Renewable Energy, Government of India. *Renewable Energy and Related Policy Publications*. New Delhi: Government of India.
8. Government of India. *National Green Hydrogen Mission*. New Delhi: Government of India.
9. International Solar Alliance. *Reports and Publications on Solar Energy Development*. Gurugram: International Solar Alliance.
10. World Bank. *Tracking SDG 7: The Energy Progress Report*. Washington, DC: World Bank.
11. Lund, H. (2014). *Renewable Energy Systems: A Smart Energy Systems Approach*. Academic Press.
12. Boyle, G. (Ed.). (2012). *Renewable Energy: Power for a Sustainable Future*. Oxford University Press.
13. Twidell, J., & Weir, T. (2015). *Renewable Energy Resources*. Routledge.
14. Kalogirou, S. A. (2014). *Solar Energy Engineering: Processes and Systems*. Academic Press.
15. Sørensen, B. (2017). *Renewable Energy: Physics, Engineering, Environmental Impacts, Economics and Planning*. Academic Press.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Transforming Library Services through Smart Technologies

Dr. Sainath Shivaji Lokhande
Librarian, Sant Rawool Maharaj Mahavidyalaya, Kudal.

Manuscript ID:
BN-2026-030934

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 181-186

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22915767
DOI link:
https://doi.org/10.5281/zenodo.22915767

Abstract

The rise of electrical technologies has made some fundamental modifications in contemporary library's nature, functions and services. "The libraries have been making changes in its role from traditional to computerized record system of collection, preservation and circulations of books. Due to Innovative developments in digital technology like Cloud computing, AI, Internet, robotics, robotics, Radio Frequency Identification (RFID), mobile apps, smart sensors, digital help and computerized libraries got new opportunity to make it services more fast user-friendly, flexible and user-oriented services. A smart library is being transform with information, people, technology and information resources and intelligent systems to form a responsive and efficient information environment. This paper examines the impact of smart technologies on traditional library services which are changing due to it. The paper elaborates and points out which major technologies are used in smart libraries. The paper aims to deal with how the technological effects on acquisition, cataloging, circulation, reference, user education, resource discovery, security and library management. The paper also stresses the advantages and disadvantages of adopting smart technologies, especially concerning costs, infrastructure, staff training, data privacy, cyber security and online literacy. The conclusion of the study is that successful modification of libraries not only depends on technology, but also on user participation, skilled library professionals, proper planning, and continuous innovation.

Keywords- Smart Library, Smart Technologies, Artificial Intelligence, Internet of Things, Robotics, RFID, Library Automation, Digital Library, Library Services, Technology.

Introduction

We cannot imagine education without library. It has played a significant role in supporting education, research, knowledge creation and lifelong learning. Before modern world, internet and online software, library managed to serve through manual services like printed collections, manual registers, physical catalogues and face-to-face interactions between users and library staff. Still today, this traditional form of serving its users is having an important value but library has to change due to rapid growth in digital technology to cope with transitional world. Libraries have to implement technology to make its services more flexible, efficient and technology-enabled library services. The library converts into the smart library because it became computerized, automation due to the digital library development. The combination of interconnected technologies and intelligent system is helpful to understand user needs as well as to deal with recourses of information to provide services efficiently. Artificial Intelligence, IOT, RFID, robotics, cloud computing, mobile technology, big data analytics and digital assistants will inculcate into library functions. To due to the modernity, researcher and student hopes to get quick information with convenience from various devices. There is rapid growth to access books, journal, database institutional repositories and digital learning resources online through smartphones and computers.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sainath Shivaji Lokhande, Librarian, Sant Rawool Maharaj Mahavidyalaya, Kudal.
Email: srmcollegekudal12@gmail.com

How to cite this article:
Lokhande, S. S. (2026). Transforming Library Services through Smart Technologies. Bulletin of Nexus Journal, 3(9(II)), 181–186. https://doi.org/10.5281/zenodo.22915767

Quick Response Code:

Website: https://bnir.us

Thus, library has to cope with this change and go beyond its traditional service system to more develop advanced technology emblemed services which satisfy the demands form the users to get quick information at anytime, anywhere. Such technologies make progress in library in both internal operations and user-friendly services. For example, RFID can automate book circulation and stock verification, IOT can monitor environmental situations, AI can assist reference and information discovery, robotics can support in material handling, and mobile applications can give remote access to the library services.

Therefore, modifications through smart technologies is not a matter of simply installing new equipment. But it represents a change in the way libraries plan, manage and provide information services.

Objectives of the Study

The major objectives of this research paper are:

1. To understand the concept and importance of smart technologies in libraries.
2. To identify major smart technologies applicable to modern library services.
3. To examine the applications of smart technologies in different library operations.
4. To study the benefits of smart technologies for library users and professionals.
5. To identify the major challenges associated with smart library development.
6. To suggest strategies for effective implementation of smart technologies in libraries.

Research Methodology

The present research paper is based on a descriptive and conceptual research methodology**.** Information has been collected through secondary sources like books, research papers, professional literature, reports, websites and scholarly discussions related to library automation, digital libraries, smart libraries, Artificial Intelligence, IOT, robotics and emerging technologies.

After collection of data, it has been analyzed and organized thematically to understand the applications, advantages and challenges of smart technologies in library services. The study points out particularly on technologies that have practical relation to the academic and research libraries.

Concept of Smart Library

A smart library can be understood as a technology-enabled library that uses intelligent and interconnected systems to provide efficient, personalized and user-centric information services. It combines physical and digital resources with modern technologies to create an integrated information environment.

Traditional library automation mainly focused on computerizing routine activities such as acquisition, cataloguing, circulation and serial control. A smart library goes further by integrating automated systems, sensors, intelligent software, data analytics and digital communication technologies.

A smart library generally possesses the following characteristics:

- Technology-enabled library operations
- Automated circulation and inventory management
- Digital and electronic information resources
- Remote access to library services
- Intelligent information discovery
- Personalized user services
- Real-time data collection and analysis
- IOT-enabled monitoring
- Mobile-based services
- Automated communication and notifications
- Improved security and resource tracking

The primary objective of a smart library is to use technology not as a replacement for library professionals but as a means of improving the quality, efficiency and accessibility of library services.

Major Smart Technologies Used in Libraries

1 Artificial Intelligence

Currently Artificial Intelligence is become one of the most important emerging technologies for libraries. AI systems can analyze information, identify patterns and help decision-making.

AI can be applied in:

- Virtual reference services
- Chat-bots and digital assistants
- Intelligent search systems
- Recommendation services
- Automatic classification and indexing
- Text and data analysis
- User behave our analysis
- Frequently Asked Questions (FAQ) services
- Personalized information recommendations

An AI-based library assistant can answer routine queries such as library timings, membership rules, availability of books and basic database information. This allows library professionals to concentrate on more complex reference and research-support activities.

2 Internet of Things

The Internet of Things connects physical devices and sensors through networks to collect and exchange information. In libraries, IOT can connect books, shelves, computers, entry systems, environmental sensors and other equipment.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Applications include:

- Smart entry and attendance systems
- Smart shelves
- Real-time book tracking
- Temperature and humidity monitoring
- Energy management
- Occupancy monitoring
- Equipment monitoring
- Automated alerts
- Location-based services

IOT can help libraries monitor their physical environment and improve the preservation of collections.

3 Radio Frequency Identification

RFID is an important technology for modern library automation. RFID tags can be attached to books and other library materials. RFID readers can identify items without requiring direct line-of-sight scanning.

RFID can support:

- Self-check-in and self-check-out
- Automated circulation
- Book security
- Shelf management
- Stock verification
- Misplaced book identification
- Faster transaction processing

Compared with traditional barcode systems, RFID can significantly improve the efficiency of circulation and inventory-related activities.

4 Robotics

Robotics represents another emerging area in smart library development. Robots can perform repetitive and physically demanding activities.

Possible applications include:

- Book transportation
- Shelf scanning
- Material sorting
- Automated retrieval
- User guidance
- Information assistance
- Inventory management

Although advanced library robotics may require substantial investment, robotic technologies have potential for large academic and research libraries.

5 Cloud Computing

Cloud computing enables libraries to access computing resources, software and data through network-based infrastructure. Cloud-based Integrated Library Management Systems can reduce the need for extensive local hardware and simplify system maintenance.

Cloud technology can support:

- Library management systems
- Digital repositories
- Remote access
- Backup and data storage
- Collaborative cataloguing
- Resource sharing
- Online databases
- Library websites and discovery systems

Cloud-based services are particularly useful for institutions seeking scalable and cost-effective technology solutions.

6 Mobile Technology

Smartphones and mobile applications have changed the way users interact with libraries. Libraries can provide mobile-friendly services through websites, applications and QR codes.

Mobile library services may include:

- Mobile OPAC
- E-book access
- Digital library access
- Book renewal
- Reservation services
- Notifications
- New arrival information
- Digital membership cards
- QR-code-based information access

Mobile services make library resources more accessible to students and researchers.

Transformation of Library Services

1 Acquisition Services

Smart technologies can improve the acquisition process by supporting electronic ordering, vendor communication, budget monitoring and automated records. Data analytics can also help libraries identify frequently used subjects and resources that require additional investment.

Usage statistics from electronic resources can support evidence-based collection development decisions.

2 Cataloguing and Classification

AI-assisted cataloguing systems can reduce repetitive work by generating bibliographic information, subject suggestions and metadata. Automated tools can support classification and indexing while maintaining professional oversight.

Library professionals remain essential for quality control, authority control and intellectual organization of information.

3 Circulation Services

Circulation is one of the areas where automation has produced significant improvements. Barcode and RFID-based systems can automate issue and return activities.

Smart circulation services can provide:

- Faster issue and return
- Self-service facilities
- Automated due-date notifications
- Renewal reminders

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- Reservation alerts
- Reduced manual errors

Such systems improve user convenience while reducing repetitive administrative work.

4 Reference Services

Reference services are changing from traditional face-to-face assistance to multi-channel digital support. AI chat-bots, email reference, online forms and virtual communication platforms can provide assistance beyond normal working hours.

AI can handle simple and repetitive questions, while professional librarians can focus on advanced research consultations, literature searches and information evaluation.

5 Information Discovery

Modern discovery systems allow users to search multiple information resources through a single interface. AI and semantic technologies can improve search results by identifying relationships between concepts rather than relying exclusively on exact keywords.

Personalized recommendation systems can suggest books, articles, databases and other resources based on user interests and previous interactions.

6 Digital Library Services

Smart technologies strengthen digital library services by providing access to electronic resources from remote locations. Libraries can offer digital collections, institutional repositories, open educational resources and digitized documents.

This is especially important for distance education, blended learning and online teaching environments.

7 User Education and Information Literacy

Technology can transform library orientation and information literacy programmes. Instead of relying only on classroom lectures, librarians can use:

- Online tutorials
- Video demonstrations
- QR codes
- Interactive presentations
- Learning management systems
- Digital guides
- Online quizzes
- Virtual orientation programmes

These tools enable students to learn library skills at their own pace.

8 Library Security

Smart technologies can improve the security of library collections and facilities. RFID-based security gates can detect unauthorized removal of materials. Smart access-control systems can restrict entry to authorized users.

CCTV, electronic access systems and digital monitoring can also improve the security of library spaces and resources.

9 Stock Verification

Stock verification is traditionally a time-consuming activity. RFID, handheld scanners and automated inventory systems can make the process faster and more accurate.

Smart inventory systems can help identify:

- Missing books
- Misplaced books
- Duplicate records
- Items requiring repair
- Books located in incorrect sections

This enables library staff to maintain accurate collection records.

Benefits of Smart Technologies in Libraries

The implementation of smart technologies provides several benefits.

1 Improved Efficiency

Automation reduces repetitive manual tasks and improves the speed of routine operations.

2 Better User Experience

Users can access information and services quickly through computers, smartphones and other digital devices.

3 24/7 Accessibility

Digital resources and online services can be made available beyond traditional library working hours.

4 Personalized Services

AI and data analytics can help libraries provide recommendations based on user interests and information needs.

5 Improved Resource Management

Smart technologies provide better control over collections, circulation, inventory and electronic resources.

6 Data-Based Decision Making

Usage statistics and analytics can support evidence-based decisions related to collection development, space utilization and service improvement.

7 Reduction in Manual Errors

Automated systems can reduce errors in circulation, data entry and inventory management.

8 Enhanced Security

RFID, smart access control and monitoring systems can improve the security of library collections and users.

9 Support for Sustainable Libraries

Smart energy management, automated lighting and environmental monitoring can contribute to energy efficiency and sustainable library operations.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Challenges in Implementing Smart Technologies

Despite their advantages, smart technologies present several challenges.

1 Financial Constraints

Advanced technologies such as RFID, robotics, AI infrastructure and IoT systems can require significant investment. Small and rural libraries may face difficulties in allocating adequate funds.

2 Lack of Technical Infrastructure

Reliable internet connectivity, computers, servers, networking infrastructure and technical support are essential for smart library services.

3 Staff Training

Library professionals need continuous training to understand and operate emerging technologies. Technology adoption without appropriate staff development may reduce the effectiveness of implementation.

4 Data Privacy

Libraries collect various types of user information. Smart systems can generate detailed usage data. Therefore, libraries must establish appropriate policies for data collection, storage, access and retention.

5 Cybersecurity

Digital systems may face threats such as unauthorized access, malware, data theft and service disruption. Strong cybersecurity measures are essential.

6 Resistance to Change

Some staff members and users may initially hesitate to adopt new technologies. Effective communication, training and gradual implementation can reduce resistance.

7 Technology Obsolescence

Technology changes rapidly. Systems installed today may become outdated within a few years. Libraries therefore need flexible and scalable solutions.

8 Digital Divide

Not all users possess the same level of digital literacy or access to digital devices and reliable internet connections. Smart library development must therefore remain inclusive.

Role of Library Professionals in the Smart Library

The introduction of smart technologies does not eliminate the importance of librarians. Instead, it changes the nature of their professional responsibilities.

The modern librarian increasingly functions as:

- Information professional
- Digital resource manager
- Technology facilitator
- Research support specialist
- Information literacy educator
- Data and metadata manager
- Digital preservation professional
- Technology trainer
- User experience facilitator

Library professionals must develop competencies in AI literacy, digital tools, data management, cybersecurity awareness, metadata, electronic resources and emerging technologies.

The future library professional will need both traditional library knowledge and technological competence.

Strategies for Developing Smart Libraries

Libraries can adopt the following strategies for successful technological transformation:

1. Develop a clear technology plan based on institutional objectives.
2. Assess user needs before introducing new technologies.
3. Prioritize high-impact services such as circulation, discovery and digital access.
4. Provide continuous staff training and professional development.
5. Adopt interoperable and scalable systems.
6. Establish data privacy and cybersecurity policies.
7. Use open-source technologies where appropriate.
8. Develop partnerships with academic institutions and technology providers.
9. Evaluate services regularly using user feedback and usage statistics.
10. Ensure accessibility and inclusion for all categories of users.

A phased implementation approach can help institutions manage financial and technical limitations.

Future Perspectives

Artificial Intelligence will be integral part of tomorrow's smart libraries. Not only AI, but IOT, robotics, cloud computing, analytics and immersive technologies also will become integrated with smart library. This AI-based search systems will become as capable of understanding natural-language queries and providing contextual recommendations.

Smart shelves and IOT devices are helpful to enable real-time collection monitoring. Automated robots could support material transportation and inventory operations. Such a digital assistants might become a routine component of reference services.

After fusing AI with library discovery systems, it will support research workflows by assisting users to identify relevant literature, summarize information and discover relationships among scholarly resources. Moreover, professional librarians will remain necessary to ensure

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

information quality, ethical use, intellectual freedom, privacy and appropriate interpretation of information.

Future smart library should be viewed not simply as a technologically advanced building but as an intelligent information ecosystem where people, technology, resources and services work together.

Conclusion

Smart technologies are transforming libraries from traditionally managed information centres into dynamic, connected and user-oriented learning environments. Technologies such as Artificial Intelligence, IOT, RFID, robotics, cloud computing, mobile applications and data analytics can improve library operations and create new opportunities for information delivery.

One can observe such changes if technologies implemented in its major activities-including acquisition, cataloguing, circulation, user education, security, reference, stock verification and digital resource management. Due to integration of smart technologies library will become more efficient, improvement in accessibility also it reduces repetitive work and also support personalized services.

However, technology alone cannot convert traditional library into a successful smart library. Without proper strategic planning, adequate infrastructure, skilled professionals, financial support, cybersecurity, data privacy and continuous evaluation, library cannot be modified. Libraries must also ensure that technology does not create new barriers for users who have limited digital skills or access to technology.

The bright future of libraries depends upon a balanced mingling of technology and human expertise**.** Librarians will continue to play a significant role as educators, information professionals, research facilitators and guides in the growing complex digital information environment.

To conclude, library transformation is continuous process of innovation of smart techniques or technologies rather than just a project of technology. Libraries who have adopted appropriate technologies while preserving their core values of equitable access, intellectual freedom, user privacy and knowledge sharing will remain very important institutions in the digital era.

Acknowledgment

The author sincerely expresses gratitude to the management and authorities of Sant Rawool Maharaj Mahavidyalaya, Kudal, for providing the necessary support and encouragement for the preparation of this research paper. The author is also thankful to the library professionals, researchers, scholars, and authors whose books, research papers, professional literature, reports, and scholarly discussions contributed valuable information to this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Chowdhury, G. G. (2010)., "Introduction to Modern Information Retrieval" (3rd ed.), Facet Publishing, PP-125-129.
2. Kroski, E. (2021), "Law Librarianship in the Digital Age", Rowman & Littlefield, pp -150-160.
3. Lankes, R. D. (2016).,"The New Librarianship Field Guide", MIT Press, pp – 96-102.
4. Mannan, S. (2020)., "Emerging technologies and their applications in library services", Library Philosophy and Practice.
5. Singh, S. P. (2019)., "Emerging Technologies in Libraries", Ess Ess Publications, pp-56-75.
6. Tenopir, C., & King, D. W. (2000)., "Towards Electronic Journals: Realities for Scientists, Librarians and Publishers", SLA Publishing, pp-12-28.
7. Zhang, Y., & Ma, L. (2022)., "Smart library development and intelligent information services", Library Hi Tech, pp-21-37.
8. Zhou, J. (2021)., "Internet of Things applications in smart libraries: Opportunities and challenges", The Electronic Library pp.37-48.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Sustainable Chemical Techniques for Clean energies and Vikasit Bharat 2047

Tabbu Salim Kavathekar
Assit. Prof. department of Chemistry

Manuscript ID:
BN-2026-030935

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 187-189

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22915980
DOI link:
https://doi.org/10.5281/zenodo.22915980

Abstract:

Viksit Bharat by 2047 is the vision of the Indian government to transform the country into a developed nation by that year. The year 2047 will mark the 100th anniversary of India's independence. To achieve this goal, all sectors of the country must contribute effectively. Researchers in every field, including chemistry, have been doing excellent work to make India proud so far. It is now even more important for those working in the field of chemistry to conduct high-quality research. This will help increase the quantity of research outputs, which in turn will support the country's progress. Chemistry plays a crucial role in developing eco-friendly chemical methods to produce various chemicals, green chemicals, fuels, gases, solvents, and more at cost-effective prices. This will help boost India's economy at a faster rate. Hence, the vision of Viksit Bharat can be achieved successfully in due course.

Keywords:

Viksit Bharat, Sustainable development, Chemistry, Agri chemical, green chemical.

Introduction:

Viksit Bharat @ 2047 is an Indian government vision of making India developed country by the 2047. All the sector of economy including chemical industry will play an important role in achieving this goal. This article highlights the main pillar of Viksit Bharat mission and importance and role of chemistry for sustainable growth of Indian economy for making India a developed country.

Discussion:

To become a developed country by making continuous growth in all sectors of the economy is a very challenging task for any country. To achieve this target, honesty and hard work with good moral values is the key factor as these qualities make a country happier in all aspects. In ancient time our country India was known by the name 'golden bird' for its prosperity. Many philosophers who gave the idea to respect the nation and they carried Bharat forward by their ideas. A developed nation should have a growing economy as well as good physical and mental health of the citizens. The mentally healthy with good physical health human resources will do wonders for any country. To become a country rich in all aspects, holistic development is required. The primary criteria of a developed country in the form of economical values are gross domestic product and per capita income of citizens of the country. These two criteria are very important as a growing economy would create great job and earning opportunities for the people. The overall development of a nation starts with the development of an individual self. When any individuals get good economic earning then they become an asset to the family to fulfill their day-by-day needs in a proper manner. When a family got upgraded in a Mohalla or village, it helps others in many ways for their uplifting like giving them earning opportunities, motivation and financial support.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

Tabbu Salim Kavathekar, Assistant Prof. department of Chemistry
Email: tabbu7457@gmail.com

How to cite this article:

Kavathekar, T. S. (2026). Sustainable Chemical Techniques for Clean energies and Vikasit Bharat 2047. Bulletin of Nexus Journal, 3(9(II)), 187–189. https://doi.org/10.5281/zenodo.22915980

Quick Response Code:

Website: https://bnir.us

By similarly a developed village help the small cities to become richer and more prosperous, going through town to cities and then metro cities this development reached a point where the country gets enters in the list of developed country. Human developed index is a parameter who includes health, education and standard of the living, both these economical and human development factors are of very high standard in developed countries.

In India there are a lot of development happened from the ancient time. In modern times when we got independence in 1947 the economical and poor mortality ration in infants, low life span was the major challenging factor for the country. Till date we as a country comes a long way to uplift ourself in all these parameters. Yet we are still in the list of developing countries. To get entry in the developed country list, the government of India launches the Viksit Bharat Abhiyan with a vision to become developed country by 2047, the 100th year of our independence the vision and objective of Viksit Bharat Abhiyan involves economics prosperity, social advancement, environmental sustainability with the help of good and effective governance.

There are many key pillars and areas identified by the government to be focused to achieve target of developed nation. The main 4 core pillars are - youth, poor, women and farmers. Making global manufacturing hub, education/skill development system, export Indian food, harvesting green energy, expansion of tourism, economic enhancement, cultural activity promotion etc. are need to be addressed in proper manner. Some other key pillars are innovation in science, technology advancement, advancement in the field of Artificial Intelligence, chip making, electrical equipment making, toys making, medicine making, chemical production, fertilizer production, production of cost efficient LED, mobile manufacturing, palm oil production, laptop manufacturing, security weapons production, fuel production, mining sector development, building and purification of different metals from their ore and minerals, high quality research etc. are the need of the hour for getting a move on at faster rate than the rate at which we are going now towards becoming rich country. The economic growth projection made by NITI Aayog is to made India a USD 30-40 trillion economy by the year 2047.The conservative target of what today is $30-051 trillion USD economy. To achieve this target 7 to 10% growth of GDP at various points throughout the journey in this this tenure is required. Chemistry the science of material is very important in making all the equipment and material to be used as tools in making environment friendly sustainable development for reaching this GAP target. Iron, gold, silver, zinc, nickel, rare earth metal, copper, tin, lead etc. are some commonly used metals almost in every field of life. These metals are obtained from the ore and mineral by using a chemical technique known as metallurgy.

For a country to become auto independent the production of this metal at cost efficient level is very necessary. The most of our money is to use on the import of gold and silver beside other fuels in the form of crude oil. In metallurgy process different type of chemicals is used at various steps. The nature of chemicals and type of chemical varies from metallurgy of one element to another elements. From ancient time our chemistry knowledge was of very high standard with reference to zinc and its metallurgy. Advanced knowledge of chemistry and metallurgy techniques are arising with researchers doing intensive work in this field. As the new methods with advancement get evaluated, the cost and fuel efficiency of obtaining these metals will be ensured in the near future. This will help the country in saving money and fuel. A faster rate of growth in this industry will be guaranteed as the time in making these metals will be reduced drastically. All in all, the material made by use of various metals will be easy to make and therefore their availability to the citizens will be very accessible. For example, a number of devices made by using these metals are now reaching among the society. In early 2000, the automobile in the form of two-wheeler was not easily accessible to the middle class and lower middle class. But nowadays with advancement of technology and easy availability of raw material in the form of different chemical elements made it possible that in almost all the houses in villages have bikes. Further, the four-wheel automobiles are now making their presence in low-income areas within the country. In old time we listen from our grandparents that the availability of food grain in the form of wheat was very difficult. Only when the relative arrived, only then roti made of wheat was properly cooked in the home. The work done in the field of biochemistry and biotechnology. With the help of green revolution, the availability of seed is there in almost every house of the India. Further in the future with advancement of various kind of quality seed in combination of chemical fertilizer will increase this production so that country will be able to export these food grains get money to strengthen its economy. This will play an important role in achieving goal of developed country. In agriculture sector our country is depending on import of fertilizer to meet the demand of farmers. Chemically fertilizers are those chemicals who supplies and categorizes the nutrients to the plant in the form of micro and macro. Potash, phosphate, nitrogen, DAP, NPK, urea is the fertilizer material that is imported by us. The import price made a dent to the economy of fertilizer sector. Chemistry can solve this issue in the future making cost effect fertilizers. For example, in western UP and in 2021-22 nano urea in

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

the form of nano was introduced. The urea in the form of nano supposed to be very useful in reducing the demand of normal urea in near future. Social and Economical stand of farmer in Meerut and Adjuring area. this help in making them prosperous. The role of chemistry in the form of fertilizers, hybrid seeds and Agri medicine is very important in making India developed by the year 2047.

The research on alternative source of on fuel energy is going on in full tilt. The Hydrogen as a fuel is gaining very popularity now a days. when hydrogen is combusted with oxygen, the end product with water vapor. Thus, the Environmental pollution caused by automobiles is in reducing these days. The vehicles using Hydrogen fuel as core component are deployed In Himachal in the form of Buses are using this type green energy technologies are launched by Oleta green company. Electrical vehicle is become very popular now, EV scooter, EV sooty, EV bike, EV four-wheeler is the result of deep and intense research in the field of chemistry. This alternative fuel area will help in reducing Petroleum import from outside the country. This role of chemistry research work will boost the Indian Economy by descending dependence upon Petroleum fuel and therefore automotive path to become developed county become very smoothed and fast. The chemical advancement in the field of Agri medicine field makes their presence in the agriculture field. The improved variety of sugarcane combining with pesticide, herbicide and insecticide plays a key role in uplifting the agriculture sector. Another important role of chemistry in making India develop in each sector is medicinal field. The research on medicine to cure the health of people helps in making their life span prolonged. The design and production of new cost-efficient drugs will be a key factor in making India an exporter in this field. The medicine sector is very helpful in two ways - one is to make people more fit and another is to derive money in the form of export.

Chemistry also helps in the field of producing world class knowledge of different chemicals. As all the matter around us is made up of atoms and molecules of various types. With ever increasing knowledge of chemistry opens the pathways for making eco-friendly material that will be used for making various goods need for our life.

Conclusion:

Our country has a very good ancient knowledge of chemistry. Chemistry is very important in developing new chemicals, materials, medicines, fuels, energy, renewable energy, fertilizers, pesticides, insecticides, fungicides. Etc. All these will help our country to become developed country by 2047 under Viksit Bharat 2047 Abhiyan initiated by current Indian government. Chemistry will reduce import and will increase export to support our economy.

Acknowledgment

I would like to express my sincere gratitude to all those who have supported and encouraged me in the completion of this research paper, "Sustainable Chemical Techniques for Clean Energies and Vikasit Bharat 2047." I am deeply thankful to my institution and the Department of Chemistry for providing the necessary academic environment, guidance, and resources for undertaking this work. I extend my heartfelt appreciation to my colleagues, teachers, researchers, and well-wishers whose valuable suggestions and encouragement contributed to the development of this paper.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Bagley, M. (2014). Live Science Contributor. livescience.com/45986-what is chemistry.html
2. Branscomb, L.M., and Brooks, H. (1993). Empowering Technology: Implementing a US Strategy.
   MIT Press, Boston, 202-234. "A History of Hindu Chemistry Vol. 1". Internet Archive. Retrieved 6 November 2022.
3. "A History of Hindu Chemistry, Vol. 2". Internet Archive. Retrieved 6 November 2022.Stevenson, H.H., and Mossi J.C.J. (1986). Preserving Entrepreneurship as companies grow. Journal of Business
   Strategy, 10-23.
4. "Chemical Industry, Chemicals Manufacturers and Exporters in India - IBEF". India Brand Equity Foundation. May 2022. Retrieved 13 June 2022.
5. Padder, A.H. (2023). Viksit Bharat@ 2047. Research Gate, Retrieved, from https ://www
   Research Gate.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Artificial Intelligence in Sustainable Chemistry: Applications, Challenges and Future Perspectives towards Viksit Bharat @2047

Diksha Krushnat Kamble
Assistant Professor of Chemistry, Shripatrao Chougule Arts and Science college Malwadi – Kotoli.

Manuscript ID:
BN-2026-030936

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 190-194

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22932745
DOI link:
https://doi.org/10.5281/zenodo.22932745

Abstract
The chemical industry is essential for modern society, but conventional chemical processes may require substantial quantities of energy, solvents and raw materials and can generate undesirable waste and emissions. Sustainable chemistry seeks to address these concerns by designing chemical products and processes that use resources more efficiently and reduce environmental and health risks. In parallel, Artificial Intelligence (AI) has emerged as a powerful computational approach for analysing complex chemical information, predicting molecular and material properties, optimizing reactions and supporting scientific decision-making. The integration of AI with sustainable chemistry creates an opportunity to accelerate the development of safer, cleaner and more resource-efficient chemical technologies. This review examines the emerging role of AI in sustainable chemistry, with particular emphasis on machine learning, predictive modelling, reaction optimization, catalyst discovery, solvent selection, sustainable materials, carbon management, green hydrogen, waste valorization and analytical chemistry. The potential of AI to support the principles of green chemistry and life-cycle-based decision-making is also discussed. Recent studies indicate that AI can reduce experimental effort and improve the efficiency of chemical discovery and process development, although limitations related to data quality, interpretability, validation, computational requirements and industrial scale-up remain significant. The review further considers the relevance of AI-enabled sustainable chemistry to India's long-term development objectives under Viksit Bharat @2047. A future-oriented framework for responsible AI-driven chemistry is proposed, emphasizing scientific validation, environmental assessment, interdisciplinary collaboration and indigenous innovation.

Keywords: *Artificial Intelligence; Sustainable Chemistry; Green Chemistry; Machine Learning; Chemical Process Optimization; Sustainable Materials; Catalysis; Circular Chemistry; Viksit Bharat @2047*

Introduction

Chemistry has played a central role in the development of pharmaceuticals, agricultural products, polymers, energy technologies, construction materials and consumer goods. However, increasing industrial production has also intensified concerns regarding resource consumption, hazardous substances, waste generation, greenhouse-gas emissions and environmental degradation. These concerns have encouraged a transition from conventional chemical manufacturing toward approaches that consider environmental performance during the design stage itself. Green chemistry provides an important foundation for this transition. Instead of treating pollution after it has been generated, green chemistry emphasizes prevention through the design of safer substances, efficient reactions, renewable feedstocks, catalytic processes and reduced waste. At the same time, chemical research is becoming increasingly data-intensive. Modern chemistry generates information from spectroscopy, chromatography, computational chemistry, reaction databases, material characterization and high-throughput experimentation.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Diksha krushnat kamble, Shripatrao Chougule Arts and Science college Malwadi-Kotoli
Email: kambalediksha2@gmail.com

How to cite this article:
Kamble, D. K. (2026). Artificial Intelligence in Sustainable Chemistry: Applications, Challenges and Future Perspectives towards Viksit Bharat @2047. Bulletin of Nexus Journal, 3(9(III)), 190–194.
https://doi.org/10.5281/zenodo.22932745

Quick Response Code:

Website: https://bnir.us

Artificial Intelligence offers a complementary solution. Machine-learning models can identify relationships between chemical structures, experimental conditions and observed properties. AI-based optimization can explore numerous variables simultaneously and identify promising experimental conditions with fewer trials. The convergence of these two fields therefore raises an important question: Can AI help chemistry become not only faster and more predictive, but also fundamentally more sustainable? This review explores this question by examining major applications, limitations and future opportunities for AI in sustainable chemistry, with particular attention to India's development objectives under Viksit Bharat @2047.

Artificial Intelligence as a Tool for Sustainable Chemistry

AI in chemistry encompasses several computational approaches rather than a single technology. Machine learning, deep learning, neural networks, graph-based models, natural language processing and optimization algorithms can be selected according to the chemical problem being addressed.

A simplified AI-assisted chemical workflow can be represented as:

Chemical Data → AI Model → Prediction → Optimization → Experimental Validation → Improved Chemical Process

- Prediction of molecular properties
- Reaction-yield prediction
- Catalyst screening
- Solvent selection
- Toxicity assessment
- Material-property prediction
- Environmental monitoring
- Process optimization
- Automated experimental planning

The value of AI in sustainable chemistry lies not merely in prediction but in reducing unnecessary experimentation and directing resources toward the most promising chemical solutions. However, AI should be regarded as an enabling tool rather than a substitute for chemical knowledge. Experimental validation and chemical interpretation remain essential.

AI for Sustainable Reaction Development

1 Reaction Optimization

Chemical reactions are influenced by numerous variables, including temperature, pressure, catalyst loading, solvent, concentration, reaction time and reactant ratio. Conventional optimization can require a large number of experiments.

AI can treat reaction development as a multidimensional optimization problem. Instead of independently changing one variable at a time, algorithms can learn from previous experiments and propose new conditions. Potential benefits include improved reaction yield, enhanced selectivity, lower solvent consumption, reduced reaction time, lower energy requirements, reduced formation of side products and fewer experimental trials. Bayesian optimization and other data-driven approaches are particularly useful when experiments are expensive because they can balance exploration of new conditions with exploitation of promising ones. This approach changes the traditional experimental philosophy from **"Try → Observe → Adjust" to "Learn → Predict → Experiment → Learn again."**

Catalysis is one of the most important strategies for sustainable chemical production. An effective catalyst can increase reaction efficiency while potentially lowering energy requirements and improving selectivity. AI can assist catalyst development by correlating catalyst structure with catalytic performance.

A general computational relationship can be represented as

Catalyst Structure + Reaction Conditions → Activity + Selectivity

Machine-learning models can screen large numbers of candidate catalysts before experimental synthesis. Computational datasets generated through quantum-chemical calculations can also be combined with experimental observations. Potential applications include heterogeneous catalysis, homogeneous catalysis, photocatalysis, electrocatalysis, biocatalysis, hydrogen-production catalysts, CO_2 conversion catalysts and catalysts based on more abundant elements.

AI for Safer Chemical and Solvent Design

The choice of chemical substances is a fundamental sustainability decision. AI can assist researchers in predicting properties such as toxicity, biodegradability, persistence, bioaccumulation, volatility, solubility, thermal stability and environmental behaviour. This enables a shift from testing safety after synthesis toward considering safety during molecular design.

1 Green Solvent Selection

Solvents frequently constitute a substantial component of chemical processes. Their environmental impact can arise from toxicity, volatility, energy-intensive recovery and waste generation. AI-based models can compare solvent candidates using multiple properties simultaneously. This can support the selection of safer alternatives while maintaining the required chemical performance. Potential sustainable solvent systems include water-based systems, bio-derived solvents, deep eutectic solvents, solvent-free approaches and recyclable solvent systems. The integration of AI with green-solvent development can reduce the experimental effort required to evaluate large solvent spaces.

AI and Sustainable Materials

Materials science provides another major opportunity for AI-enabled sustainability. The development of a new material generally requires optimization of several properties simultaneously. A material may

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

need high mechanical strength, thermal stability, conductivity, durability or adsorption capacity while also being affordable and environmentally acceptable.

AI can identify relationships between structure, processing, properties and performance. Applications include biodegradable polymers, recyclable materials, bio-based composites, membranes, adsorbents, battery materials, fuel-cell materials, photocatalysts and carbon-capture materials. Instead of experimentally synthesizing every possible material, researchers can use AI to prioritize candidates for laboratory investigation, thereby reducing unsuccessful experiments and accelerating material discovery.

AI for Carbon Management

Reducing atmospheric carbon emissions requires technological solutions for both emission reduction and carbon utilization. AI can contribute through carbon-capture modelling, prediction of adsorption behaviour, screening of solvents and materials, catalyst selection for CO_2 conversion, process optimization and life-cycle comparison of alternative technologies. The combination of AI with materials modelling and process optimization may accelerate the development of more efficient carbon-management systems.

AI in Green Hydrogen and Energy Chemistry

The transition toward low-carbon energy requires improved technologies for hydrogen production, energy storage and conversion. AI can support research on water-splitting catalysts, electrolyzers, fuel cells, hydrogen-storage materials, battery materials, solar-energy conversion, electrochemical systems and energy-storage optimization.

AI models can predict relationships between catalyst composition and electrochemical performance, allowing researchers to focus experimental efforts on promising candidates. Similarly, AI can optimize operating conditions in electrochemical systems, potentially improving efficiency and reducing resource consumption.

AI for Waste Valorization and Circular Chemistry

Sustainable chemistry must address the entire life cycle of chemical products. The conventional linear model can be represented as Raw Materials → Production → Consumption → Waste. Circular chemistry aims to transform this into Raw Materials → Production → Use → Recovery → Reprocessing → New Product.

AI can support waste-stream classification, prediction of waste composition, chemical recycling, and biomass valorization, recovery of valuable metals, wastewater treatment, plastic-waste processing and identification of high-value products from waste materials. Thus, AI can help shift the chemical industry from waste management toward waste valorization.

AI in Analytical and Environmental Chemistry

Analytical chemistry produces complex datasets through UV–Visible spectroscopy, infrared spectroscopy, Raman spectroscopy, NMR spectroscopy, mass spectrometry, chromatography and electrochemical analysis. AI can identify patterns in these datasets and support rapid chemical identification and quantitative analysis. Potential applications include automated spectral interpretation, pollutant detection, process monitoring, quality control, chemical fingerprinting, environmental surveillance and prediction of analytical parameters. For sustainable chemistry, AI-assisted analysis can reduce sample preparation, reagent use and repeated measurements. AI-supported environmental monitoring can also provide faster identification of pollutants and process deviations.

AI and the Principles of Green Chemistry

Green Chemistry Principle	Possible Contribution of AI
Prevention	Prediction and minimization of waste
Atom Economy	Identification of efficient reaction pathways
Less Hazardous Synthesis	Prediction of hazardous intermediates and conditions
Designing Safer Chemicals	Molecular toxicity prediction
Safer Solvents	Computational solvent screening
Energy Efficiency	Optimization of temperature, pressure and reaction time
Renewable Feedstock	Identification of suitable biomass-derived resources
Reduce Derivatives	Route optimization
Catalysis	Catalyst discovery and performance prediction
Design for Degradation	Prediction of degradation behaviour
Real-Time Analysis	Intelligent process monitoring
Inherently Safer Chemistry	Hazard and risk prediction

AI can support several green-chemistry objectives simultaneously. Nevertheless, AI does not automatically make a chemical process green. Sustainability must be assessed using appropriate chemical, environmental and life-cycle criteria.

AI-Enabled Autonomous Laboratories

A particularly important future development is the integration of AI with robotics and automated analytical systems. A closed-loop laboratory can operate through the cycle: **Data Collection → AI Prediction → Experimental Design → Automated Experiment → Analytical Measurement → Data Feedback → New AI Prediction.** Such systems can support reaction optimization, catalyst discovery, materials development, pharmaceutical synthesis, electrochemical research and sustainable process development. The development of AI-enabled autonomous laboratories could reduce repetitive experimental work and accelerate chemical discovery.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Life-Cycle Thinking and AI

A chemical process cannot be considered sustainable solely because it produces less waste in the laboratory. A broader assessment should consider the complete pathway from raw material through synthesis, manufacturing, transportation and use to recovery or disposal. AI can assist life-cycle assessment by analysing large datasets and estimating environmental impacts. Relevant indicators may include greenhouse-gas emissions, energy consumption, water demand, resource utilization, toxicity, waste generation and recyclability. The integration of AI with life-cycle assessment could allow sustainability to become an optimization criterion rather than an evaluation performed only after a process has been developed.

Major Challenges

1 Data Quality

Chemical AI models are strongly dependent on the quality of their training data. Missing measurements, inconsistent experimental conditions and differences between laboratories can reduce model reliability.

2 Model Interpretability

Highly complex models may provide accurate predictions without clearly explaining the chemical reasoning behind them. For chemists, understanding why a model predicts a particular result can be as important as the prediction itself.

3 Experimental Validation

Computational predictions must be tested experimentally. A model trained on historical data may perform well computationally but fail when applied to unfamiliar chemical systems.

4 Computational Sustainability

AI itself consumes computing resources and energy. Therefore, an AI-based solution should not be called sustainable without considering its computational footprint.

5 Scale-Up

A successful laboratory experiment does not guarantee successful industrial implementation. Heat transfer, mass transfer, equipment design, safety and economic feasibility become important at larger scales.

6 Interdisciplinary Skill Requirements

Effective application of AI to chemistry requires collaboration among chemists, data scientists, chemical engineers, environmental scientists and AI specialists.

Responsible AI for Sustainable Chemistry

The objective should not be simply to increase the use of AI in chemistry. Instead, AI systems should themselves be developed according to principles of responsible innovation. Important requirements include transparent model development, high-quality and standardized datasets, reproducible workflows, experimental validation, consideration of computational energy consumption, appropriate data governance, human oversight, life-cycle assessment and cross-laboratory testing.

The future objective should therefore be Responsible **AI + Green Chemistry + Life-Cycle** Thinking rather than AI adoption alone.

Relevance to Viksit Bharat @2047

India's vision of Viksit Bharat @2047 is linked with long-term economic development, technological advancement, innovation, sustainability and human-capital development. AI-enabled sustainable chemistry can contribute to this vision through cleaner chemical manufacturing, sustainable pharmaceutical production, renewable-energy technologies, circular economy practices, sustainable agriculture and indigenous innovation. AI can optimize industrial processes to reduce energy use, raw-material consumption, waste and emissions. India's pharmaceutical sector could benefit from AI-based reaction optimization, solvent selection, route design and waste reduction. AI-assisted catalyst and material discovery can support hydrogen, electrochemical and energy-storage technologies. AI can improve waste classification, chemical recycling and recovery of valuable resources. It can also support controlled-release fertilizers, safer agrochemicals, soil-management technologies and biodegradable agricultural materials. India-specific chemical datasets and computational platforms could help researchers develop technologies suited to Indian feedstocks, industrial processes and environmental conditions.

Proposed Framework for India

A strategic framework for AI-driven sustainable chemistry can be developed as follows:

1. Identify a Sustainability Challenge
2. Collect and Standardize Chemical Data
3. Develop AI/ML Model
4. Predict and Optimize Chemical Solutions
5. Experimentally Validate the Prediction
6. Evaluate Environmental and Economic Performance
7. Scale Up the Technology
8. Integrate Circularity and Life-Cycle Thinking
9. Industrial and Societal Implementation

This framework ensures that AI is not treated as an isolated computational tool but as part of a complete sustainable innovation pathway.

Future Perspectives

1 Generative AI for Molecular Design

Generative models may increasingly assist in designing molecules with targeted properties such as high performance, low toxicity and improved degradability.

2 AI–Quantum Chemistry Integration

Combining machine learning with quantum-chemical calculations could improve prediction of molecular and catalytic behaviour while reducing computational costs.

3 Digital Twins for Chemical Processes

Digital representations of industrial chemical processes could allow researchers to simulate alternative operating conditions before implementing them physically.

4 Autonomous Sustainable Chemistry

AI-controlled laboratories may eventually select experiments, perform them using robotic systems,

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

analyse the results and independently propose subsequent experiments.

5 Circular Chemical Intelligence

Future AI systems may optimize not only individual reactions but entire material cycles, including production, use, and recovery and recycling.

6 India-Specific AI Chemistry Platforms

India could develop open and standardized databases covering Indian biomass resources, industrial by-products, waste streams, indigenous minerals, environmental contaminants, sustainable materials and chemical manufacturing processes.

Research Gaps

- Development of standardized sustainability-focused chemical datasets.
- Greater availability of experimentally validated AI models.
- Integration of environmental indicators directly into AI optimization.
- Improved interpretability of chemical AI models.
- Cross-laboratory and cross-instrument validation.
- Better assessment of AI's own energy and environmental footprint.
- Industrial-scale validation of AI-generated chemical solutions.
- Development of India-specific chemical datasets.
- Greater collaboration between chemistry, AI and engineering researchers.
- Integration of AI with life-cycle and techno-economic assessment.

Conclusion

Artificial Intelligence is creating a new opportunity to rethink the way chemical research and manufacturing are conducted. Its ability to process complex datasets, recognize chemical patterns, predict properties and optimize multiple variables can reduce dependence on conventional trial-and-error approaches. Applications in reaction optimization, catalyst discovery, solvent selection, sustainable materials, carbon management, green hydrogen, waste valorization and analytical chemistry demonstrate the broad potential of AI for sustainable chemistry. At the same time, limitations related to data quality, interpretability, validation, computational requirements and scale-up must be addressed before these technologies can achieve widespread industrial impact. For India, AI-enabled sustainable chemistry can become an important component of technological self-reliance and environmentally responsible industrial growth. The combination of India's chemical research capabilities, growing digital infrastructure, skilled scientific workforce and emerging AI ecosystem creates an opportunity to develop indigenous solutions for sustainable manufacturing, energy, materials and circular resource utilization. The vision of Viksit Bharat @2047 therefore provides a meaningful context for integrating AI with chemistry. The objective should not be merely to make chemical research faster, but to make it safer, cleaner, resource-efficient, economically viable and socially beneficial.

AI + Chemistry + Green Principles + Life-Cycle Thinking + Indian Innovation = Sustainable Chemistry for Viksit Bharat @2047

Acknowledgment

The author expresses sincere gratitude to all researchers, scientists, and academicians whose published studies and scholarly contributions provided valuable insights for the preparation of this review paper. Special thanks are extended to colleagues and mentors in the field of chemistry for their guidance and encouragement.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

1. Yadav, S., Chandra, H., Tiwari, K. S. et al. "A review on the role of artificial intelligence and data science in green and sustainable chemistry: current trends and futuristic pathways." Discover Chemical Engineering, 6, Article 1, 2026.
2. Elkhatat, A. & Al-Muhtaseb, S. A. "Harnessing Artificial Intelligence (AI) for a greener future: a review of AI advancements in green chemistry, chemical processes and sustainable materials." Applied Intelligence, 2026.
3. Ali, M., Mahmood, T. & Khan, F. "Review of artificial intelligence applications in sustainable chemical engineering." Discover Sustainability, 7, 1181, 2026.
4. Kurul, F., Doruk, B. & Topkaya, S. N. "Principles of green chemistry: building a sustainable future." Discover Chemistry, 2, 68, 2025.
5. NITI Aayog. DPI@2047 for Viksit Bharat: A Strategic Roadmap to Enable Non-linear Inclusive Socio-economic Growth. NITI Frontier Tech Hub, Government of India, 2026.
6. NITI Aayog. AI for Inclusive Societal Development: Roadmap on AI for Inclusive Societal Development. Government of India, 2025.
7. NITI Aayog. Reimagining Skilling for Viksit Bharat@2047. Government of India, 2026.
8. Ghasemlou, M. et al. "Artificial Intelligence (AI) for More Sustainable Chemistry and a Greener Future." ACS Sustainable Chemistry & Engineering, 2025.
9. Shields, B. J. et al. "Bayesian reaction optimization as a tool for chemical synthesis." Nature, 2021, 590, 89–96.
10. de Almeida, A. F. et al. "Synthetic organic chemistry driven by artificial intelligence." Nature Reviews Chemistry, 2019, 3, 589–604.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

A Study of Investment Preferences of Working Women in India

Rahul Prakash Udasi
Research Student, Department of Economics, Dr. Babasaheb Ambedkar Marathwada University, Chh. Sambhajinagr

Manuscript ID:
BN-2026-030937

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 195-198

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22916614
DOI link: https://doi.org/10.5281/zenodo.22916614

Abstract

In recent years, the participation of women in the workforce in India has significantly increased, leading to greater financial independence and decision-making in economic policy. This research study examines the evolving trends in investment preferences among working women in India. It explores factors influencing their investment decisions, preferred financial instruments, risk tolerance, and awareness levels. The study highlights a shift from traditional savings methods to diversified investment portfolios, such as mutual funds, stocks, equities, bonds and digital financial platforms.

Keywords: *investment, return, profit, risk, financial literacy, growth, saving interest rate*

Introduction

The economic empowerment of women in India has transformed their role from passive savers to active investors. Traditionally, Indian women always preferred safe investment avenues such as gold and savings bank accounts. They generally used this investment for her difficult time. But now with increased education, financial literacy, financial awareness and digital access, their investment behavior is undergoing a significant transformation. In this modern and digital generation women want to actively participate in all economic activities such as workforce, education, politics, media, science and technology & become financially independent. Modern women are a hard taskmaster. She smartly balanced between a homely work & professional life. They are become financially independent now. They have more earning potential & more influence over their financial decisions than ever before. That is result as her increasing literacy rate and participation in workforce. But in society women's income is always considered as a supplementary income within the family. Because it is universally considered as women and children in the family are consumers and not producers. generally, women investment preferences have diversified with passing of time. There are various investment options available for working women such as mutual funds, shares, insurance, children education plan, bank savings, gold, real estate, post services etc. That all investment option has different objectives such as profit, security, appreciation, income stability. Though their investment decisions depend upon the various parameters such as degree of their risk-taking capability, return scale, influence of family members and friends, their income, expenditure, savings, awareness and knowledge about various investment instruments. hence, the Investment behavior of each working women is different due to many factors as safety associated with investment, regular flow of income, tax saving benefits, security of job, retirement benefits etc. But to make a correct investment decision they should be aware about various investment plans & their financial needs.

Creative Commons *(CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Rahul Prakash Udasi, Research Student, Department of Economics, Dr. Babasaheb Ambedkar Marathwada University, Chh. Sambhajinagr
Email: rahuludasi93@gmail.com

How to cite this article:
Udasi, R. P. (2026). A Study of Investment Preferences of Working Women in India. Bulletin of Nexus Journal, 3(9(II)), 195–198. https://doi.org/10.5281/zenodo.22916614

Quick Response Code:

Website: https://bnir.us

So here in this present research paper make focus on define the traditional and modern investment option for working women in India and also define the various factor that affect her investment decision.

Meaning of Investment

Investment is traditionally defined as the commitment of resources into something expected to gain value over time. The motive of invest is always for earning something more extra amount on basic principle amount. Simple it meaning as If an investment involves money, then it can be defined as a commitment of money to receive more money later. In finance the purpose of investing is to generate an additional return on the invested asset. The return on invested asset may be consist of a capital gain (which mean as profit) or capital loss realised if the investment is sold unrealised capital appreciation (or depreciation) if yet unsold.

There are two types of investment decision one is risky investment which have high return possibility and second is low risky investment with low but fixe return possibility. Investors generally expect higher returns from their riskier investments. When a low-risk investment is made the return is also generally low. Similarly, high-risk investment comes with a chance of high losses. But the investor always trays to invest in both type of investment option that known as rational portfolio management investment decision.

Investment Options

There are several types of investment option available for working women in India. But here describes some impotent investment option according to economic point of view. so, there are two types of investment option available for working women in India which describe as below.

I) Traditional Investment Options

Traditional investment options for women in India prioritize security, liquidity and steady returns often favored by conservative investors. If we rank the Indian women's investment option what they preferred, we find that they have top choices which describe as below.

- **Fixed Deposits (FDs):** A special saving schemes tailored for women's which have, high-liquidity option offered by banks, ideal for risk-averse investors seeking predictable, guaranteed interest (ranging between 0.05% to 0.50 %) payments and it including monthly income options too.
- **Gold (Physical):** A highly favoured traditional investment practiced by all age groups of women, which providing high security and hedge against price inflation, available through jewellery or coins. It is one of the most favourite investment options for women and it use most of the time by working women.
- **National Savings Certificate (NSC):** A highly secure provide by institute, low-risk, it gives five-year savings plan via post offices, offering guaranteed returns (approximate 7.5% per annum) and provide tax benefits under Section 80C in NSC has minimum investment limits from Rs 1000 to 2 lakh.
- **Post Office Savings Account/RD:** This investment option is most famous in India especially rural area. RD account uses that rural woman for regular small saving to her emergency need purpose. This investment option is excellent for small investment purpose. It has a disciplined savings with high safety returns for short-to-medium term goals.

That all above are the primary traditional investment options in India which working women used for investment purpose.

II) Modern Investment Options

Modern investment options for women in India focus on high safety, tax efficiency and wealth growth, featuring instruments like Public Provident Fund, Sovereign Gold Bonds (SGBs) for digital gold etc. all modern investment option are available in India are describe below.

- **Public Provident Fund (PPF):** This is a safe and zero risk investment option available for woman. This investment option is back by government. This investment use for long-term at least 15-year investment scheme which offering competitive interest rates (approx. 7.1% per annum) and it also provided tax-exempt status under Section 80C of income tax return. So, this scheme is very important for women as saving option and tax-exempt option.
- **Sukanya Samriddhi Yojana (SSY):** A government-backed scheme stands as the most rewarding for a girl child is born until she reaches 10 years age. It saving schemes offering higher interest rates than PPF. The investment instrument perfect for education purpose and girl child marriage goals. This scheme is for a government scheme specifically for a girl child's future and it featuring higher interest rates (e.g., 8.2 %) and Section 80C tax benefits.
- **Mutual Funds (SIPs):** A systematic investment plan (SIP) allows women with a moderate-to-high risk appetite to invest in equity, debt, or hybrid funds, offering professional management and high growth potential but it has more risk compare with other.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- **Sovereign Gold Bonds (SGBs) and Digital Gold**: This is Modern investment options, which gives safer alternatives to hold physical jewellery as investment. This government schemes providing returns on gold prices plus a fixed interest rate (for SGBs) without storage costs.
- **National Pension System (NPS):** This investment scheme is a market-linked scheme. It has a low-cost retirement savings account that offers flexibility to invest in equity and debt with extra tax benefits. It helpful investment option for retirement purpose for working woman.
- **Fixed Deposit (FDs) with Corporate Deposit:** This investment scheme offers high safety to woman for her saving. It gives guaranteed returns and flexibility facility to investor. It can withdrawal her amount according to need and also choose her investment plan as per her capacity. some banks providing higher interest rates for women within this investment option.
- **Real Estate Investment Trusts (REITs):** A modern avenue allowing investment in commercial real estate without buying property and also it providing steady income through dividends too. So, it also a provide safety about future.

That all above are the modern investment options in India which working women used for investment purpose. But for using this modern investment option the women should have financial literate and also, she has basic digital tool for connecting online investment platform.

Role of Financial Literacy

Financial literacy is the ability to understand and use personal finance skills like budgeting, saving, investment and managing debt. Financial literacy in Indian women is crucial for fostering economic independence, boosting confidence, and driving national growth. It enables informed decisions on budgeting, investing and debt management, allowing women to secure their future and build assets. Since independence we make progress in many sectors progress but the ratio of financially literate women in India are still very low. That's why its highlighting a need for improved financial education in India.

Impact of Financial Literacy:

- Financially literate women make independent decisions about her future. By taking decision, she reducing reliance on male family members and breaking societal stereotypes.
- When a women have financial knowledge then she starts her businesses at higher rates, manage businesses better and contribute to GDP growth.
- Knowledge of investments helps women build long-term wealth, manage inflation and secure their retirement.
- Women who understand budgeting are better equipped to handle financial emergencies and optimize household savings.
- Financial education improves women's capability to use formal credit markets, reducing reliance on high-interest loans.

Conclusion

Educating women on financial matters not only secures their personal lives but also has a significant, positive impact on the overall economic landscape of India. Financial literacy plays a crucial role in shaping investment behavior. Women with better financial knowledge tend to various investments plans which help the women to select investment option according to her need. When women are financially literate, they Use digital platforms efficiently for making the investment. Working women in India are becoming financially independent and more aware of investment opportunities. While traditional investment avenues still dominate, there is a clear shift towards modern and diversified financial instruments. Enhancing financial literacy and accessibility can further strengthen their participation in investment activities.

Acknowledgment

I would like to express my sincere gratitude to all those who supported and encouraged me in completing this research paper entitled "A Study of Investment Preferences of Working Women in India." First and foremost, I am deeply thankful to my respected research guide, teachers, and the Department of Economics for their valuable guidance, constructive suggestions, and continuous encouragement throughout the preparation of this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

Reference:

1. Vohra, T. & Kaur, M. (2017). Women investors: A literature review. Metamorphosis
2. Jain, P.A. & Ashalatha, K. (2026). Closing the confidence gap: A behavioral finance perspective on women's equity-market participation in India. Indian Journal of Finance

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

3. Paramashivaiah, P., Puttaswamy, S. & Reddy, S.K. (2014). Changing risk perception of women investors: An empirical study. Indian Journal of Finance
4. Barber, B.M. & Odean, T. (2001). Boys will be boys: Gender, overconfidence, and common stock investment. Quarterly Journal of Economics
5. making in India. Research Journal of Finance and Accounting
6. 12. Jagongo, A. & Mutswenje, V. (2014). Factors influencing investment decisions. International Journal of Humanities and Social Science
7. 13. Xia, T., Wang, Z. & Li, K. (2014). Financial literacy and stock market participation. Social Indicators Research
8. 14. Hung, A., Yoong, J. & Brown, E. (2012). Empowering women through financial education. OECD Working Papers.
9. 15. Lusardi, A. & Mitchell, O.S. (2014). The economic importance of financial literacy. Journal of Economic Literature
10. 16. Reserve Bank of India (2024). Report on household financial savings.
11. 17. SEBI (2023). Investor survey report on financial literacy in India.
12. 18. AMFI (2025). Annual Mutual Fund Report.
13. 19. World Bank (2022). Gender equality and financial inclusion report.
14. www.wikipedia.com

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI-Driven Green Chemistry for Sustainable Development: A Comprehensive Review Towards Viksit Bharat @2047

Sourabh Mahadev Wagare
Assit. Prof. department of Chemistry, Shripatrao chougule art and science college malwadi kotoli

Manuscript ID:
BN-2026-030938

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 199-205

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22916797
DOI link:
https://doi.org/10.5281/zenodo.22916797

Abstract

The escalating global demand for chemicals, materials, and energy has intensified concerns regarding resource depletion, hazardous waste generation, energy consumption, and environmental pollution. Green chemistry provides a sustainable paradigm by minimizing waste, reducing hazardous substances, improving energy efficiency, and promoting renewable resources. However, developing greener chemical processes traditionally requires extensive experimentation and optimization. Artificial intelligence (AI)—particularly machine learning (ML), deep learning, and predictive modeling—offers transformative opportunities to accelerate this transition. AI enables reaction prediction and optimization, catalyst discovery, green solvent selection, sustainable material design, toxicity prediction, waste minimization, and environmental monitoring by analyzing large chemical datasets and identifying relationships recognized through conventional approaches. Integration of AI with automation and advanced analytical techniques further enables faster, more efficient chemical research. This review discusses major applications of AI in green chemistry, emphasizing sustainable synthesis, catalysis, solvents, materials, waste management, energy technologies, and analytical chemistry. We address challenges associated with data quality, model interpretability, experimental validation, computational energy consumption, and industrial scale-up. Finally, we examine the potential of AI-driven green chemistry to support sustainable manufacturing, circular economy, resource efficiency, and technological innovation in India within the context of Viksit Bharat @2047. We conclude that integrating chemical expertise with AI provides a powerful pathway toward cleaner, safer, and more sustainable chemical technologies.

Keywords: *Artificial Intelligence; Green Chemistry; Machine Learning; Sustainable Chemistry; Catalysis; Green Synthesis; Circular Economy; Sustainable Development; Viksit Bharat @2047*

Introduction

Chemistry plays a central role in pharmaceuticals, agriculture, energy, materials, and industrial manufacturing. However, conventional chemical processes often consume large quantities of raw materials and energy while generating hazardous waste. Green chemistry addresses these challenges by designing chemical processes that prevent pollution at its source, guided by twelve principles emphasizing waste prevention, atom economy, safer chemicals and solvents, energy efficiency, renewable feedstocks, catalysis, and real-time pollution prevention. The development of greener processes traditionally relies on trial-and-error experimentation, which is time-consuming, resource-intensive, and often fails to identify optimal sustainable pathways. AI can support many green chemistry principles by enabling prediction, optimization, and data-driven decision-making across the chemical value chain. The convergence of AI and green chemistry therefore provides an opportunity to transition from conventional experimentation toward predictive, sustainable chemical research.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sourabh Mahadev Wagare, Assit. Prof. department of Chemistry, Shripatrao chougule art and science college malwadi kotoli
Email: sourabhwagare5839@gmail.com

How to cite this article:
Wagare, S. M. (2026). AI-Driven Green Chemistry for Sustainable Development: A Comprehensive Review Towards Viksit Bharat @2047. Bulletin of Nexus Journal, 3(9(II)), 199–205.
https://doi.org/10.5281/zenodo.22916797

Quick Response Code:

Website: https://bnir.us

Recent reviews highlight that AI is already reshaping how researchers pursue green chemistry, with applications spanning catalysis, CO_2 capture, sustainable materials, drug development, and waste control.

Role of AI in Green Chemistry

Machine learning and related AI techniques can process large volumes of chemical and experimental data to support diverse applications:

- **Reaction prediction and optimization** – ML models learn from prior experiments to predict promising conditions, reducing experimental burden.
- **Catalyst discovery** – AI predicts catalyst performance using molecular structure, electronic properties, surface characteristics, and reaction conditions.link.springer+1
- **Green solvent selection** – Data-driven pipelines assess solvent sustainability and identify greener substitutes with comparable performance
- **Molecular and material design** – Generative models design safer molecules and sustainable materials with optimized properties.
- **Toxicity prediction** – ML models estimate environmental, health, and safety hazards early in design.
- **Waste reduction** – AI optimizes processes to minimize waste and supports circular economy workflows.link.springer+1
- **Environmental monitoring** – AI-enhanced sensors enable real-time pollutant detection and water-quality assessment.pubmed.ncbi.nlm.nih+2
- **Process optimization** – AI integrates multi-objective optimization balancing yield, selectivity, energy, waste, and safety

AI evaluates multiple parameters simultaneously, allowing researchers to optimize chemical performance together with sustainability metrics such as E-factor, process mass intensity (PMI), energy consumption, and life-cycle impacts.

AI-Assisted Green Chemical Synthesis

1 Reaction Optimization

Traditional reaction optimization requires repeated experiments across temperatures, solvents, catalysts, concentrations, and reaction times. AI-based models learn from previous experimental results and predict promising reaction conditions, significantly reducing unnecessary experiments and chemical consumption.

A major advantage is **multi-objective optimization**, where yield is considered together with:

Yield+Selectivity+Energy Efficiency+Waste Reduction+Safety\text{Yield} + \text{Selectivity} + \text{Energy Efficiency} + \text{Waste Reduction} + \text{Safety}Yield+Selectivity+Energy Efficiency+Waste Reduction+Safety

Bayesian optimization and active-learning loops have demonstrated the ability to reduce chemical waste by approximately 18–35% and improve process efficiency by 20–35% in reported studies.

2 Retrosynthetic Planning

AI assists retrosynthetic planning by identifying synthetic routes requiring fewer steps, safer reagents, and less waste. Recent platforms integrate retrosynthesis with reaction optimization and closed-loop robotic automation, enabling end-to-end AI-driven synthesis.

Reproducible benchmarks such as step count, time-to-in vitro, and green metrics (E-factor, PMI) are increasingly emphasized to ensure translational relevance in medicinal and fine-chemical synthesis.

AI in Sustainable Catalysis

1 Catalyst Discovery and Design

Catalysts are fundamental to green chemistry because they reduce energy requirements and improve selectivity. AI predicts catalyst performance using information about molecular structure, electronic properties, surface characteristics, reaction conditions, and experimental performance.link.springer+1

Recent advances include ML-assisted development of two-dimensional (2D) green catalysts for pollutant and gas degradation. The overall ML workflow for catalyst discovery begins with data collection from literature, databases, and experimental sources, followed by cleaning, normalization, and preprocessing to ensure high-quality inputs.link.springer+1

In the model development stage, feature selection and engineering focus on key physicochemical properties and reaction conditions. Appropriate algorithms—ranging from black-box neural networks to interpretable gray- and glass-box models—are selected and validated. The resulting models enable accurate prediction of reaction pathways, catalytic activity, and optimal conditions, supporting iterative refinement of catalyst design.link.springer+1

2 Heterogeneous and Electrocatalysis

AI is transforming heterogeneous catalysis through AI-ready data ecosystems, multimodal foundation models, and autonomous laboratories. In energy catalysis, ML is increasingly used to rank catalysts and accelerate discovery, with emphasis shifting from static descriptors to operando-relevant representations, from offline prediction to closed-loop discovery, and from single-objective

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

activity optimization to sustainability-aware multi-objective optimization.pubs.rsc+2

For green hydrogen production via water splitting, ML approaches model heterogeneous catalysis with neural network potential energy surfaces that capture local chemical surroundings determining catalytic activity, yielding DFT-like accuracy for adsorbate energies.

3 Sustainability-Oriented Catalyst Design

Recent studies integrate ML with life-cycle assessment (LCA) frameworks to support sustainability-oriented catalyst design. In ML-LCA workflows, supervised learning models such as random forests, artificial neural networks, and gradient boosting are trained to predict environmental impact indicators—including greenhouse gas emissions, energy consumption, and material usage—derived from life-cycle inventory datasets.

An important future direction is the development of catalysts based on abundant, inexpensive, and less-toxic elements, aligned with circular economy and resource efficiency goals.

AI for Green Solvents and Sustainable Materials

1 Green Solvent Selection

Solvents can represent a major component of chemical processes. AI assists in identifying safer alternatives by comparing properties such as toxicity, volatility, solubility, biodegradability, and process performance.

Existing methods for estimating solvent sustainability rely on Solvent Selection Guides (SSGs), which assign scores based on environmental, health, and safety criteria. However, identifying greener alternatives within limited SSG pools is challenging due to conflicting criteria such as sustainability, cost, and performance. To address these limitations, data-driven pipelines have been developed for assessing solvent sustainability and identifying greener substitutes. Three models—Gaussian Process Regression (GPR), fine-tuned GPT, and GPT with in-context learning—were trained and evaluated on the GlaxoSmithKline Solvent Sustainability Guide (GSK SSG) to predict "greenness" metrics. GPR slightly outperformed language-based GPT models and was used to evaluate 10,189 solvents, forming **GreenSolventDB**—the largest public database of green solvent metrics. These predictions are combined with Hansen solubility parameter-based metrics to identify greener solvents with solubility behavior similar to hazardous solvents.

2 Sustainable Materials Design

AI is increasingly valuable for designing:

- Sustainable polymers
- Nanomaterials
- Battery materials
- Photocatalysts
- Adsorbents
- CO_2-capture materials

Instead of synthesizing thousands of candidates experimentally, researchers use AI to prioritize the most promising materials, accelerating discovery while reducing waste.

Generative ML is used to design safer alternative industrial chemicals with required functionality and lower life-cycle hazards, supporting green substitution strategies.

AI for Waste Management and Circular Chemistry

1 Waste-to-Value Pathways

Green chemistry aims to prevent waste, while circular chemistry focuses on keeping materials and resources in productive use. AI supports workflows from waste identification to conversion into valuable chemicals or products for reuse:

Waste→Identification→Conversion→Valuable chemical/product→Reuse\text{Waste} \rightarrow \text{Identification} \rightarrow \text{Conversion} \rightarrow \text{Valuable chemical/product} \rightarrow \text{Reuse}Waste→Identification→Conversion→Valuable chemical/product→Reuse

Applications include plastic recycling, agricultural-waste valorization, industrial waste reduction, and recovery of useful chemical resources.link.springer+1

AI is integrated into reuse and circularity workflows, primarily through vision and spectroscopy classifiers that sort plastics in mixed waste streams. Models estimate property retention over recycling cycles to guide decisions on remelting, reinforcement, or diversion to other uses.

2 Agricultural Biomass Valorization

Agricultural biomass can serve as a renewable source of chemicals, biofuels, polymers, and carbon-based materials. India generates over 500 million tonnes of agricultural waste annually, much of which is lignocellulosic biomass rich in silica, calcium, potassium, and carbon elements favorable for catalytic applications.nature

Recent studies highlight the valorization of abundant agro-wastes such as rice husk (up to 20% silica), coconut shell (74%–78% fixed carbon), sugarcane bagasse (45%–55% cellulose), and tamarind seed (rich in polysaccharides and carbon) as cost-effective and sustainable catalysts. Agro-waste-derived catalysts exhibit high performance, achieving over 90% conversion in transesterification, efficient alcohol oxidation under mild conditions, and up to 98% dye degradation (e.g., methylene blue) within 60–90 minutes.nature

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

AI-assisted catalyst design, combined with life-cycle assessments, indicates a potential reduction of up to 40% in greenhouse gas emissions, supporting the transition to a circular, low-carbon chemical economy.nature

AI in Analytical and Environmental Chemistry

1 AI-Enhanced Spectroscopy

AI combined with spectroscopy and analytical chemistry enables rapid chemical identification and quantitative analysis. Potential applications include:

- UV–Visible spectroscopy
- FTIR spectroscopy
- Raman spectroscopy
- NMR spectroscopy
- Mass spectrometry

Machine learning identifies patterns in complex spectral data and supports automated chemical analysis. Artificial intelligence is transforming vibrational spectroscopy by automating calibration, feature extraction, and interpretation across Raman, infrared, near-infrared (NIR), and hyperspectral imaging (HSI) systems. Raman spectroscopy and AI are used for microplastics detection, with CNN-based classification producing fast and highly selective polymer fingerprinting.

2 Environmental Pollutant Detection and Water-Quality Monitoring

AI-enabled sensors support real-time detection of environmental pollutants and water-quality monitoring. Recent advances include:

- **Trace organic pollutants in water** – ML-based spectral detection methods enable rapid, sensitive, large-scale, real-time, and on-site detection of trace organic pollutants, addressing limitations of traditional methods.pubmed.ncbi.nlm.nih+1
- **AI-powered rapid water testing systems** – Next-generation systems integrate capacitance, resistance, UV, IR, and Raman spectroscopy with embedded AI models to assess water quality within seconds, detecting heavy metals, synthetic dyes, microplastics, and pathogens.pubs.rsc+1
- **Hyperspectral imaging and drones** – AI-driven hyperspectral imaging identifies specific pollutants in water bodies with up to 95% accuracy, exceeding traditional sampling methods. Drone-based systems provide continuous, real-time data for early warning of contamination episodes.sciencepublishinggroup+1
- **Intelligent sensors with edge computing** – AI-enhanced fluorescence, electrochemical, and Raman spectroscopy-based sensors analyze signals directly in the field for near real-time water quality assessment, rapidly identifying multiple pathogens or discriminating harmful algal species with high accuracy.pubmed.ncbi.nlm.nih+1

Real-time monitoring is particularly relevant to green chemistry because it helps prevent pollution rather than treating it after formation.

Challenges

Despite its potential, AI-driven green chemistry faces several challenges:

1 Data Quality and Standardization

- Poor-quality or incomplete chemical datasets
- Lack of standardized experimental data and metadata
- Need for FAIR (Findable, Accessible, Interoperable, Reusable) data principles

2 Model Interpretability and Trust

- Limited interpretability of complex AI models
- Need for explainable, uncertainty-aware models tailored to chemical contexts
- Importance of cross-laboratory validation and reproducibility

3 Experimental Validation and Scale-Up

- Need for robust experimental validation
- Difficulty in industrial scale-up and technology transfer
- Gaps between academic models and industry requirements

4 Computational Energy and Ethics

- Computational energy consumption and carbon footprint of AI training
- Data ownership, intellectual property, and ethical governance concerns
- Need for sustainability-aware AI that accounts for its own environmental impact
- Therefore, AI predictions must be combined with chemical knowledge, uncertainty quantification, and experimental verification to ensure reliability and trust.

AI-Driven Green Chemistry Towards Viksit Bharat @2047

1 Strategic Importance for India

For India, AI-driven green chemistry can contribute to sustainable development through:

- Cleaner chemical manufacturing with reduced waste and emissions
- Development of indigenous catalysts and sustainable materials
- Green hydrogen technologies and CO_2 capture/utilization
- Waste-to-value technologies and circular economy development
- Sustainable agricultural chemicals and bio-based products

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- Environmental monitoring and regulatory compliance
- Technological self-reliance and innovation in high-impact sectorssribdc

India's policy landscape is increasingly supportive. NITI Aayog's "Scenarios Towards Viksit Bharat and Net Zero" highlights emission-intensive materials including chemicals, while CEEW's "Building a Green Economy for Viksit Bharat" emphasizes improving economic viability of green solutions through public procurement, blended finance, tax incentives, and viability gap funding.scribd

2 Priority Capability Pillars

2.1 National Green-Chemistry Data Infrastructure

Curated, standardized datasets for reactions, catalysts, solvents, life-cycle assessment (LCA), and toxicity, following FAIR principles, are essential for training reliable AI models and enabling cross-laboratory validation.

2.2 Trustworthy AI Models

Explainable, uncertainty-aware models tailored to Indian feedstocks, process conditions, and regulatory contexts will enhance adoption and trust among stakeholders.

2.3 Autonomous and Automated Laboratories

Closed-loop design–make–test–analyze platforms enable faster validation and scale-up, reducing time from discovery to deployment.

3 High-Impact Sectors for India

3.1 Agro-Chemicals and Bio-Based Chemicals

AI-guided routes from agricultural biomass to chemicals, biofuels, polymers, and carbon materials can leverage India's abundant agro-waste resources.nature

3.2 Pharmaceuticals and Fine Chemicals

Greener syntheses with reduced solvent hazard and waste, supported by AI retrosynthesis and solvent substitution, can enhance India's position as a global pharmaceutical hub.

3.3 Energy and Decarbonization

Green hydrogen, CO_2 capture/utilization, and electro/photocatalysis using AI-discovered catalysts and materials align with India's net-zero commitments.sciltp

3.4 Materials and Circularity

Sustainable polymers, battery materials, and recycling/value recovery from plastic and industrial wastes support circular economy development.

4 Policy and Ecosystem Enablers

- **Open platforms and standards** – Shared benchmarks, data schemas, and model cards for sustainability metrics.
- **Industry–academia testbeds** – Pilot-scale validation, techno-economic analysis, and LCA-integrated AI workflows.
- **Talent and interdisciplinary training** – Chemistry + AI/automation + LCA + process engineering to build a future-ready workforce.
- **Regulatory sandboxes and incentives** – Support for R&D, public procurement of green technologies, and blended finance mechanisms.scribd

5 Roadmap Towards Viksit Bharat @2047

A possible roadmap is:

AI→Green Chemical Innovation→Resource & Energy Efficiency→Circular Economy→Sustainable Industry→Viksit Bharat @2047\text{AI} \rightarrow \text{Green Chemical Innovation} \rightarrow \text{Resource \& Energy Efficiency} \rightarrow \text{Circular Economy} \rightarrow \text{Sustainable Industry} \rightarrow \text{Viksit Bharat @2047}AI→Green Chemical Innovation→Resource & Energy Efficiency→Circular Economy→Sustainable Industry→Viksit Bharat @2047

Intermediate milestones can include KPIs such as waste intensity, solvent hazard scores, energy per kg product, percentage of renewable feedstock, and recycling rates.

Future Perspectives

Future research should focus on:

1 Generative AI for Safer-by-Design Molecules

Generative models explicitly optimizing for low toxicity, biodegradability, and end-of-life considerations can enable safer chemical design from the outset.

2 AI-Guided Discovery of Green Catalysts

Emphasis on earth-abundant, low-toxicity catalysts, including 2D materials and bioinspired systems, will enhance sustainability and scalability.cambridge

3 Autonomous Chemical Laboratories

Closed-loop platforms integrating AI, robotics, and real-time analytics will accelerate discovery and reduce experimental burden.frontiersin

4 AI-Assisted Spectroscopy

Rapid, automated chemical analysis and monitoring using AI-enhanced spectroscopy will support real-time process control and environmental compliance.pubmed.ncbi.nlm.nih+1

5 Sustainable Materials Discovery

AI-driven design of sustainable polymers, battery materials, and CO_2-capture materials with integrated performance and sustainability metrics will advance circular economy goals.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

6 AI-Integrated Life-Cycle Assessment

Embedding LCA into AI workflows will ensure net sustainability gains and avoid burden-shifting across life-cycle stages.

7 Circular Chemical Manufacturing

Integration of Safe-and-Sustainable-by-Design (SSbD) principles from the outset will align chemical innovation with circular economy and pollution mitigation goals.

8 Indian Databases and Benchmarks

Development of Indian databases for sustainable chemistry—covering reactions, solvents, catalysts, and LCA—will reduce dependence on foreign data and improve model relevance to local contexts.

The future of green chemistry will likely involve close collaboration between chemists, AI systems, robotics, and advanced analytical technologies, supported by ethical AI governance and transparent data practices.

Conclusion

Artificial intelligence is emerging as a powerful tool for accelerating the transition toward sustainable chemistry. By supporting reaction optimization, catalyst discovery, solvent selection, material design, waste management, and analytical chemistry, AI can help reduce the environmental and resource footprint of chemical processes.

However, AI should complement—not replace—chemical expertise. Its successful application requires reliable data, explainable models, experimental validation, and life-cycle thinking. For India, the integration of AI with green chemistry can support cleaner manufacturing, technological self-reliance, circular economy, and sustainable innovation.

Thus, AI-driven green chemistry can become an important technological pathway toward sustainable development and the realization of Viksit Bharat @2047.

Acknowledgments

The authors thank [funding agencies, institutions, or collaborators] for support. The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support during the preparation of this review paper entitled "AI-Driven Green Chemistry for Sustainable Development: A Comprehensive Review Towards Viksit Bharat @2047." The author is especially thankful to the Department of Chemistry for providing an academic environment and the necessary support to undertake this work.

Conflict of Interest

The authors declare no conflict of interest.

Financial support and sponsorship

Nil.

Author Contributions

[Specify author contributions, e.g., conceptualization, literature review, writing, editing, etc.]

Selected References

1. Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*. Oxford University Press, 1998.
2. Shields, B. J. et al. Machine learning optimization of chemical reactions. *Nature* **2021**, *590*, 89–96.
3. Braconi, E. Bayesian optimization as a valuable tool for sustainable chemical reaction development. *Nature Reviews Methods Primers* **2023**.
4. Ghasemlou, M.; Pfeffer, F. M.; Barrow, C. J. Artificial Intelligence for More Sustainable Chemistry and a Greener Future. *ACS Sustainable Chemistry & Engineering* **2025**.
5. Bozal-Ginesta, C. et al. Machine learning for heterogeneous catalysis with experimental and computational data. *Nature Reviews Chemistry* **2025**.
6. Wang, H. et al. Using Machine Learning for Green Substitution of Industrial Chemicals. *Chemical Reviews* **2026**.
7. Elkhatat, A.; Al-Muhtaseb, S.A. Harnessing Artificial Intelligence (AI) for a greener future: a review of AI advancements in green chemistry, chemical processes and sustainable materials. *Springer* **2026**.link.springer
8. Gohr, C. et al. Artificial intelligence as a driver of sustainable materials and circularity. *Nature Reviews Materials* **2026**.
9. Yadav, S. et al. A review on the role of artificial intelligence and data science in green and sustainable chemistry: current trends and futuristic pathways. *Discover Chemical Engineering* **2025**.
10. Safe-and-Sustainable-by-Design and Digital Innovation Convergence for Pollution Mitigation. *IEES* **2025**.
11. NITI Aayog. *Scenarios Towards Viksit Bharat and Net Zero*. **2026**.scribd
12. CEEW. *Building a Green Economy for Viksit Bharat*. **2025**.
13. Chenchen, Q. et al. Catalytic applications of 2D materials aided by machine learning. *AI Materials* **2025**.cambridge+1
14. Machine Learning for Green Solvents: Assessment, Selection and Substitution. *PubMed* **2025**.link.springer
15. Transforming Indian Agro-Waste into High-Performance Green Catalysts: An AI-Driven

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Techno-Environmental Roadmap for Circular Chemistry. *PubMed* **2025**.nature
16. Advances and innovations in machine learning-based spectral detection methods for trace organic pollutants. *Analyst* **2026**.pubmed.ncbi.nlm.nih+1
17. AI-Based Rapid Water Testing System. *Cambridge Open Engage* **2026**.pubs.rsc
18. Roadmap for transforming heterogeneous catalysis with artificial intelligence. *Nature Catalysis* **2026**.pubs.rsc+1
19. AI-Accelerated Discovery of Electrocatalyst Materials. *PubMed* **2025**.pubs.rsc
20. Artificial Intelligence in Energy Catalysis: From Catalyst Screening to Sustainability-Aware Multi-Objective Optimization. *Sustainable Energy and Environment* 2026.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Role of E-Commerce in Enhancing the Performance and Market Reach of Small Businesses

Atish P. Waghchaure
Assistant Professor, SIES College of Commerce and Economics, Sion (East), Mumbai

Manuscript ID:
BN-2026-030939

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 206-210

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22916887
DOI link: https://doi.org/10.5281/zenodo.22916887

Abstract:
E-commerce has emerged as an important component of the modern business environment, providing small businesses with opportunities to overcome geographical limitations, access wider customer markets and improve their overall business performance. The rapid growth of digital platforms, online marketplaces, digital payments and social media commerce has transformed the way small businesses market, sell and deliver their products and services. However, despite these opportunities, small businesses continue to face challenges related to digital skills, cybersecurity, logistics, online competition, transaction costs and customer trust. Against this background, the present study aims to examine the role of e-commerce in enhancing the performance and market reach of small businesses. The study proposes to assess the extent of e-commerce adoption, examine its relationship with business performance and market reach, and identify the major challenges experienced by small businesses in adopting digital commerce. The study will employ a quantitative research approach and collect primary data from small-business owners/managers through a structured questionnaire. Descriptive statistics, reliability analysis, correlation and regression techniques will be used to analyze the collected data. The study is expected to provide insights into how e-commerce adoption can contribute to sales growth, customer acquisition, operational efficiency, geographical expansion and competitiveness among small businesses. The findings may also assist policymakers, business support institutions and small-business owners in developing strategies for effective digital adoption and sustainable business growth.

Keywords: *E-Commerce, Small Businesses, Digitalisation, Business Performance, Market Reach*

Introduction:

The Significant changes due to rapid digital growth has transformed the business environment and the way enterprises engage with customers. The increasing use of the internet, smartphones, digital payments, social media and online marketplaces has contributed to the rapid expansion of e-commerce. E-commerce enables businesses to promote, sell and deliver products and services through digital platforms, providing new opportunities for enterprises to expand their operations and reach a wider customer base. Small businesses play an important role in economic development through employment generation, entrepreneurship, income creation and local economic activity. However, they often face limitations such as restricted financial resources, high marketing costs, dependence on local customers and limited access to wider markets. In this context, e-commerce can provide small businesses with opportunities to overcome geographical barriers and connect with customers beyond their traditional markets. The adoption of e-commerce can influence business performance through increased sales, revenue, customer acquisition and operational efficiency.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Atish P. Waghchaure, Assistant Professor, SIES College of Commerce and Economics, Sion (East), Mumbai
Email: atishwagh1970@gmail.com

How to cite this article:
Waghchaure, A. P. (2026). Role of E-Commerce in Enhancing the Performance and Market Reach of Small Businesses. Bulletin of Nexus Journal, 3(9(II)), 206–210. https://doi.org/10.5281/zenodo.22916887

Quick Response Code:

Website: https://bnir.us

Online marketplaces, social media commerce, business websites and digital payment systems provide additional channels through which small businesses can promote their products and interact with customers. At the same time, e-commerce can enhance market reach by enabling businesses to access customers across different geographical locations and market segments.

Despite these opportunities, small businesses face several challenges in adopting e-commerce, including lack of digital skills, cybersecurity concerns, logistics problems, online competition, platform costs and customer trust issues. Therefore, the benefits of e-commerce may vary depending on the ability of businesses to effectively adopt and utilise digital technologies.

Against this background, the present study examines the role of e-commerce in enhancing the performance and market reach of small businesses. The study focuses on the extent of e-commerce adoption, its relationship with business performance and market expansion, and the major challenges faced by small businesses in adopting digital commerce. The findings are expected to provide useful insights for small-business owners, policymakers and other stakeholders in promoting effective digital adoption and sustainable business growth.

Objectives:

1. To assess the impact of e-commerce adoption on the performance of small businesses.
2. To examine the role of e-commerce in expanding the market reach of small businesses.
3. To analyse the relationship between e-commerce adoption and business performance of small businesses.
4. To identify the major challenges faced by small businesses in adopting e-commerce.

Review of Literature:

(Setiawan, 2023): This study used secondary data from 1,084 MSIs in Kalanganyar District, Central Java Province, Indonesia, and multiple linear regression (OLS) method as an analytical tool. The results show that e-commerce has a significant positive impact on financial performance of MSIs, as judged by income, gains, and return on assets (ROA).Firm size, reflected in the number of employees, moderates the impact of e-commerce on financial performance and has a moderating effect. This means that by adopting e-commerce as a resource to improve their customer base, brand awareness, and advertising, smaller MSI companies can experience higher financial performance gains than larger MSI companies. This study extends RBV theory to the role of e-commerce in improving the performance of MSI resources. The results also demonstrate the value of e-commerce techniques to enhance performance of governments and small and medium-sized enterprises (MSEs) and encourage e-commerce usage.

(Sharma, 2023): This article examines the positive impact of e-commerce on small and medium-sized businesses and explores how e-commerce adoption is proving to be a growth driver for these companies. Through an in-depth analysis of case studies, interviews, and industry reports, we show how e-commerce has opened new markets, increased revenue, streamlined operations, and expanded customer reach for small and medium-sized businesses. The introduction of e-commerce has enabled small and medium-sized businesses to compete on a level playing field with larger, more established companies. As the global e-commerce market continues to expand, small and medium-sized enterprises (SMEs) that have not yet adopted e-commerce risk being left behind.

(Feindt, 2002): This article focuses on the birth of the Internet economy. Examines the critical success factors that fast-growing e-commerce companies should consider during the start-up phase. Based on the results of the EU KITE project, this article shows the connections between critical success factors and highlights the competitive advantages that arise from the application of certain critical success factors. The KITE project compares the critical success factors identified for high-growth, early-stage e-commerce businesses with research on the success of high-growth businesses in general.

(Bharadwaj, 2007): As a result, the main elements of an e-commerce infrastructure include (1) information flow; (2) Organizational image. (3) Responding to customer needs. (4) Increase in sales. (5) Access to new markets. The number one reason companies don't pursue e-commerce is because they don't believe it's strategically important to their business. This paper describes research findings and policy recommendations related to geography, sales tax issues, human resources infrastructure, and Internet security issues.

(Wymer, 2005): The purpose of this study was to integrate these factors and determine their level of positive or negative influence on hiring decisions from the adopter's perspective. A set of 26 factors used as variables in different implementation models from the literature was presented in a neutral way, without prior classification as barriers or enablers, through a questionnaire sent to SMEs. Respondents were asked to rate the influence of these factors on their decision to transition to EEIT.

Research Methodology:

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

This study uses questionnaires and interviews to investigate the role of e-commerce in improving the efficiency and commercial scope of small and medium-sized enterprises. Data is collected to understand how small business owners and managers use online marketplaces, social media, digital payments, and other e-commerce platforms. To cover a diverse group of respondents, information such as industry, age in business, number of employees, and level of e-commerce adoption are also taken into account. The responses collected are analysed to identify patterns and relationships between e-commerce adoption, performance, and market expansion. The study also explores the main challenges faced by small and medium-sized enterprises when using e-commerce. Ethical principles will be observed to protect the privacy and confidentiality of respondents. The overall goal is to understand how e-commerce contributes to the growth, productivity and market reach of small and medium-sized enterprises, and to provide useful suggestions to improve its effective implementation.

Data Analysis & Interpretation:

Commerce Adoption and Business Performance

The given data is based on 100 small-business owners/managers.

Level of E-Commerce Adoption	Number of Respondents	Improved Business Performance	Percentage
Low Adoption	20	10	50%
Moderate Adoption	35	25	71.40%
High Adoption	45	38	84.40%
Total	**100**	**73**	**73%**

Explanation: The data from 100 small-business respondents reveals that business performance tends to improve with higher levels of e-commerce adoption. Among businesses with low e-commerce adoption, 10 (50%) reported improved business performance. In the moderate-adoption group, 25 (71.4%) reported improvement, while 38 (84.4%) of businesses with high e-commerce adoption reported improved performance. These findings indicate that businesses with greater adoption of e-commerce are more likely to experience improvements in sales, revenue, customer acquisition and operational efficiency. Thus, the findings support the objective that e-commerce adoption plays an important role in enhancing the performance of small businesses.

Commerce Adoption and Market Reach.

Level of E-Commerce Adoption	Number of Respondents	Expanded Market Reach	Percentage
Low Adoption	20	9	45%
Moderate Adoption	35	26	74.30%
High Adoption	45	40	88.90%
Total	**100**	**75**	**75%**

Explanation: The data indicates a clear difference in market reach according to the level of e-commerce adoption. Among businesses with low e-commerce adoption, 9 (45%) reported an expansion in their market reach. This increased to 26 (74.3%) among businesses with moderate adoption and to 40 (88.9%) among businesses with high e-commerce adoption. The findings suggest that greater use of e-commerce enables small businesses to reach customers beyond their traditional geographical markets, increase their customer base and access new market segments. Therefore, the findings support the objective that e-commerce contributes to expanding the market reach of small businesses.

Relationship between E-Commerce Adoption and Business Performance

Level of E-Commerce Adoption	Number of Respondents	Businesses Reporting Improved Performance	Percentage
Low Adoption	20	10	50%
Moderate Adoption	35	25	71.40%
High Adoption	45	38	84.40%
Total	**100**	**73**	**73%**

Explanation: The data indicates a positive relationship between e-commerce adoption and business performance. Among businesses with low e-commerce adoption, 10 (50%) reported improved performance. This increased to 25 (71.4%) among businesses with moderate adoption and 38 (84.4%) among businesses with high adoption. The findings suggest that businesses making greater use of e-

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

commerce are more likely to experience improvements in sales, revenue, customer acquisition and overall business performance. Therefore, the objective is **supported**, indicating a positive relationship between e-commerce adoption and business performance.

Major Challenges Faced by Small Businesses in Adopting E-Commerce

Major Challenge	Number of Respondents	Percentage
Lack of Digital Skills	24	24%
Online Competition	22	22%
Logistics and Delivery Problems	20	20%
Cybersecurity Concerns	18	18%
Platform and Transaction Costs	16	16%
Total	**100**	**100%**

Explanation: The data shows that lack of digital skills is the most commonly reported challenge, identified by 24 (24%) respondents. This is followed by online competition, reported by 22 (22%) respondents, and logistics and delivery problems, reported by 20 (20%). Cybersecurity concerns were identified by 18 (18%) respondents, while 16 (16%) reported platform and transaction costs as a major challenge. The findings indicate that although e-commerce provides significant opportunities for small businesses, businesses face several technological, operational and financial barriers in adopting and effectively using e-commerce.

Findings of the Study:

1. E-commerce adoption helps small businesses improve their overall business performance.
2. Small businesses using e-commerce are able to reach more customers beyond their local markets.
3. Higher e-commerce adoption is associated with better business performance and wider market reach.
4. Lack of digital skills is the major challenge faced by small businesses in adopting e-commerce.
5. Online competition, delivery problems, cybersecurity concerns and transaction costs are other important challenges.
6. Overall, e-commerce provides small businesses with opportunities to increase sales, attract new customers and expand their markets.

Limitations:

The study has certain limitations that should be considered while interpreting the findings. The study is based on a limited sample of 100 small-business respondents, which may not fully represent all small businesses. The data collected through questionnaires may also be influenced by the personal opinions and responses of the participants. The study focuses mainly on e-commerce adoption, business performance, market reach and related challenges, while other factors that may influence business growth are not considered. In addition, differences in the type, size and location of businesses may affect the results. Therefore, the findings should be interpreted within the scope of the study and may not be generalized to all small businesses.

Conclusion:

The study concludes that e-commerce plays an important role in enhancing the performance and market reach of small businesses. The findings indicate that greater adoption of e-commerce is associated with improved business performance, increased customer reach and opportunities to enter new markets. However, small businesses face challenges such as lack of digital skills, online competition, logistics issues, cybersecurity concerns and transaction costs. Overall, effective adoption and use of e-commerce can help small businesses increase sales, attract new customers and expand their market presence. Therefore, small businesses should focus on developing digital skills and effectively utilising e-commerce platforms to achieve sustainable business growth.

Acknowledgement

The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "Role of E-Commerce in Enhancing the Performance and Market Reach of Small Businesses." The author is especially thankful to the SIES College of Commerce and Economics, Sion (East), Mumbai, for providing a supportive academic environment and the necessary facilities to undertake this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Bharadwaj, P. N. (2007). E-commerce usage and perception of e-commerce issues among small firms: results and implications from an empirical study. Journal of small business management, 45(4),, 501-521.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

2. Feindt, S. J. (2002). Identifying success factors for rapid growth in SME e-commerce. Small business economics, 19(1), 51-62.
3. Setiawan, D. A. (2023). E-commerce and micro and small industries performance: The role of firm size as a moderator. Journal of Open Innovation: Technology, Market, and Complexity, 9(3), 100142., 1-10.
4. Sharma, S. (2023). Revving Up Growth: A Study of the Positive Impact of e-Commerce Adoption by SMEs. Scholedge International Journal of Business Policy & Governance.
5. Wymer, S. A. (2005). Factors influencing e-commerce adoption and use by small and medium businesses. Electronic markets, 15(4), 438-453.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Impact of Digital Business on Global Market: A Study

Dr. Dhanaji Baburao Ingawale,
Associate Professor, M. H. Shinde College Tisangi, Gaganbavada, Kolhapur,

Manuscript ID:
BN-2026-030940

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 211-215

Submitted: 08 Aug 2026

Revised: 18 Aug 2026

Accepted: 13 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22916919
DOI link:
https://doi.org/10.5281/zenodo.22916919

Abstract

Digital business transformation reshapes traditional operations by integrating modern tools like artificial intelligence and cloud computing to boost efficiency and create new customer value. Digital India improves public service delivery, boosts financial inclusion, and transforms the country into a digitally empowered economy. Systems like Unified Payments Interface and digital bank accounts connect millions of unbanked citizens to the formal financial network. Online portals make government paperwork fast, transparent, and paperless through platforms like Digital India and Digi Locker. Direct Benefit Transfers send subsidies straight to bank accounts, cutting out middlemen and stopping leaks. Digitalization is one of the most powerful development opportunities of our time. Connectivity, data, and digital tools are now essential to how hospitals deliver care, how farmers access markets, how teachers reach students, and how governments serve their citizens.

Keywords: *Digital Business, Marketing, Income, Transport, Global Market, Society, Producrion, Investment, Technology, Development etc.*

Introduction:

The human society is permanently changing in all aspects. It has experienced many challenges like wars, political conflicts, and financial systems collapse. Today it is hurt by an old well-known enemy the pandemic. To make the things better and even to survive current society is investing in market, production, communications and technological progress. The common base of all these fields is the digitalization on the Communication and Information Technology Since of the 20th Century the IT is in permanent development, but this has not impacted all layers of the society. In the last decade it is observed a new trend. The IT impacts almost all layers and the technologies of the society communications, productions, management, analysis, forecasts, education, health, social and medical security. This chapter is concentrated on the basics and tools of digital transformation of business and trends in the business and production in the frame of this new paradigm. In today's interconnected global economy, technology is transforming international business. Through technological innovations, businesses can now operate across the world with efficiency and precision, making the importance of technology in this arena undeniable. From advanced communication tools to AI-driven analytics, the role of technology includes bridging cultural and linguistic divides, creating opportunities for real-time collaboration across continents. For businesses aiming to expand their reach, digital innovation not only enhances operational efficiency but also ensures greater access to global consumers.

Problems of the Study:

The Digital Age is a challenge for companies. It has transformed the way companies interact with their customers, changing the processes and business models.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Dhanaji Baburao Ingawale, Associate Professor, M. H. Shinde College Tisangi, Gaganbavada, Kolhapur,
Email: idhanaji@gmail.com

How to cite this article:
Ingawale, D. B. (2026). Impact of Digital Business on Global Market: A Study. Bulletin of Nexus Journal, 3(9(II)), 211–215. https://doi.org/10.5281/zenodo.22916919

Quick Response Code:

Website: https://bnir.us

The digital disruption can change businesses according to digital transformations. With the development of digital technologies, the classical system of doing business has been disrupted and many companies must react to digitalization. The digital transformation brings innovations not only into the delivering of product. The companies are trying to rebuild a business approach to agile by using a new innovative business model. Digital transformation radically changes the way we live, work and treat one another.

Objectives of the Study:

The primary objective of this research is to study the impact of digital marketing and business activities on the global market; the researchers have outlined specific objectives as follows.

1. To Study the digital business.
2. To Study the global factors affecting digital business.
3. To Study the impact of technology on the global market.
4. To Study the digital marketing and the current scenario.

Significance of the Study:

Digital Transformation is the application of technology to build new business models, processes, software and systems that results in more profitable revenue, greater competitive advantage, and higher efficiency. Businesses achieve this by transforming processes and business models, empowering workforce efficiency and innovation, and personalizing customer experiences.

Scope of the Study:

Digital transformation has fundamentally altered global business management practices. This article analyses how digital technologies reshape global operations, coordination mechanisms, and competitive strategies. It highlights the integration of digital platforms, data analytics, and automation in managing international activities. The study demonstrates that digital transformation enhances global efficiency while introducing new managerial challenges related to cybersecurity and digital governance. Drawing on contemporary global business practices, the study highlights how firms adjust organizational structures, decision-making processes, and strategic priorities to respond effectively to external shocks.

Limitation of the Study:

The analysis underscores adaptability as a dynamic capability that enables multinational firms to maintain resilience, seize emerging opportunities, and mitigate international risks. It integrates sustainability principles with strategic internationalization decisions, emphasizing long-term value creation and stakeholder engagement. Economic, and operational risks and their implications for strategic decision-making. The study emphasizes proactive risk assessment and strategic diversification as key tools for managing uncertainty. The article argues that digitalization enables firms to reconfigure international strategies by reducing transaction costs and enhancing strategic agility. The article provides insights into how firms can develop context specific strategies to succeed in emerging economies.

Period of the Study:

To study the impact of digital business on the global market, the researcher has reviewed data from 2026.

Research Methodology:

Researchers have utilized various forms of secondary research to study the factors influencing digital marketing and relevant business aspects. This includes research papers, articles, general newspapers, audio-visual materials, books, annual reports, and other publications.

Research Method:

Researchers have completed the study using a descriptive analysis method to conduct a detailed examination of the impact of globalization on the digital marketplace, as well as business growth and development.

Results and Discussion:

The article also highlights the growing importance of financial risk management and compliance in an increasingly interconnected global economy. The article further examines how technological advancements and geopolitical uncertainties influence multinational strategies. By synthesizing theoretical insights with practical implications, this article contributes to a deeper understanding of how multinational enterprises navigate complexity while maintaining global competitiveness. The global business environment is increasingly influenced by digital technologies that transcend national boundaries. Digital platforms enable firms to coordinate activities across continents in real time, reshaping traditional management practices. Global business management now requires technological literacy alongside strategic insight. Firms that leverage digital tools effectively can optimize global value chains and enhance responsiveness to market changes. The digital economy has transformed the foundations of international business strategy. Digital platforms, analytics, and communication technologies enable firms to operate seamlessly across borders. As a result, traditional barriers to internationalization are diminishing, prompting firms to rethink strategic approaches to global

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

expansion and coordination, the integration of sound financial management practices into international business strategy will remain essential for sustainable global growth.

Marketing Effectiveness:

Local responsiveness, a tension that shapes organizational structures and decision-making processes. In recent years, rapid digitalization, sustainability concerns, and geopolitical shifts have further intensified the complexity of multinational operations. Understanding how MNEs adapt strategically to these evolving conditions is essential for scholars, managers, and policymakers seeking to enhance the effectiveness and resilience of global business operations. Cultural diversity influences managerial behaviour and employee interactions in international firms. Misunderstanding cultural norms can lead to conflict, while effective cross-cultural management enhances collaboration and performance. FDI represents a critical mode of internationalization, allowing firms to exert control over foreign operations. By investing abroad, companies gain proximity to customers and resources, enhancing competitiveness. However, investment decisions are influenced by political stability, regulatory frameworks, and cultural compatibility. Cultural differences influence purchasing decisions, communication styles, and brand loyalty. Recognizing these factors is essential for achieving marketing effectiveness in international markets.

Digital Technology:

Digital technology has allowed organizations to increase their product and service reach internationally. Businesses can seize the opportunity to enhance operational efficiency and acquire a competitive edge on a global scale by using technology. The widespread use of technology has shrunk the distance between companies and their consumers. The study's overarching goal is to ascertain how digital technologies have affected global trade. Discovering the uses, consequences, and risks related to digital technology adoption is the goal.

Digital Business:

Digital transformation is redefining global business management by increasing speed, connectivity, and transparency. However, successful implementation requires strategic alignment, managerial competence, and robust governance frameworks. As digitalization deepens, global managers must balance technological opportunities with emerging risks to achieve sustainable global performance, managers must cultivate adaptive capabilities that support innovation, responsiveness, and resilience. Future global success will depend on the ability of firms to continuously learn and recalibrate strategies in a rapidly shifting international environment. The article concludes that innovation-driven international business strategies enable firms to capture global knowledge advantages. Strategic integration of innovation across borders strengthens competitiveness and long-term international success. Firms that embed sustainability into global strategy achieve more resilient and responsible growth. The study concludes that alliances enhance international competitiveness when governed strategically. Firms that integrate alliances into their broader international business strategy gain flexibility and accelerated market access.

Digital Transformation:

Digital transformation is rapidly transforming how businesses operate and interact with customers, leading to a significant shift in the global economy. The widespread adoption of digital technologies such as the Internet of Things, Artificial Intelligence, and cloud computing drives economic change by enabling organizations to automate processes, streamline operations, and improve customer experiences. This blog will explore how digital transformation drives economic change and impacts businesses, consumers, and the broader economy. Digital transformation plays a critical role in overcoming challenges and promoting economic change by enabling organizations to become more efficient, agile, and customer-centric and by promoting greater access to information, services, and opportunities. It has effectively overcome several challenges that traditionally hinder economic growth and development.

Production and Efficiency:

Digital transformation is driving economic change in several ways, from increased productivity and efficiency to creating new business models and the rise of the gig economy. As digital technologies evolve and become more widespread, their impact on the global economy will likely become even more pronounced. Businesses and individuals must embrace this change and adapt to the new realities of a digitally driven world to stay ahead of the curve and succeed in the long term. By automating routine tasks, digital transformation helps businesses to streamline processes and work more efficiently, leading to increased productivity and improved bottom lines, driving economic growth. Digital transformation is driving new markets and industries, providing businesses with new sources of revenue and growth. Businesses now have a much larger customer base, regardless of geographic location, increasing competition and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

providing new opportunities for growth and expansion.

Digital Market and Economic Growth:

Digital transformation enables businesses to develop new products and services, which can help them differentiate themselves from competitors and capture new market share, leading to increased innovation, competitiveness, and economic growth. Digital transformation empowers entrepreneurship and drives innovation by providing access to cutting-edge technologies and expertise in emerging fields. Organizations that embrace digital transformation and invest in new technologies are better equipped to compete in the global economy and stay ahead of the curve. By driving efficiency, creating new markets, empowering entrepreneurship, and providing access to new customers, digital transformation is having a profound impact on economic change and fostering economic growth.

Global Market:

In today's rapidly changing global market, digital transformation has become a cornerstone for businesses aiming to maintain competitiveness and achieve sustainable growth. As technology continues to evolve, the role of digital transformation in shaping international business strategies has grown increasingly significant. This essay explores how digital transformation impacts modern international business strategies, the challenges and opportunities it presents, and the key considerations that businesses must navigate to leverage technology effectively.

E-Commerce and Digital Marketing:

The rise of e-commerce platforms and digital marketing strategies has transformed how businesses approach international markets. Digital transformation has enabled companies to reach a global customer base through online sales channels and digital advertising. E-commerce not only expands market reach but also provides businesses with valuable data on consumer preferences and behaviours. Social media, search engine optimization (SEO), and content marketing are key components of a digital marketing strategy that can be tailored to different international markets, helping businesses build brand awareness and customer loyalty globally.

Cultural Adaptation and Location:

Digital transformation also requires businesses to adapt their strategies to different cultural and regulatory environments. In international markets, one-size-fits-all approaches are rarely effective. Companies need to understand local preferences, cultural nuances, and regulatory requirements to succeed. This includes localizing digital content, tailoring product offerings, and adjusting marketing strategies to meet the needs of diverse customer segments. Digital tools can aid in this adaptation by providing insights into local consumer behaviour and enabling businesses to test and refine their strategies quickly.

Conclusion:

Digital transformation is not just a trend but a necessity for international businesses aiming to succeed in today's competitive landscape. By leveraging technology, businesses can enhance communication, optimize operations, and expand market reach. However, it also requires careful planning, investment, and adaptation to overcome challenges such as regulatory compliance, cultural differences, and high initial costs. Companies that effectively navigate these challenges and integrate digital strategies into their business models will be well-positioned to thrive in the digital age and capitalize on new growth opportunities in international markets.

Acknowledgement

The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "Impact of Digital Business on Global Market: A Study."

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Kumar et. al. (2026), The Study of Digital Marketing and Its Impact in the Business World, pp. 10-19.
2. Edubex (2026), The Role of Digital Transformation in Modern International Business Strategies, pp. 45-53.
3. Princy et. al. (2026), A Study on Impact of Digital Transformation on Business Model, pp. 30-39.
4. Yatish et. al. (2026), Assessing the impact of digital transformation capability for international market growth: the role of leadership support, pp. 721-728.
5. Namitha et. al. (2025), Digital Transformation in International Business: Opportunities and Risks, pp. 46-57.
6. Aidin et. al. (2024), Investigating the Impact of International Markets and New Digital Technologies on Business Innovation in Emerging Markets, pp. 716-724.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

7. Singh et. al. (2025), The role of digital transformation in the internationalization process: A synthesis and way forward, pp. 429-434.
8. Woramol et. al. (2023), A Study on the Impact of Digital Marketing on Business Practices, pp.75-83.
9. Priya et. al. (2023), A Study on Role of Digital Marketing on International Business with Special Reference to Chennai, pp. 63-72.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

A Brief Study of Tenets of Russian formalism

Dr. Bharat Arvind Tupere
Associate Professor, Department of English, Sant Rawool Maharaj Mahavidyalay, Kudal, Dist. Sindhudurg

Manuscript ID:
BN-2026-030941

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 216-219

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22916989
DOI link:
https://doi.org/10.5281/zenodo.22916989

Abstract

Literary criticism updtaed in the 20th century. From Plato to T. S. Eliot, critics were mostly poets who innovated in subject matters and poetic styles and expressed their opinions or theories. From New Criticism, it was a new beginning for critical approaches. Russian formalism is another aspect and different approach of New Criticism which was developed in Russia and had huge impact on Structuralism. Both New Criticism or Anglo-American Formalism and Russian Formalism shared some similar points but Russian Formalism was interested to make theory of narration. This research paper tends to make a brief study of all the tenets of this approach of literary Criticism and bring out important critics who had contributed significantly in the world of criticism.

Keywords: *Criticism, Russian Formalism, Defamiliarization, Narrative, Motivation*

Introduction:

This approach of recent literary theory regards as New Criticism, the text in itself. It stresses on the form of a text. The word formalism denotes to both Russian formalism and Anglo-American formalism i.e., New Criticism. One might say that formalism and New Criticism explore the same theme. Both doctrine of criticism regarded text as itself and there is nothing outside the text. Both aim to express what is especially literary in the text, and they reject the lamp of spirituality and views of Romanticism. But Russian formalism differs from New Criticism. Formalists were much more interested in method, and to establish a scientific basis for the theory of literature. The formalist studies well established before the 1917 Revolution in the Moscow Linguistic circle, founded 1915, and in Opojaz (the letters stands for 'The society for the study of poetic language), started in 1916. The leading figures of the former group were Roman Jakobson and Peter Bobagtyres, Viktor Shklovsky, Yury Tenynov and Boris Eikhenbaum were prominent in Opojaz.

Rationale of the Study:

The main objective of this paper is to understand the main ideas and tenets of Russian Formalism and how they help us study literature. It focuses on how writers use language, literary form, literary style, and literary techniques to make a work unique and meaningful.

Objectives:

1. To understand the contribution of Russian Formalism in literary criticism.
2. To bring out various ideas and theories about literature by critics of this approach of criticism.
3. To explore how Russian Formalist focused on the text rather than any background- biographical, social and so on.
4. To examine forms, language and literary techniques in literature.

Creative Commons (CC BY-NC-SA 4.0)
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Bharat Arvind Tupere, Associate Professor, Department of English, Sant Rawool Maharaj Mahavidyalay, Kudal, Dist. Sindhudurg
Email: milindsperception@gmail.com

How to cite this article:
Tupere, B. A. (2026). A Brief Study of Tenets of Russian formalism. Bulletin of Nexus Journal, 3(9(II)), 216–219. https://doi.org/10.5281/zenodo.22916989

Quick Response Code:

Website: https://bnir.us

Hypothesis:

The Russian Formalism introduces a new way to understand literary work of art by focussing on the text, it's form, language and narrative techniques rather than only focusing on various background- biographical, social, economic, historical, and political etc.

Literature Review:

Patrick Flack (2024) uses a theoretical and historical-critical method to examine existing research in his work "The Word is Not Enough: Thinking Russian Formalism Beyond Literary Theory." The research shows that Russian Formalism exists as an interdisciplinary intellectual network which extends its influence beyond literature while it receives treatment as the starting point of literary theory. The paper maintains its focus on theoretical concepts without providing any actual text analysis. The current research study uses Formalist concepts which include defamiliarization to analyze selected literary texts through detailed reading.

The comparative and theoretical methodology which Riyaj Hussain (2022) uses in his work Russian Formalism & New Criticism: Understanding the Outlines enables him to study both theories through secondary sources. The study finds that Russian Formalism emphasizes form over content while New Criticism focuses on close reading which displays their different ways of analyzing texts. The paper stays descriptive because it fails to show how specific texts should be analyzed using the theories. The study demonstrates this gap through its application of Formalist principles to literary works which it examines through close reading methods.

Ravinder Gargesh (2007) uses a linguistic-stylistic approach in his study "Stylistics and Stylistic Analysis of a Modern Hindi Poem" to examine poetic language through a semiolinguistic framework. The study demonstrates that stylistics which draws from Formalist principles, enables scholars to interpret literary works through their analysis of language patterns and structural elements and their functional aspects. The research work concentrates on describing language instead of using Formalist aesthetic principles which include defamiliarization. The research work addresses this gap through its application of stylistic analysis combined with essential Formalist principles to complete detailed textual analysis.

Research Methodology:

The research uses a qualitative close-reading approach yet it has three distinct characteristics that separate it from standard practice. The research applies Formalist concepts of defamiliarization and literariness and narrative devices to selected literary texts through detailed analysis instead of maintaining a purely theoretical framework. The study combines linguistic analysis with interpretative analysis to create a bridge between Jakobson's structural analysis and Shklovsky's aesthetic theory. The study expands Formalist ideas through its recognition of contextual elements while maintaining its primary emphasis on formal aspects.

Analysis:

The important tenets of formalism are:

1. Special use of language:

The formalists technically focus on literature. They treat literature as special use of language. According to formalists there are two kinds of language-

i. Practical use of language
ii. Literary use of language

Literary language is something different from the practical language. Practical language is used for acts of communication while literary language has no practical function at all. It simply makes us see differently. For e.g. you are talking to your friend 'How long will you be?' and h/she answers-'Not long. Do wait and talk to me.' Here, you are asking to your friend about the time of his waiting for you. And your friend simply answers you. It is general communication i.e. the practical language. But these are the dialogues of Thomas hardy's novel 'Under the Greenwood Tree'. Now if you are reading this conversation in the novel, will you regard/consider this as a literary?

There is absolutely no linguistic reason to hold the words as literary. But we read them literary rather than as an act of communication because we read them as literary. One might apply this easily to a writer, Gerard Manly Hopkins, whose language is difficult in way which draws attention to itself as literary, but it is also easy to show that there is no intrinsically literary language. Literature's Constructed quality distinguishes literature from practical language. Poetry was treated by the formalists as the quintessentially literary use of language: it is 'speech organized in its entire phonic texture'.

2. Defamiarisation:

The earlier phase of formalism was dominated by Viktor Shklovsky whose theorizing, influenced by Futurists, was lively and iconoclastic. The symbolists had viewed poetry as some unseen reality, Shklovsky adopted a down-to-earth approach. He is seeking to define the techniques which writers use to produce specific effects.

He has introduced his most attractive concept defamiliarisation means making strange. He argued that we can never retain the freshness of our perceptive of objects, the demands of normal existence requires that they must become to a great extend automatized. Wordsworth's innocent vision through which nature retains the glory and the freshness of a dream is not the normal state of human consciousness. It is the special task of art to give us back the awareness of things which must have become habitual object of our everyday awareness. The purpose of a work of art is to change our mode of perception from the automatic and practical to the aesthetic.

Shklovsky makes this clear in his book entitled 'Art as Technique' -1917:

'The technique of art to make objects unfamiliar, to make forms difficult, to increase the difficulty and length of perception, because the process of perception is an aesthetic end in itself and must be prolonged. Art is a way of experiencing the artfulness of an object, the object is not important.'

The formalists have fondness about two eighteenth century writers, Lawrence Sterne and Jonathan Swift. Boris Tomashevsky shows how devices of defamiliarization are used in *Gulliver's Travels*. In order to present a satirical picture of the European social –political order, Gulliver tells his master, a horse about the customs of the ruling class in human society. Compelled to tell everything with the utmost accuracy, he removes the shell of euphemistic phrases and fictitious traditions which justify such things as war, class strife, and parliamentary intrigue and so on. Stripped of their verbal justification and thus defamiliarisation, these topics emerge in all their horror. Thus, criticism of the political system, nonliterary material, is artistically portrayed and fully involved in the narrative.

If you read above description, firstly this account seems to stress the content of the new perception itself (horror at war and class strife). But in fact, what interests Tomoshvsky is the artistic transformation of non-literary material. Defamiliarization changes our response to the world but only by submitting our habitual perceptions to a processing by literary form.

Shklovsky has written a monograph on Sterne's *Tristam Sandy*, he draws attention to the ways in which familiar actions are defamiliarised by being slowed down, dwawn out or interrupted. This technique of delaying and protracting actions makes us attend to them, so that familiar sights and movements cease to be perceived automatically and are thus defamiliarised. Mr. Sandy, lying despondently on his bed after hearing of his son Tristam's broken nose, might have been described conventionally (he lay mournfully upon his bed), but Sterne chose to defamiliarize Mr. Sandy's posture.

'The palm of his right hand, as he fell upon the bed, receiving his forehead, and covering the greatest part of both his eyes, gently sunk down with his head (his elbow giving way backwards) till his nose touch'd the quilt; his left arm hung insensible over the side of the bed, his knuckles receiving upon the handle of the chamber pot….'

This is an example to show that how often Defamiliarization affects not a perception as such but merely presentation of a perception. By slowing down the description of Mr. Sandy's posture Sterne gives us no new insight into grief, no new perception of a familiar posture, but a heightened verbal presentation. This emphasis on the actual process of presentation is called lying bare one's technique. These two notions directly influenced Bertolt Brecht's famous 'alienation effect'.

At last, literature makes strange the world of everyday perception and renews the reader's lost capacity for fresh sensation. Romantic critics had stressed the author's ability to express fresh mode of experiencing the world, while the formalists stress the function of purely literary devices to produce the effect of freshness in the reader's experience of literary work.

3. **Theories of narrative**:

Theories of narrative or distinction between 'plot' and 'story' have a prominent position in Russian formalism. The Greek tragedian had drawn their plot upon the raw material which was found in stories. Aristotle has defined plot in his the most famous book *poetic* as the arrangement of incidents, the plot is a series of events. A plot is clearly distinguished from a story, upon which a plot may be based. A plot is artful disposition of the incidents which make up a story. The Greek tragedy usually starts with a flashback; a recapitulation of the incidents of the story which occur prior to those which were selected for the plot. Vergil's *Aeneid* and Milton's *Paradise Lost,* the reader found/ plunged themselves into the middle of things; and earlier incidents in the story are introduced artfully at various stages in the plot, often in the form of retrospective narration: Aeneas narrates the fall of Troy to dido in Carthage, and Raphael relates the war in Heaven to Adam and Eve in *Paradise Lost. Paradise Lost* begins with a Satan, the real hero of this epic as considered by many critics including Shelley who declared that only a battle they lost but they have to fight a war against the God.

However, the Russian formalists stressed that only plot is strictly literary, while story is merely raw material waiting the organizing hand of the writer. The formalists have more revolutionary concepts of plot than Aristotle. Shklovsky's essay on Sterne

reveals, the plot of *Tristam Sandy* is not merely the arrangement of story incidents but delay the narration. Digression, typographical games, displacement of parts of the book (preface, dedication etc.), and extended descriptions are all devices to make us attend to the novel's form. In a sense plot in this instance is actually the action of the expected formal arrangements of incidents.

4. Motivation:

Motivation is a further concept of Russian formalist narrative theory. Tomoshavsky called the smallest unit of plot a motif which may understand a single statement of action. There are two kinds of motifs. According to him there are bound and free motifs. He makes a distinction between these two. A bound motif is one which required by the story while a free motif is inessential from the point of view of the story. However from literary point of view the free motifs are potentially the focus of art for e.g. the device of having Raphael relates the war in heaven is a free motif because it is not part of the story in question. It is formally more important than the narration artistically into his overall plots.

Conclusion:

Thus, Russian Formalism focuses on the use of language in literary works of art rather than mere story or plot. It helps us to understand the special use of language in literary texts. This approach is very useful to comprehend how writers make use of language to make ordinary things into fresh, interesting, and new through creative techniques. This criticism encourages paying attention to the style, structure, and literary devices used in the text. However, it also warns us that real meaning is not hidden with the content of the text but rather how it was presented through the text. Overall, Russian Formalism enlarges our appreciation of literature by highlighting the use of artistic language.

Recommendations:

1. One should study literature mainly giving focus on text, forms, style, language and structure.
2. The ideas and theories of Russian Formalism can be used to understand how literary devices make literary work interesting and different.
3. Russian Formalism should be studied along with other critical approaches to get a wider understanding of literature.

Acknowledgement

The author sincerely expresses his gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "A Brief Study of Tenets of Russian Formalism." The author is especially thankful to the Department of English, Snat Rawool Maharaj Mahavidyalay, Kudal, Dist. Sindhudurg, for providing a supportive academic environment and the necessary encouragement to undertake this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. Selden, Raman, Peter Widdowson, and Peter Brooker. *A Reader's Guide to Contemporary Literary Theory*. 5th ed., Pearson, 2005.
2. Nayar, Pramod K. *Contemporary Literary and Cultural Theory: From Structuralism to Ecocriticism*. Pearson, 2010.
3. Barry, Peter. *Beginning Theory: An Introduction to Literary and Cultural Theory*. 3rd ed., Manchester University Press, 2009.

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Assessment of the development of Road infrastructure in Maharashtra

Dr. Shridevi Patil[1], Nisha Mydeo[2]
[1,2] MKSSS's Shri Siddhivinayak Mahila Mahavidyalaya, Karvenagar, Pune.

Manuscript ID:
BN-2026-030942

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 220-225

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI:
10.5281/zenodo.22917074
DOI link:
https://doi.org/10.5281/zenodo.22917074

Abstract
This assessment examines the historic transformation of road infrastructure in Maharashtra, positioned as the primary supply-side catalyst driving the state's vision to become a $1 Trillion sovereign-equivalent economy. Backed by India's post-2014 public capital expenditure boom and strategic frameworks like PM Gati-Shakti, Maharashtra has scaled its infrastructure to include over 18,462 kilo meters of National Highways and a target of over 6,000 kilo meters of high-speed expressways. This study analyses the structural impact of macro-corridors-headlined by the fully operational 701 km Samruddhi Mahamarg-alongside decentralized urban integrations like the Tava-Bharvir Freight Corridor linking the upcoming Vadhvan Mega Port. Furthermore, it evaluates how Asian Development Bank (ADB)-backed rural road projects balance macroeconomic expansion with social cohesion, reducing agricultural transit losses and boosting regional equity across Vidarbha, Marathwada, and Konkan. Finally, the paper reviews operational and fiscal challenges, focusing on innovative asset monetization models, cost-overrun mitigation, and the deployment of Intelligent Transportation Systems (ITS) to improve high-speed corridor safety. Ultimately, Maharashtra's multi-layered road network presents a scalable global benchmark for multimodal connectivity and infrastructure-led economic growth.
Keywords: *Maharashtra Infrastructure, Samruddhi Mahamarg, Logistics Velocity, Macroeconomic Expansion, Economic Corridors, Asset Monetization, Smart Mobility.*

Introduction:

India's infrastructure landscape has transformed significantly since 2014, driven by a massive increase in public capital expenditure-rising from ₹2 lakh crore in FY2014-15 to ₹12.2 lakh crore by FY2026-27-and coordinated multi-sector planning through frameworks like PM Gati-Shakti.

Robust infrastructure is the primary catalyst for macroeconomic expansion. It accelerates productivity, expands market access, and catalyses capital formation across both primary and secondary sectors. "Connecting India" is more than just a catchphrase; it is a key tactic for promoting social cohesiveness, economic expansion, and national integration. In the past decade, the state of India's urban infrastructure has seen a dramatic change. The current government's persistent commitment to infrastructure development has fuelled unprecedented growth and connectivity throughout the nation. India's economy has now touched USD 4.11 trillion and is the fastest-growing among the world's trillion-dollar economies. This has been made possible by its vast and varied terrain, which calls for the development of strong transportation networks, contemporary energy systems, and dependable communication infrastructure to connect regions, connect urban and rural areas, and promote both domestic and international trade. From 'fragile five,' to now the fifth-largest economy in the world with an annual growth rate of 8.4%, India is gearing up to achieve its economic potential, provide employment, and enhance the standard of living for its people by investing in infrastructure.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Shridevi Patil, Nisha Mydeo, MKSSS's Shri Siddhivinayak Mahila Mahavidyalaya, Karvenagar, Pune.
Email: *nisha.mydeo@gmail.com*

How to cite this article:
Shridevi Patil Nisha Mydeo. (2026). Assessment of the development of Road infrastructure in Maharashtra. Bulletin of Nexus Journal, 3(9(II)), 220–225. https://doi.org/10.5281/zenodo.22917074

Quick Response Code:

Website: https://bnir.us

Furthermore, infrastructure development is essential for empowering underprivileged populations, reducing socioeconomic gaps, and advancing environmental sustainability. "Connecting India" highlights the significance of developing resilient, inclusive, and forward-thinking infrastructure as India continues on its road to prosperity, by creating the foundation for a wealthy and united country. The government has made infrastructure development a top priority because connecting India is a crucial component of raising the standard of living for its citizens. Accordingly, several ground-breaking projects to extend digital infrastructure, improve urban amenities, and update transportation networks are either ongoing, in the pipeline, or have been executed. This has become the defining feature of the government's performance.

These initiatives, which range from the construction of road and rail networks, airports, canals, ropeway systems, and the manufacture of rail coaches, are focussed on promoting unbiased and viable growth throughout the country. Following are the main critical projects which come under the infrastructure development:

Airports Advancement

- Aim to elevate the travel experience, foster economic growth, and attract global connectivity to propel the state into a hub of commerce and tourism.

Railways Renaissance

- Projects aim to enhance efficiency, safety, and connectivity, ensuring a smoother and faster rail network for the benefit of commuters and cargo transportation.

Seaports Transformation

- This initiative aims to boost trade, streamline logistics, and strengthen Maharashtra's position as a maritime powerhouse, fostering economic growth and global trade connections.

Power Prowess

- efforts include the development and modernization of power facilities, ensuring a reliable and efficient power supply to meet the growing demands of industries and households.

India is focussing on a multi-dimensional robust growth of infrastructure to improve the overall standard of living of the people of India. Following are the various sectors under which fall in the category of infrastructure development.

Transport Infrastructure

- Road Transport
- Rail Transport
- Sea & Coastal Transport
- Air Transport

Energy Infrastructure

- Mining & Quarrying
- Electricity

Irrigation Infrastructure

- Irrigation

Communication Infrastructure

- Postal Communication
- Telecommunication

Storage Infrastructure

- Storage

Public Health Infrastructure

- Medical facilities

Drinking Water Supply and Sanitation

- Drinking Water Supply
- Sanitation

Education Infrastructure

Infrastructure Facilities in School Number of Institutions, their intake capacity and students admitted

Necessity of Infrastructure Development

Infrastructure development is necessary for following changes:

Enhancing Productive Capacity:

- Logistical efficiency: Advanced transport corridors compress transit times and optimize supply chain resource allocation.
- Energy security: Resilient grids prevent costly industrial downtime and sustain continuous manufacturing processes.
- Digital integration: Ubiquitous broadband architecture democratizes information and integrates localized enterprises into global value chains.

Cultivating Human Capital

- Healthcare resilience: Clinical infrastructure preserves workforce vitality and mitigates systemic labour productivity losses.
- Knowledge ecosystems: Modern academic institutions supply the technical competencies required for high-value knowledge economies.
- Sanitation frameworks: Public water utilities eliminate epidemiological risks to stabilize community standards of living.

Systemic Macroeconomic Outcomes:

- Operational cost-reduction: Superior public assets minimize structural friction and eliminate redundant business expenditures.
- Foreign direct investment: Sophisticated logistical networks serve as key determinants for attracting global corporate capital.
- Fiscal multiplier effects: Capital expenditure on public works generates immediate employment and stimulates long-term economic velocity.

The present study evaluates the development of transport infrastructure in Maharashtra's geographical, economic, environmental, and social perspectives, focusing on its contributions to Maharashtra's urban–regional dynamics and long-term development trajectory.

The Case of Maharashtra

Maharashtra occupies the western & central part of the India and has got 720 km long coastline along the Arabian Sea and is also fortified naturally by Sahyadri and Satpuda mountain range. The geographical area of the State is about 3.08 lakh sq.km. and it is the third largest State in India in terms of area. The State is divided into six divisions which are further divided into 36 districts. Brief summary of economic and social infrastructure in the State is as follows.

Transport Infrastructure

Roads

The road infrastructure in the State is managed by various entities including Public Works Department of the State, GoM, Municipal Corporations/Municipal Councils/Nagar Panchayats, Cantonment Boards, Maharashtra State Board Development Corporation, Forest Department, Maharashtra Industrial Development Corporation (MIDC), City and Industrial Development Corporation, etc. The road network consists of highways, district roads, village roads and internal city roads. The total road length maintained by Public Works Department (PWD) and Zilla Parishad (ZP) (excluding road length maintained by other agencies) at the end of March, 2023 was 3.25 lakh km against target of 3.37 lakh km set under Road Development Plan 2001-2021. The total road length per hundred sq. km. of geographical area was 106 km. & per lakh population was 258 km. as on 31st March, 2023. Category wise road length in the State is given in the Table.

Category wise Road Length in the State*					(KM)		
Year	National Highways	Major State Highways	State Highways	Major Districts Roads	Other District Roads	Village Roads	Total Roads
2019-20	17,726	2,967	29,030	63,886	47,397	1,48,335	3,09,341
2020-21	18,089	2,900	29,076	66,200	46,407	1,57,862	3,20,535
2021-22	18,089	2,622	29,265	68,535	45,371	1,59,714	3,23,596
2022-23	18,366	2,716	30,465	71,574	43,229	1,59,139	3,25,489

Source: Public Works Department, Government of Maharashtra

* Excludes roads maintained by Municipal Councils & Municipal Corporations

The Pradhan Mantri Gram Sadak Yojana (PMGSY), a 100 per cent centrally sponsored Scheme is being implemented in the State since 2000. The primary objective of PMGSY is to provide all-weather road connectivity to the un-connected habitations in the rural areas with a population of 500 and above (250 and above for tribal areas). The GoI has sanctioned PMGSY– II in 2013 for the states which have achieved 100 per cent target of connectivity to the unconnected habitations and 75 per cent target of upgradation. Under the scheme, only upgradation of roads can be undertaken. The objective of PMDGSY – III, started in 2019 is to upgrade roads connecting secondary schools, health centres and market committee centres.

Mukhya Mantri Gram Sadak Yojana is being implemented in the State since 2015-16 for connecting unconnected habitations and upgrading existing rural roads which are not covered under Pradhan Mantri Gram Sadak Yojana. Since inception up to December, 2022 in all 30,922 km road length was sanctioned of which 21,458 km road length was completed and expenditure `13,056.70 crore was incurred. Maharashtra State Road Development Corporation (MSRDC) was established in July 1996 for development of roads & allied infrastructure, mainly through private participation. The total toll collected from the completed projects up to January, 2023 is Rs.18,835 crore as against the total expenditure of ` Rs.64,006 crore.

Selected ongoing projects of MSRDC			
Name of project	Estimated project Cost Rs. Crores)	Expenditure Incurred (Rs in Crores)	Expected year of Completion
Versova- Bandra Sea link project	11,333	943.12	2025-26
Modernisation of border check post	1,500.00	52.66	Completed
Mumbai - Pune Expressway Augmentation	6,695.37	3,602.53	2023-24

Hindu Hruday Samrat Balasaheb Thackeray Maharashtra	55,335.32	50976.03	2023-24
Samruddhi Mahamarg			
Pune ring road	26,831.24	19.65	2025-26
Thane- Ghodbunder elevated road	3,000	2.05	
Bhivandi- Kalyan -Shilphata elevated road (Phase I & II)	2,600.00	6.42	2025-26
Thane creek bridge – Phase III	775.58	290.1	2023-24
Virar - Alibaug Multimodal transport lane	39,841.13	15.96	2025-26
Revas - Reddy Coastal Road	9,572.75	7.33	20025-26
Kokan Greenfield Expressway	71,296.00	6.21	2027-28
Jalna - Nanded Expressway	6,612.00	23.84	2025-26
Versova -Virar Sea link project	32,212.00	11.46	2029-30

Source: Maharashtra State Road Development Corporation up to January, 2023 Infrastructure Statistics 2021-22-23

Maharashtra is undergoing a massive transformation with over ₹4 lakh crore in infrastructure projects underway in the Mumbai Metropolitan Region alone, backed by key state agencies like the Maharashtra State Infrastructure Development Corporation (MSIDC) and MAHARAIL, to spur regional growth and target a trillion-dollar state economy.

Major Transport and Expressway Projects

Samruddhi Mahamarg (Mumbai–Nagpur Expressway):

Hindu Hriday Samrat Balasaheb Thackeray Samruddhi Highway is a flagship access-controlled superhighway improving central connectivity. This highway passes through 11 districts to connect Nagpur with Mumbai, bringing the tide of development to the vast hinterland, is no small dream! Acquiring the required land for the highway was also handled efficiently and completed in record time by the Fadnavis government. The villagers who gave their lands for the project were paid more than the market price. This road is not another highway but is being considered a prosperity corridor.

- The foundation stone of the Samruddhi Mahamarg was laid by Prime Minister Narendra Modi on December 18, 2018, after the completion of land acquisition for the Samruddhi Mahamarg.
- The first phase of the 701 km. this super express Highway between Nagpur and Shirdi, spanning 520 km., was inaugurated by Prime Minister Narendra Modi on 11th December 2022.
- The 76 km final phase of the Samruddhi Mahamarg, from Igatpuri (Nashik) to Amane (Thane), was inaugurated by the Chief Minister Devendra Fadnavis on 5 June for public use.
- With the completion of this mega-project, the 16-hour journey from Nagpur to Mumbai is now reduced to just 8 hours. The entire project has been completed at Rs. 55,335.32 crore by the MSRDC (Maharashtra State Road Development Corporation).

Mumbai-Pune Missing Link:

An extraordinary project to boost the connectivity between the two economic power houses

The Mumbai-Pune Expressway 'Missing Link' project, to translate a great vision into a wonderful reality, is finally complete. This is a 13.3 km long, eight-lane highway built through formidable terrain on mountains, aimed at making the road journey between the two cities significantly faster, safer, and more fuel-efficient. The 'Missing Link' will bypass the accident-prone Khandala Ghat on the Mumbai-Pune Expressway, reducing the total distance by 6 km and travel time by 30 minutes, which in effect will generate an additional revenue worth ₹70,000 crore for the government to scale up Maharashtra's economic development. Built with an investment of ₹7,181 crore, the 'Missing Link' project has finally turned into a vital 'connecting link' bridging Mumbai and Pune.

This project will not only reduce the travel distance between the two cities but will also serve as a potential economic multiplier, tentatively adding ₹70,000 crore to the state's economy. Completed at a cost of approximately ₹7,181 crore, the construction of this rugged, beautiful 8-lane road overcoming steep challenges, has made it a technological wonder. The project has earned a place in the 'Guinness Book of World Records' due to its 22.33-meter-wide tunnel, recognised as the widest underground tunnel in the world.

Mumbai's Trans Harbor Link Project:

Atal Bihari Vajpayee Sewri- Nhavasheva Atal Setu (Mthl):

The Mumbai Trans Harbour Link (MTHL) has been constructed to facilitate decongestion of the island city by improving connectivity between Island city and mainland (Navi Mumbai) and development of Navi Mumbai Region and Raigad

districts was envisaged about 30years back. Govt. of Maharashtra, vide G.R. dated 4th February 2009, decided that the project will be owned and implemented by Mumbai Metropolitan Region Development Authority (MMRDA). Earlier the project was planned as transport project. Govt. of Maharashtra, vide G.R. dated 8th June 2011, designated the project as Regional Development Project. This project will provide faster connectivity with the proposed Navi Mumbai International Airport (NMIA).

Project information: The project includes an approximately 21.8 km length of 6-lane (3 + 3 lane). The length of Sea Bridge is approximately 16.5 km, while the total length of the bridge on land is approximately 5.5 km. Approved Total Project Cost is ₹17,843Crore. The work was started in March, 2018 and completed on 05/01/2024.

Benefits of Project: The Bridge is designed based on modern technology, which has reduced the possibilities of accidents. Moreover, travelers have a faster and safer route, making their travel experience more pleasant. The bridge has been contributed to the development of tourism in the city and surrounding areas. It has benefitted trade and industrial sectors, strengthening the local economy. By reducing traffic load, the Atal Setu has alleviated pressure on local roads in Mumbai, providing local residents with improved daily commuting.

The project has created lots of job opportunities during its construction and post- inauguration, which has improved the local economic conditions. The Orthotropic Steel Deck technology helps protect the flight paths of flamingos, minimalizing distractions to their natural habits. Noise barriers have been installed to minimize the disturbance caused to flamingos due to traffic, prioritizing their conservation.

Present Status: The project is Inaugurated with the Auspicious hands of Hon'ble PM. Narendra Modiji on 12.01.2024 and the Bridge is opened for traffic from 13.01.2024.

Since its inauguration and opening for public use on 13th January 2024. The Atal Setu has significantly enhanced regional mobility between Mumbai and Navi Mumbai, reducing travel time and easing congestion on existing corridors.

Economic Blueprint & Core Macro-Metrics

Maharashtra is India's largest sub-national economy. The state is leveraging large-scale physical capital to compress logistics timelines and support industrial expansion.

- **Economic Output:** Nominal Gross State Domestic Product (GSDP) reached ₹51–54 trillion (~$578–615 billion), commanding a 14.3% share of India's total GDP.
- **Foreign Capital Anchor:** The state consistently captures approximately 31% to 33% of India's total Foreign Direct Investment (FDI) inflows.
- **Growth Targets:** The state's capital expenditure strategy under the *Viksit Maharashtra* vision aims for a $1 trillion economy by 2030.
- **Key Structural Drivers & Economic Corridors**
- The infrastructure strategy relies heavily on multi-modal corridor development. This structural shift moves away from piecemeal project clearances to interconnected networks.

Negative Impact of Road Infrastructure development on Regional Growth

1. Deep Regional Disparities

Economic data reveals a significant imbalance in regional growth. The Mumbai-Thane-Pune golden triangle accounts for roughly 50% of the state's total GDP. Districts in the Marathwada and Amravati divisions continue to lag in terms of infrastructure density, credit absorption, and industrial employment.

2. Fiscal Deficits and Debt Management

Aggressive capital expenditure has increased pressure on state finances.

- **Outstanding Debt:** Reached approximately ₹9.32 lakh crore (18.3% of GSDP).
- **Revenue**. **Balance:** The state runs a structural revenue deficit, projected around 0.7% of Gross State Domestic Product. This dynamic limits the government's capacity to fund projects entirely through public finances, making Public-Private Partnerships (PPPs) essential for long-term project delivery.

3. Execution and Supply-Side Complexities

Converting intent into operational reality remains a challenge due to regulatory and structural hurdles:

- High land acquisition costs in densely populated urban and agricultural zones.
- Prolonged environmental and coastal regulatory clearances for large maritime and expressway projects.
- Urban infrastructure systems under strain from rapid population growth, contributing to local gridlock and traffic congestion

1. Policy Recommendations

To sustain long-term infrastructure-led growth, the Government of Maharashtra should focus on the following institutional and fiscal policies:

- **Establish a Centralized State Corridor Authority:** Create a unified agency combining the highway development functions of MSRDC, MMRDA, and PWD to streamline multi-modal planning, speed up land acquisition, and eliminate inter-departmental delays.
- **Scale Institutional Land Monetization:** Establish structured land-pooling and Value

Capture Financing (VCF) frameworks around upcoming expressways and ring roads to fund capital expenditure internally without overleveraging the state budget.

- **Enforce Toll-to-Toll Safety and Speed Compliance:** Mandate the implementation of section-control speed cameras, automated drone surveillance, and AI-driven lane-discipline tracking on all high-speed corridors to curb accidents.
- **Create Integrated Multi-Modal Logistics Parks (MMLPs):** Pass policies to legally designate land for freight-handling hubs at the intersections of state expressways and the Dedicated Freight Corridor (DFC) to lower secondary logistics costs.
- **Standardize Asset Maintenance Models:** Transition from traditional construction contracts to long-term Operate-Maintain-Transfer (OMT) models to preserve road quality using private sector efficiencies.

2. Environmental Sustainability

Rapid road deployment must coexist with environmental conservation through eco-friendly engineering and climate-resilient designs:



- **Eco-Sensitive Engineering & Wildlife Corridors:** Build dedicated wildlife overpasses and underpasses, similar to the 90+ structures deployed along the Samruddhi Mahamarg, to preserve natural animal migration paths through sanctuaries like Katepurna and Karanja Sohol.
- **Deploy Noise and Light Barriers:** Install specialized sound-damping panels and light deflectors on structural bypasses near eco-sensitive zones to prevent disturbing local wildlife and adjacent rural communities.
- Integrate Renewable Energy:
- Utilize open land along expressway right-of-way's to install solar highway grids, directly powering smart toll plazas, emergency telephone booths, and Intelligent Transportation Systems (ITS).
- **Build Green Materials Infrastructure:** Mandate the use of reclaimed asphalt pavement (RAP), industrial fly ash, and plastic-blended bitumen in all mid-tier and rural road construction to lower carbon emissions.
- **Incorporate Smart Water Management:** Build rainwater harvesting channels and bioswales alongside expressways to stop soil erosion, recharge local water tables, and prevent waterlogging during monsoon seasons.

Acknowledgement

The authors sincerely express their gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "Assessment of the Development of Road Infrastructure in Maharashtra." The authors are especially thankful to MKSSS's Shri Siddhivinayak Mahila Mahavidyalaya, Karvenagar, Pune, for providing a supportive academic environment and the necessary encouragement and facilities to undertake this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References:

1. https://www.pib.gov.in
2. https://mmrda.maharashtra.gov.in
3. http://devgatha.in
   Transforming India through Connectivity by Chitra Shekhavat India Foundation Journal, May-June 2024.
4. Infrastructure Statistics 2021-22, 2022-23. Directorate of Economics and Statistics, Planning Department, Govt. of Maharashtra.

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

The Nalanda-Takshashila Paradigm of Indian Knowledge Systems (IKS): Reimagining Cultural Governance in Contemporary Libraries

Dr. Sanadi Dinesh Annappa
Librarian, St. Joseph College of Arts & Commerce, (Affiliated to the University of Mumbai)
Satpala, Post - Agashi, Virar (W), Tal. Vasai, Dist. Palghar

Manuscript ID:
BN-2026-030943

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 226-229

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22917248
DOI link:
https://doi.org/10.5281/zenodo.22917248

Abstract
The Indian Knowledge Systems (IKS) are a repository of immense knowledge ranging from philosophical insights, mathematics, holistic medicine, ecology, to literature. Historically, libraries have been essential institutions that preserved and disseminated these highly complex traditions. This paper discusses The Nalanda-Takshashila Paradigm as a historical benchmark for knowledge management through a careful study of historical institutional models such as the Dharmaganja library complex at Nalanda. Against the backdrop of present-day trends in arts, humanities, and social sciences, this paper envisions the role of modern libraries beyond the mere function of storing information to becoming agents of cultural governance and sustainable development. In the first part of the paper, the challenges associated with IKS today are explored: geographic, language, and systemic. In the second part, a dual approach is proposed that includes technology (like artificial intelligence, digital text mining, and semantic web) and policies like NEP 2020 of India. Ethical aspects of the suggested solution are discussed in the third part of the paper (informed consent, intellectual property rights for traditional knowledge holders).

Keywords: *Indian Knowledge Systems (IKS), Nalanda-Takshashila Paradigm, Cultural Governance, Digital Archiving, Academic Libraries, Sustainable Development, NEP 2020.*

Introduction

The intellectual, scientific, and spiritual ideas which make up Indian Knowledge Systems (IKS) have been accumulated over many millennia throughout the Indian subcontinent. This traditional heritage is maintained by a variety of means, including classical works (such as the Vedas, the Upanishads, and various scientific treatises), oral traditions, and established practices within communities. Although it has an evident historical background and is of considerable value today in areas such as ecological sustainability and holistic health, IKS has still been given little use and little representation in modern academic programmes and in global information systems. In the arts, humanities, and social sciences today there is a strong focus on interdisciplinary innovation, cultural governance, and sustainable development. In order to meet these requirements, modern libraries should move on from their old role of simply being repositories of printed materials. They should then take on the role of active and dynamic platforms for cultural governance. In the past, the libraries of the ancient universities of Nalanda and Takshashila provided excellent early examples of this method. These libraries did more than just keep manuscripts; they operated as dynamic ecosystems in which knowledge was organised, systematically updated, and shared around the world. If modern libraries understand and adopt the Nalanda-Takshashila Paradigm, they will be able to successfully connect traditional Indian systems of knowledge with today's digital networks and ensure that this valuable heritage is preserved for the future.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sanadi Dinesh Annappa, Librarian, St. Joseph College of Arts & Commerce, (Affiliated to the University of Mumbai) Satpala, Post - Agashi, Virar (W), Tal. Vasai, Dist. Palghar
Email: dineshsanadi@gmail.com

How to cite this article:
Sanadi, D. A. (2026). The Nalanda-Takshashila Paradigm of Indian Knowledge Systems (IKS): Reimagining Cultural Governance in Contemporary Libraries. Bulletin of Nexus Journal, 3(9(II)), 226–229. https://doi.org/10.5281/zenodo.22917248

Quick Response Code:

Website: https://bnir.us

Historical Grounding: The Nalanda-Takshashila Library Ecosystem

To build a modern framework for cultural governance, we must first look at the institutional design of India's ancient learning centers. Nalanda and Takshashila did not view information management as a secondary administrative task. Instead, they treated their libraries as the absolute core of their educational ecosystems.

1. The Nalanda University Library Architecture (*Dharmaganja*)

Nalanda operated as a premier residential university, and its library complex—collectively known as **Dharmaganja** (the Mart of Religion) or *Dharma Ghara*—was the central driving force of its intellectual life. The library was organized across three massive, specialized buildings:

- **Ratnasagara (Ocean of Jewels):** A multi-story structure dedicated to preserving sacred texts, linguistic treatises, and primary philosophical discourses.
- **Ratnodadhi (Ocean of Gems):** The central hub housing specialized manuscripts on astronomy, geography, logic, and core scientific inquiry.
- **Ratnaranjaka (Jewel-Adorned):** A facility dedicated to creative arts, literature, drama, and local cultural documentation.

This structural separation shows an early, highly sophisticated understanding of subject classification and spatial knowledge management. By gathering thousands of manuscripts under one roof, *Dharmaganja* drew scholars from across the globe, transforming Nalanda into an international center for cross-cultural research and validation.

2. The Takshashila University Library Model

As one of the world's earliest centers of learning, Takshashila specialized in varied branches of practical and theoretical knowledge. Its libraries housed essential manuscripts detailing:

- Statecraft, political economy, and governance (*Arthashastra* traditions)
- Advanced holistic medicine and surgical techniques (*Ayurveda*)
- Military science, warfare strategies, and archery (*Dhanurveda*)
- Classical performing arts, music, and grammar

The Takshashila model focused on the practical application of knowledge. Its library served as an open network where incoming scholars, travelers, and state officials could interact directly with texts to solve real-world problems in governance, health, and social organization.

Dimensions of IKS for Sustainable Development

The integration of IKS into modern library infrastructure directly supports the United Nations Sustainable Development Goals (SDGs), particularly **SDG 4 (Quality Education)** and **SDG 12 & 13 (Responsible Consumption and Climate Action)**. Traditional Indian knowledge offers valuable insights for resolving modern socio-ecological crises across several key areas:

Core Iks Domain	Key Canonical/Practical Focus	Contemporary Relevance & Sdg Mapping
Philosophy & Ethics	Upanishads, Bhagavad Gita, Classical Darshanas	Global Ethical Frameworks, Mindfulness, Mental Health Models, And Conflict Resolution.
Medicine & Wellness	Ayurveda, Siddha, Yoga Systems	Preventative Healthcare, Holistic Wellness, And Plant-Based Pharmacology (**Sdg 3**).
Mathematics & Sciences	Vedic Mathematics, Surya Siddhanta, Conceptualization Of Zero	Alternative Algorithmic Computation, Historical Astronomy, And Mathematics Education.
Ecology & Architecture	Vrikshayurveda, Traditional Water Harvesting, Agroforestry	Sustainable Agricultural Models, Climate Resilience, And Eco-Friendly Urban Planning (**Sdg 13**).

Challenges in Contemporary IKS Preservation

Replicating the successes of the Nalanda-Takshashila model within contemporary libraries presents several key institutional, linguistic, and structural challenges:

- **Scattered and Fragmented Repositories:** A large percentage of IKS documentation remains scattered across vulnerable private family collections, remote rural monastic institutions, and local community archives, making systematic curation highly difficult.
- **Linguistic Barriers and Paleographic Obstacles:** The primary source materials for IKS are predominantly composed in ancient languages and scripts—such as Sanskrit, Pali, Prakrit, and Grantha. Modern researchers often lack the specialized linguistic and paleographic training required to translate and interpret these texts accurately.
- **Institutional Neglect and Low Public Awareness:** Decades of Eurocentric bias in formal education have left academic and public

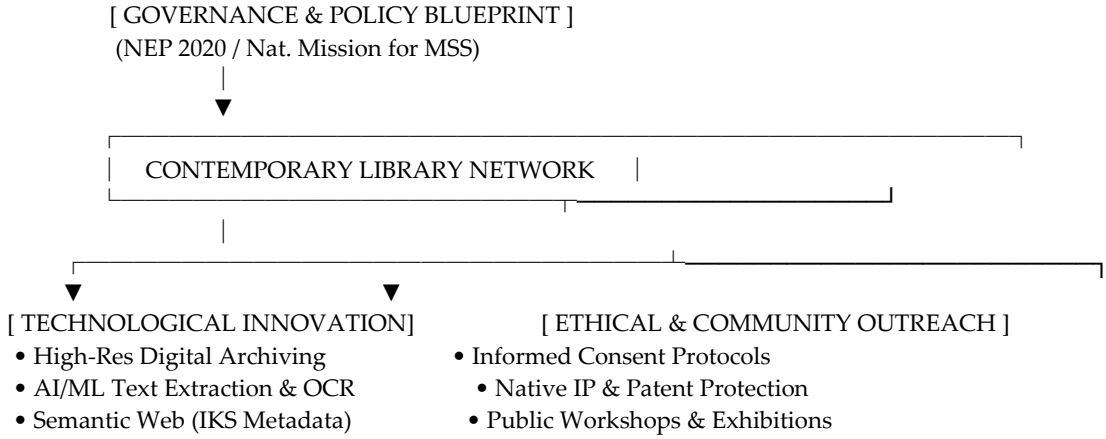
© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

library networks with minimal programming, weak indexing structures, and low public awareness regarding the value of IKS.

- **Severe Resource and Infrastructure Constraints:** Most regional libraries lack the specialized funding, climate-controlled archival infrastructure, and high-resolution scanning equipment necessary to properly preserve delicate palm-leaf and bark manuscripts.

Reimagining Cultural Governance: The Modern Library Framework

To transform these challenges into opportunities, modern library networks can implement a structured framework for cultural governance that builds upon government policy initiatives and technological innovations.



1. Technology-Driven Innovation

- **Advanced Digital Archiving:** Implementing non-destructive, high-resolution digitization pipelines ensures long-term preservation of fragile palm-leaf and birch-bark manuscripts, creating stable, cloud-based mirrors for international research access.
- **Artificial Intelligence and Machine Learning (AI/ML):** Deploying specialized Optical Character Recognition (OCR) tools trained on historical scripts facilitates automated transcription, language translation, and semantic search queries across deep manuscript repositories.
- **Virtual and Augmented Reality (VR/AR):** Libraries can design interactive, immersive spaces that digitally recreate the physical libraries of Nalanda and Takshashila, allowing users to visually engage with ancient historical artifacts and learning spaces.

2. Alignment with Policy Frameworks

Modern libraries must align their operational goals with national structural policies:

- **National Education Policy (NEP 2020):** Libraries can actively support the NEP 2020 mandate to integrate IKS across mainstream school and university curricula by curating dedicated, accessible IKS resource corners.
- **National Mission for Manuscripts (NMM):** Collaborating directly with the NMM allows local academic libraries to serve as regional nodes for locating, cataloging, and metadata-tagging undocumented local manuscripts.
- **IKS Division of the Ministry of Education:** Partnering with this division helps institutions secure targeted research grants, standardize curriculum materials, and run verified, high-quality reference collections.

3. Contemporary Institutional Case Studies

Several major Indian institutions provide successful blueprints for modern IKS archiving and curation:

- **The National Library of India (Kolkata):** Manages massive, systematically preserved collections of rare classical documents covering ancient astronomy, statecraft, and philosophical schools.
- **The Sarasvati Mahal Library (Thanjavur):** Serves as a vital archive for thousands of palm-leaf manuscripts, documenting continuous lines of South Indian medicine, literature, and performing arts.
- **The Bhandarkar Oriental Research Institute (Pune):** A premier research facility that combines classic indological scholarship with modern reference tools to publish highly verified editions of core Sanskrit texts.
- **National Digital Library of India (NDLI):** Provides open-access, aggregated digital environments that compile disparate IKS materials into an organized online catalog for global researchers.

Ethical Considerations and Best Practices

When integrating traditional knowledge into open-access modern library frameworks, librarians must follow strict ethical guidelines:

1. **Informed Consent:** Libraries must secure clear, documented permission from indigenous groups and traditional knowledge holders before recording, digitizing, or publicly

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

distributing local community practices or oral traditions.

2. **Intellectual Property Rights (IPR) Protection:** Institutions must respect traditional ownership structures and use legal frameworks, such as the Traditional Knowledge Digital Library (TKDL), to protect local heritage from bio-piracy and unethical commercial patenting.
3. **Cultural Sensitivity in Curation:** Knowledge organization systems should be updated carefully. Traditional classification, naming conventions, and sacred contexts must be respected, rather than forcing texts into rigid, Eurocentric indexing categories.

Conclusion

The **Nalanda-Takshashila Paradigm** proves that libraries reach their highest potential when they operate as the active heart of a society's intellectual and cultural governance, rather than serving as quiet storage rooms for books. While modern efforts to preserve Indian Knowledge Systems face clear obstacles—such as scattered resources, language barriers, and institutional funding limits—the combination of progressive national policy mandates, like NEP 2020, and advanced digital technologies provides a clear path forward.

By building smart digital archives, ensuring ethical copyright protection, and launching active public literacy programs, contemporary libraries can preserve India's intellectual history and make it useful for modern research. This balanced approach—connecting historical institutional wisdom with future digital tools—ensures that the deep insights of IKS remain preserved, active, and accessible for generations to come.

Acknowledgement

The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "The Nalanda-Takshashila Paradigm of Indian Knowledge Systems (IKS): Reimagining Cultural Governance in Contemporary Libraries." The author is especially thankful to St. Joseph College of Arts & Commerce, Satpala, Agashi, Virar (West), for providing a supportive academic environment and the necessary encouragement and facilities to undertake this study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Altekar, A. S. (1965). *Education in Ancient India*. Varanasi: Nand Kishore & Bros.
2. Bhattacharya, S. (2010). *Libraries and Librarianship in India*. New Delhi: Concept Publishing Company.
3. Chakrabarti, D. K. (2001). *Archaeological Geography of the Ganga Plain: The Lower and the Middle Ganga*. New Delhi: Permanent Black.
4. Dharampal, F. R. S. (2000). *The Beautiful Tree: Indigenous Indian Education in the Eighteenth Century*. Goa: Other India Press.
5. Goswami, K. (2014). *Rediscovering Indian Knowledge Systems: A Journey Through Time*. New Delhi: D.K. Printworld.
6. Kumar, S. (2018). Digital Preservation of Indian Manuscripts: Challenges and Opportunities. *Journal of Library and Information Science*, 43(2), 45-58.
7. Mukherjee, S. N. (1977). *Sir William Jones: A Study in Eighteenth-Century British Attitudes to India*. Cambridge: Cambridge University Press.
8. Ranganathan, S. R. (1961). *Library Development in India*. Delhi: University of Delhi.
9. Sharma, R. N. (2005). *Libraries in the Early 21st Century: An International Perspective*. New Delhi: Atlantic Publishers.
10. Singh, A. (2019). Indian Knowledge Systems: A Historical Perspective. *Journal of Indian Philosophy*, 47(3), 521-540.
11. Thapar, R. (2002). *Early India: From the Origins to AD 1300*. Berkeley: University of California Press.
12. UNESCO. (2003). *Convention for the Safeguarding of the Intangible Cultural Heritage*. Paris: UNESCO.
13. Wujastyk, D. (2003). *The Roots of Ayurveda: Selections from Sanskrit Medical Writings*. London: Penguin Classics.
14. Zvelebil, K. V. (1973). *The Smile of Murugan: On Tamil Literature of South India*. Leiden: E.J. Brill.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Technology in Agriculture: A Comprehensive Review of Digital Transformation, Precision Farming and Sustainable Agricultural Development

Dr. Sabahat Anjum Qureshi
Assistant professor, Department of Chemistry, Govt College Chourai Dist Chhindwara M.P.

Manuscript ID:
BN-2026-030944

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 230-235

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22917318
DOI link:
https://doi.org/10.5281/zenodo.22917318

Abstract
The Indian Knowledge Systems (IKS) are a repository of immense knowledge ranging from philosophical insights, mathematics, holistic medicine, ecology, to literature. Historically, libraries have been essential institutions that preserved and disseminated these highly complex traditions. This paper discusses The Nalanda-Takshashila Paradigm as a historical benchmark for knowledge management through a careful study of historical institutional models such as the Dharmaganja library complex at Nalanda. Against the backdrop of present-day trends in arts, humanities, and social sciences, this paper envisions the role of modern libraries beyond the mere function of storing information to becoming agents of cultural governance and sustainable development. In the first part of the paper, the challenges associated with IKS today are explored: geographic, language, and systemic. In the second part, a dual approach is proposed that includes technology (like artificial intelligence, digital text mining, and semantic web) and policies like NEP 2020 of India. Ethical aspects of the suggested solution are discussed in the third part of the paper (informed consent, intellectual property rights for traditional knowledge holders).
Keywords: *Indian Knowledge Systems (IKS), Nalanda-Takshashila Paradigm, Cultural Governance, Digital Archiving, Academic Libraries, Sustainable Development, NEP 2020.*

Introduction

The intellectual, scientific, and spiritual ideas which make up Indian Knowledge Systems (IKS) have been accumulated over many millennia throughout the Indian subcontinent. This traditional heritage is maintained by a variety of means, including classical works (such as the Vedas, the Upanishads, and various scientific treatises), oral traditions, and established practices within communities. Although it has an evident historical background and is of considerable value today in areas such as ecological sustainability and holistic health, IKS has still been given little use and little representation in modern academic programmes and in global information systems. In the arts, humanities, and social sciences today there is a strong focus on interdisciplinary innovation, cultural governance, and sustainable development. In order to meet these requirements, modern libraries should move on from their old role of simply being repositories of printed materials. They should then take on the role of active and dynamic platforms for cultural governance. In the past, the libraries of the ancient universities of Nalanda and Takshashila provided excellent early examples of this method. These libraries did more than just keep manuscripts; they operated as dynamic ecosystems in which knowledge was organised, systematically updated, and shared around the world. If modern libraries understand and adopt the Nalanda-Takshashila Paradigm, they will be able to successfully connect traditional Indian systems of knowledge with today's digital networks and ensure that this valuable heritage is preserved for the future.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sabahat Anjum Qureshi, Assistant professor, Department of Chemistry, Govt College Chourai Dist Chhindwara M.P.
Email: sabaq9254@gmail.com

How to cite this article:
Qureshi, S. A. (2026). Technology in Agriculture: A Comprehensive Review of Digital Transformation, Precision Farming and Sustainable Agricultural Development. Bulletin of Nexus Journal, 3(9(II)), 230–235. https://doi.org/10.5281/zenodo.22917318

Quick Response Code:

Website: https://bnir.us

FAO identifies improved productivity, cost efficiency, market opportunities and better communication as some of the potential benefits of digital technologies. At the same time, it highlights the importance of connectivity, affordability, digital skills and supportive policies for successful adoption. In India, technologies such as mobile-based agricultural advisory services, satellite-based crop monitoring, soil-health information, automated irrigation, drones, GIS, IoT and AI are increasingly being explored for improving agricultural decision-making. ICAR has highlighted AI, blockchain, IoT and sensor-based precision farming as important emerging areas for Indian agriculture.

Rationale of the Study

Agricultural production is increasingly affected by environmental, economic and technological challenges. Farmers need reliable information to make decisions about crop selection, sowing, irrigation, fertilizer application, pest management and harvesting. Traditional agricultural practices often depend heavily on experience and generalized recommendations. Although farmer knowledge remains extremely valuable, modern technology can supplement this knowledge by providing real-time and location-specific information. The rationale for studying technology in agriculture is based on the following considerations-

- **Increasing food demand:** Growing population and changing consumption patterns require improvements in agricultural productivity.
- **Limited natural resources:** Land and water resources are limited; therefore, agricultural inputs must be used efficiently.
- **Climate variability:** Unpredictable weather and extreme climatic events increase production risks.
- **Rising input costs:** Efficient application of fertilizers, pesticides, water and energy can potentially reduce production costs.
- **Labour shortages:** Mechanization, automation and robotics can reduce dependence on manual labour for certain operations.
- **Need for timely information:** Weather, pest, disease and market information can improve farmers' decision-making.
- **Sustainable agriculture:** Technology can support resource conservation and environmentally responsible production.
- **Digital transformation:** Agriculture is increasingly becoming data-driven, making digital literacy and technological awareness important components of modern farming.

FAO evidence suggests that digital and automated technologies can improve productivity, efficiency, resilience and environmental sustainability, but their adoption is constrained by cost, infrastructure and limited knowledge and skills. Therefore, systematic study of agricultural technology is important for understanding both its benefits and the barriers that may prevent farmers from benefiting from it.

Need and Significance of the Study

The study is significant for farmers, agricultural institutions, policymakers, researchers and rural development organizations.

- **For Farmers:** Technology can help farmers make better decisions, monitor crops and use agricultural inputs more efficiently.
- **For Agricultural Development:** Technological innovation can contribute to increased productivity and more efficient resource management.
- **For Environmental Sustainability:** Precision application of fertilizers, pesticides and irrigation water can potentially reduce unnecessary input use and environmental pressure.
- **For Rural Development:** Digital platforms can connect farmers with agricultural experts, markets, financial services and information.
- **For Policymakers:** Understanding technological barriers can help governments develop appropriate infrastructure, training programmes, subsidies and policies.
- **For Researchers:** The subject provides opportunities for interdisciplinary research involving agriculture, chemistry, biology, environmental science, computer science, economics and social sciences.

Objectives of the Study

- The major objectives of the study are:
- To examine the role of modern technology in agricultural development.
- To identify major technologies currently used in agriculture.
- To assess the perceived benefits of technology for agricultural productivity.
- To examine the role of technology in efficient utilization of water, fertilizers, pesticides and other resources.
- To study farmers' awareness and adoption of agricultural technologies.
- To identify the major barriers to adoption of agricultural technologies.
- To examine the role of digital technology in sustainable and climate-smart agriculture.
- To suggest strategies for improving technology adoption among farmers.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Research Approach

The present review adopts a narrative, thematic, and literature-based research approach to examine the role of emerging technologies in modern agriculture. The methodology was designed to synthesize existing scientific knowledge concerning the development, application, benefits, limitations, and future prospects of agricultural technologies. Particular attention was given to the transition from conventional and mechanized farming toward precision agriculture, digital agriculture, Agriculture 4.0, and the emerging Agriculture 5.0 framework.

The review focuses on the ways in which technological innovations can contribute to agricultural productivity, resource-use efficiency, environmental sustainability, climate resilience, farm management, and decision-making. In addition, the review considers the socioeconomic and infrastructural factors that influence technology adoption, particularly among small and marginal farmers.

Rather than collecting new experimental or survey data, the study synthesizes findings reported in previously published research articles, review papers, institutional reports, and authoritative agricultural publications. The literature was critically examined to identify common findings, emerging trends, technological opportunities, limitations, and research gaps.

The literature was organized into the following major thematic areas: a) Digital agriculture and digital transformation b) Precision agriculture and site-specific crop management c) Smart farming and Agriculture 4.0 4) Agriculture 5.0 and human-centred agricultural technology 5) Artificial intelligence (AI) 6) Machine learning (ML) 7) Internet of Things (IoT) 8) Agricultural drones and unmanned aerial vehicles (UAVs) 9) Remote sensing and satellite-based agricultural monitoring 10) Geographic Information Systems (GIS) 11) Robotics and agricultural automation 12) Smart irrigation and sensor-based water management 13) Big-data analytics and cloud computing 14) Mobile agricultural applications and digital advisory services 15) Agricultural decision-support systems 16) Sustainable and climate-smart agriculture 17) Technology adoption and the digital divide 18) Technological challenges faced by small and marginal farmers.

The thematic approach allows the different technologies to be examined individually as well as in combination. This is particularly important because modern agricultural systems increasingly depend on the integration of multiple technologies rather than on a single technological intervention.

Evolution of Technology in Agriculture

The technological development of agriculture can broadly be divided into several stages.

Traditional Agriculture: Traditional farming depended largely on human and animal labour, indigenous knowledge, seasonal observations and locally available resources. Although these systems often incorporated valuable ecological knowledge, their capacity for large-scale monitoring and precise input management was limited.

Mechanization Era: The introduction of tractors, mechanical harvesters, pumps and other machinery significantly changed agricultural production. Mechanization reduced physical labour requirements and improved operational timeliness. FAO notes that mechanization has historically contributed to productivity improvement and reduction of agricultural drudgery.

Precision Agriculture: The development of GPS, GIS, remote sensing and variable-rate technologies created the foundation for precision agriculture. Instead of treating an entire farm uniformly, precision agriculture recognizes variability within fields and attempts to match inputs with site-specific requirements.

Digital Agriculture: The widespread availability of smartphones, internet connectivity, cloud computing and digital platforms expanded agricultural information services. Farmers could increasingly access weather forecasts, market information, crop advisories and digital communication.

Agriculture 4.0: Agriculture 4.0 represents the convergence of IoT, AI, big-data analytics, drones, robotics, cloud computing, remote sensing and automated machinery.

Recent reviews describe this phase as a transition toward interconnected, data-intensive farming systems.

Agriculture 5.0: Agriculture 5.0 extends digital agriculture toward more human-centred and sustainability-oriented systems. It emphasizes: human–machine collaboration, intelligent automation, responsible AI, digital twins, regenerative agriculture, resilience, ethical data governance and inclusive innovation.

Benefits of Agricultural Technology

The integration of modern agricultural technologies has significantly transformed farming practices by improving decision-making, optimizing resource utilization, and enhancing the efficiency and sustainability of agricultural production. Technologies such as artificial intelligence (AI), machine learning (ML), Internet of Things (IoT) devices, remote sensing, drones, robotics, geographic information systems (GIS), and precision

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

agriculture provide farmers with timely and location-specific information for managing crops and farm resources. The major benefits include-

Improved agricultural productivity: Data-driven technologies enable precise management of crops, nutrients, irrigation, and other production factors, potentially increasing yield and productivity.

Better resource-use efficiency: Precision application of water, fertilizers, pesticides, and other inputs can improve resource utilization while reducing unnecessary consumption.

Reduced input wastage: Variable-rate technologies and sensor-based systems allow agricultural inputs to be applied according to actual crop and soil requirements, thereby minimizing wastage.

Improved irrigation management: Soil-moisture sensors, weather information, automated irrigation systems, and IoT technologies facilitate more precise irrigation scheduling and can reduce unnecessary water use.

Early detection of pests and diseases: AI-based image analysis, drones, and remote sensing can assist in identifying early symptoms of pest infestation and plant diseases, supporting timely intervention.

Reduced agricultural drudgery: Mechanization, automation, robotics, and digital tools can reduce dependence on physically demanding manual operations and improve working conditions for agricultural workers.

Enhanced crop monitoring: Satellite imagery, UAVs, sensors, and GIS enable continuous monitoring of crop health, vegetation conditions, soil characteristics, and field variability.

Better weather-based decision-making: Digital weather forecasting and farm advisory systems can support decisions related to sowing, irrigation, fertilizer application, harvesting, and protection against adverse weather.

Improved access to market information: Digital platforms can provide farmers with information concerning market prices, demand, buyers, agricultural inputs, and opportunities for commercialization.

Increased operational efficiency: Farm-management software, automated machinery, GPS-based systems, and digital record-keeping can improve planning, monitoring, and coordination of agricultural operations.

Potential reduction in environmental impacts: More efficient use of fertilizers, pesticides, water, and energy may reduce nutrient losses, chemical overuse, water consumption, and other environmental pressures.

Improved resilience to climate variability: Technology-supported forecasting, monitoring, precision management, and climate-smart decision-making can help farmers respond more effectively to droughts, excessive rainfall, heat stress, pest outbreaks, and other climate-related risks.

Overall, agricultural automation and digital technologies have the potential to contribute simultaneously to productivity, product quality, resource-use efficiency, resilience, and environmental sustainability. However, these benefits depend strongly on affordability, accessibility, technical capacity, appropriate infrastructure, and the suitability of technologies to local farming conditions.

Challenges and Limitations

Despite the considerable potential of agricultural technology, its adoption is not universally beneficial or equally accessible. Technological transformation can create economic, infrastructural, technical, social, and institutional barriers, particularly for smallholder farmers and communities with limited access to digital resources. The major challenges and limitations are discussed below.

High Initial Cost: Advanced agricultural machinery, sensors, drones, automated irrigation systems, robotics, GPS-enabled equipment, and other precision technologies often require substantial initial investment. In addition to the purchase price, farmers may need to bear expenses related to software subscriptions, data services, training, maintenance, and equipment upgrades. Such costs can discourage adoption among small and marginal farmers.

Digital Divide: The benefits of digital agriculture may not be equally accessible to all farming communities. Farmers without smartphones, reliable internet access, digital devices, or adequate digital literacy may have limited opportunities to use technology-based agricultural services. Consequently, technological development may unintentionally widen existing socioeconomic inequalities unless inclusive access mechanisms are established.

Poor Rural Infrastructure: Agricultural technologies frequently depend on reliable electricity, mobile networks, broadband connectivity, transportation, and technical support services. In areas where electricity supply and internet connectivity are inadequate, the effectiveness of digital and automated agricultural systems can be substantially reduced.

Lack of Technical Skills: Modern agricultural technologies require appropriate knowledge and technical skills for installation, operation, data interpretation, troubleshooting, and maintenance. Farmers may find sophisticated systems difficult to understand without adequate training and extension support. Therefore, capacity building and farmer-

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

oriented digital literacy programs are essential for successful technology adoption.

Data Privacy and Governance: Digital agriculture generates large quantities of farm-related information, including data concerning soil conditions, crop performance, weather, production practices, machinery, and farm operations. Such information may have commercial and economic value. Appropriate policies concerning data ownership, privacy, consent, security, access, and responsible data sharing are therefore necessary to protect farmers' interests.

Interoperability Problems: Agricultural technologies are frequently developed by different manufacturers and service providers. Differences in hardware, software, communication protocols, data formats, and platforms can create interoperability problems. When devices and systems cannot communicate effectively, farmers may experience difficulties integrating information from multiple sources.

Dependence on Technology: Increasing reliance on automated and digital systems can introduce new vulnerabilities. Equipment breakdowns, software errors, cyber threats, battery failure, satellite-data interruptions, or loss of internet connectivity may disrupt agricultural operations. Farmers therefore need appropriate backup mechanisms and technical support rather than complete dependence on automated systems.

Small Farm Size: The economic feasibility of certain precision-agriculture technologies can be limited on very small landholdings. Purchasing expensive machinery or sophisticated equipment may not be economically justified when the area under cultivation is small. Custom-hiring centres, cooperatives, farmer-producer organizations, technology-as-a-service models, and shared-equipment platforms can provide possible solutions to this limitation.

Maintenance and Repair Difficulties: Advanced agricultural equipment may require specialized technical knowledge and spare parts for maintenance and repair. In remote rural areas, such services may be unavailable or expensive. Equipment downtime can consequently reduce the economic benefits expected from technological adoption.

Unequal Distribution of Benefits: Technological innovations may initially benefit farmers with greater financial resources, better education, larger farms, and stronger access to markets. Without appropriate policies and institutional support, technological advancement may therefore contribute to rather than reduce existing inequalities within the agricultural sector.

Environmental and Electronic-Waste Concerns: Although agricultural technology can reduce the environmental footprint of farming through more efficient resource use, the production, operation, replacement, and disposal of electronic devices, batteries, sensors, and machinery can create environmental concerns. Sustainable technology design, repairability, recycling, and responsible disposal are therefore important components of long-term digital agriculture.

Need for Local Adaptation: Technologies developed for large-scale or highly mechanized farming systems may not always be suitable for diverse smallholder farming conditions. Differences in climate, soil, crops, farm size, socioeconomic conditions, and farming practices require technologies to be adapted to local contexts.

Conclusion

Technology is becoming an increasingly important component of modern agriculture. The transition from conventional farming toward precision, digital and data-driven agriculture provides opportunities to improve productivity, resource efficiency, profitability and environmental sustainability.

Technologies such as AI, IoT, drones, remote sensing, GIS, precision farming, robotics, smart irrigation and mobile applications can support farmers throughout the agricultural production cycle. They can assist in crop monitoring, irrigation management, pest and disease identification, input management, harvesting and marketing.

However, technology alone cannot solve all agricultural problems. Successful adoption requires appropriate infrastructure, affordable equipment, reliable internet connectivity, farmer training, digital literacy, technical support and policies that consider the needs of small and marginal farmers. FAO's research emphasizes that inclusive adoption requires investment in connectivity, electricity, digital skills and enabling policy environments.

Therefore, the future of agricultural technology should focus not simply on introducing sophisticated technologies, but on developing affordable, accessible, locally appropriate and farmer-centred technological solutions.

Acknowledgement

The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "Technology in Agriculture: A Comprehensive Review of Digital Transformation, Precision Farming and Sustainable Agricultural Development." The author is especially thankful to the Department of Chemistry, Govt. College Chourai, District Chhindwara, Madhya Pradesh, for providing a supportive academic environment and

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

the necessary encouragement and facilities to undertake this study.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Food and Agriculture Organization of the United Nations (FAO). (2019). Digital technologies in agriculture and rural areas: Status report. FAO.
2. Food and Agriculture Organization of the United Nations. (2022). The State of Food and Agriculture 2022: Leveraging automation in agriculture for transforming agrifood systems. FAO.
3. Ceccarelli, T., Chauhan, A., Rambaldi, G., Kumar, I., Cappello, C., Janssen, S., & McCampbell, M. (2022). Leveraging automation and digitalization for precision agriculture: Evidence from the case studies. FAO Agricultural Development Economics Technical Study No. 24.
4. McCampbell, M. (2022). Agricultural digitalization and automation in low- and middle-income countries: Evidence from ten case studies. FAO Agricultural Development Economics Technical Study No. 25.
5. Lowenberg-DeBoer, J. (2022). Economics of adoption for digital automated technologies in agriculture. FAO Agricultural Development Economics Working Paper No. 22-10.
6. Food and Agriculture Organization of the United Nations. (2022). Transforming agriculture with digital automation. FAO Agricultural Development Economics Policy Brief No. 54.
7. Food and Agriculture Organization & International Telecommunication Union. (2023). Digital excellence in agriculture report. FAO/ITU.
8. Indian Council of Agricultural Research (ICAR). (2022). Revolutionizing Agriculture: The Digital Transformation of Farming. ICAR, New Delhi.
9. Indian Council of Agricultural Research. (2019). National Consultation on Application of ICT in Agriculture. ICAR, New Delhi.
10. Naik, M. R., Apparao, C., Neelima, T. L., Ravi Teja, R., Singh, T., & Ramanjaneyulu, A. V. (2025). Digital agriculture and data-driven farming solutions for sustainable development. Indian Farming, 75(12), 84–87.
11. FAO. (2025). Digital technologies for agriculture: Country and regional perspectives. Food and Agriculture Organization of the United Nations.
12. Food and Agriculture Organization of the United Nations. (2026). Digital Agriculture and AI Innovation Roadmap. FAO e-Agriculture.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Building Career Opportunities by Improving Communication Skills in English

Dr. B. S. Savase
Assistant Professor, Department of English, Uma Mahavidyalya, Pandharpur, Maharashtra, India

Manuscript ID:
BN-2026-030945

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 236-239

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22917380
DOI link: https://doi.org/10.5281/zenodo.22917380

Abstract

In the modern globalized world, proficiency in English communication plays an important role in creating career opportunities. This research paper explores the importance of developing English communication skills in both personal and professional contexts. It examines how effective communication can enhance employability, career advancement, and professional relationships. Drawing from various studies, expert opinions, and real-world examples, the paper highlights the significance of language proficiency as a core competency in diverse industries. The paper also provides insights into methods for improving English communication, including language courses, immersion practices, and technological tools, to help individuals and professionals enhance their careers.

Key words: *Career, Communication Skills*

Introduction

In today's interconnected world, English has emerged as the dominant global lingua franca, facilitating communication across cultures, industries, and nations. According to a study by the British Council, English is spoken by over 1.75 billion people globally, and its prevalence continues to rise as international trade, education, and technology make it essential for both personal and professional growth (British Council, 2020). The globalized economy demands a workforce capable of participating in cross-border communication, negotiations, and collaboration, making English communication skills increasingly valuable.

Communication Skills in Professional Settings

While technical knowledge and expertise are fundamental for career success, communication skills are often considered the most important attribute for professional advancement. Employers in a wide range of sectors seek candidates who can articulate ideas clearly, interact confidently with colleagues and clients, and navigate complex, multicultural work environments. Effective communication, particularly in English, enhances one's ability to build relationships, influence others, and contribute to team goals. This research paper explores how developing strong communication skills can open doors to better career opportunities, from securing initial employment to climbing the corporate ladder.

Job Market Trends

The demand for English proficiency in the job market has increased significantly in recent decades. Globalization has created a network of multinational companies, requiring employees to communicate seamlessly across different regions. In sectors such as business, finance, technology, healthcare, and education, English is often the primary language of communication.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:

B. S. Savase, Assistant Professor, Department of English, Uma Mahavidyalya, Pandharpur, Maharashtra, India
Email: drbssavase@gmail.com

How to cite this article:

Savase, B. S. (2026). Building Career Opportunities by Improving Communication Skills in English. Bulletin of Nexus Journal, 3(9(II)), 236–239. https://doi.org/10.5281/zenodo.22917380

Quick Response Code:

Website: https://bnir.us

The ability to read, write, speak, and listen in English is no longer optional; it is a key requirement for most job positions, particularly in international organizations.

A survey by the Economist Intelligence Unit found that 56% of employers worldwide view English proficiency as a crucial factor in recruitment decisions, and this trend is expected to continue (Economist Intelligence Unit, 2018). In addition, the rise of remote work, facilitated by digital technologies, has further amplified the need for professionals to communicate effectively in English, as it remains the language of choice in virtual meetings, emails, and online collaborations.

Demand of English Proficiency for Employability

Employers today look for a range of soft skills in potential employees, with communication being one of the most sought-after qualities. According to the National Association of Colleges and Employers (NACE), communication is consistently ranked among the top skills employers desire in candidates (NACE, 2021). Clear, concise, and effective communication helps to reduce misunderstandings, fosters collaboration, and improves decision-making. The ability to express oneself fluently in English, particularly in written forms such as reports, presentations, and email correspondence, is crucial in making a lasting impression in professional settings. In client-facing roles, such as customer service, sales, or consultancy, communication plays a vital role in building trust and rapport. A professional who can explain complex concepts in simple, accessible language has a distinct advantage in engaging clients and colleagues alike.

Soft Skills and Professional Success

Communication skills are often considered a subset of broader "soft skills," which include interpersonal abilities such as empathy, active listening, and conflict resolution. These skills are critical in fostering positive working relationships, both within organizations and with external stakeholders. In the modern workplace, soft skills complement technical expertise, and professionals who can balance both are more likely to thrive in leadership positions. As English becomes the primary medium for many professional interactions, fluency in the language becomes a key factor in cultivating these essential soft skills.

Improved Job Prospects and Career Advancement

Fluent communication in English opens up a wide range of job opportunities. For individuals seeking to work in global companies or relocate to different countries, English proficiency serves as a valuable asset. Additionally, as industries become increasingly competitive, employees with strong communication abilities are more likely to stand out in the hiring process. Research indicates that companies with employees who communicate well are more productive, have higher employee satisfaction rates, and experience lower turnover (Gartner, 2021).

Beyond securing a job, good communication skills can accelerate career progression. Professionals who can present ideas clearly and persuasively are often considered for leadership roles, as they are perceived as effective decision-makers and influencers within their organizations. Managers and executives who can communicate effectively with teams, stakeholders, and clients are better positioned to lead initiatives, negotiate contracts, and manage crises.

Facilitating Global Networking and Collaboration

In an era of cross-cultural collaboration, English has become the primary language for international business. Professionals who speak English fluently can connect with peers, mentors, and industry leaders worldwide, enhancing their career prospects. Through online platforms such as LinkedIn, professionals can network with individuals across continents, gaining access to new job opportunities, partnerships, and insights.

In the workplace, effective communication in English enables professionals to collaborate with colleagues from diverse backgrounds, fostering innovation and problem-solving. Multinational teams benefit from shared communication in a common language, ensuring that all members are on the same page, regardless of their native languages.

Enhancing Professional Credibility and Confidence

Mastering communication in English also boosts a professional's confidence, making them more willing to take on challenging tasks, present in public forums, and engage in high-stakes negotiations. This increased self-assurance can translate into better performance, higher recognition, and greater career satisfaction. Furthermore, effective communication contributes to professional credibility, allowing individuals to gain the respect and trust of their peers, clients, and supervisors.

Methods for Developing Effective Communication Skills

Formal Education and Language Learning Programs

One of the most structured ways to improve English communication skills is through

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

formal education, such as enrolling in language courses, university programs, or professional development workshops. Institutions around the world offer specialized courses in English for business, academic writing, or public speaking. Online platforms such as Coursera, Udemy, and edX also offer affordable options for individuals seeking to improve their English proficiency.

Language Skills- (LSRW) Listening, Speaking, Reading and Writing

Effective communication involves four main skills: speaking, writing, listening, and reading. To improve speaking skills, individuals can practice by engaging in conversation with native speakers, joining language exchange programs, or participating in public speaking events. Writing skills can be developed through regular practice, including writing reports, essays, and business correspondence. Listening skills can be enhanced by watching English-language news programs, podcasts, and webinars, while reading books, articles, and professional journals in English can broaden vocabulary and comprehension.

Technology and Tools for Language Improvement

Technology has revolutionized language learning, providing numerous tools and resources for individuals to practice and improve their English skills. Mobile apps like Duolingo, Babbel, and Memrise offer interactive language lessons, while platforms like Grammarly assist with grammar and writing style. Virtual reality tools and online language immersion programs also provide opportunities for more immersive learning experiences.

Cultural Competency and Its Impact on Communication

Effective communication is not just about language proficiency but also cultural awareness. Understanding cultural nuances, body language, and context is essential for successful interaction, especially in international settings. Professionals who can navigate cultural differences and communicate respectfully are more likely to build strong relationships with clients and colleagues worldwide.

Challenges in Developing English Communication Skills

Language Barriers and Accents

For non-native speakers, the journey to mastering English can be challenging. One of the most common obstacles is overcoming language barriers, including difficulties with grammar, pronunciation, and vocabulary. Moreover, accents can sometimes create barriers to clear communication, especially in multinational settings. However, with consistent practice and exposure to different accents through media, online courses, and social interactions, individuals can improve their intelligibility and comfort in speaking English.

Dealing with Self-Doubt and Communication Anxiety

Many individuals experience anxiety when speaking or writing in English, particularly in professional settings where stakes are high. Overcoming this fear requires practice and a mindset shift. Creating a supportive learning environment, seeking feedback, and practicing in low-pressure settings can help individuals build confidence in their communication abilities.

Socioeconomic Factors Affecting Access to Learning Resources

Access to quality language learning resources can be limited by socioeconomic factors. Individuals from low-income backgrounds may struggle to afford language courses or technology tools that can facilitate learning. Governments, non-profits, and educational institutions can play a role in addressing these disparities by providing accessible and affordable language learning opportunities.

Conclusion

As the world becomes more interconnected, the role of English as a tool for career building will continue to grow. Professionals who invest in improving their communication skills in English are more likely to succeed in a competitive global job market. In the future, fluency in English will not only be a valuable asset for career opportunities but also a necessary skill for slowing the complexities of an increasingly diverse and multicultural workplace. For job seekers and professionals alike, it is clear that communication skills in English are vital for career success. By investing in language learning, utilizing available resources, and practicing consistently, individuals can enhance their employability, build professional relationships, and unlock new career opportunities.

Acknowledgement

The author sincerely expresses gratitude to all those who provided valuable guidance, encouragement, and support in the preparation of this research paper entitled "Building Career Opportunities By Improving Communication Skills In English." The author is especially thankful to the Department of English, Uma Mahavidyalya, Pandharpur, Maharashtra, for providing a supportive academic environment and the necessary encouragement to undertake this research work.

Financial support and sponsorship

Nil.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

Works Cited

1. British Council. (2020). *English for the Workplace*. British Council.
2. Economist Intelligence Unit. (2018). *English Proficiency and Global Business*. Economist Intelligence Unit.
3. Ganmote, Dipak Prakashand Bapuso Sitaram Savase. —Artificial Intelligence and the Future of English Semantics.‖ Global Dimensions of Multidisciplinary Research: 47.
4. Gartner. (2021). *The Impact of Communication on Business Performance*. Gartner Research.
5. Khairdi, Iftekhar M., Savase Bapuso S. and Ganmote Dipak P. —A Study of Barriers to Communication among Engineering Students.‖ Recent Advancements in Environment, Agriculture and Climatic Change, Economics, Business, Accounting, Management and Entrepreneurship, Science and Technology, Pharmacy and Health Humanities and Social Sciences, vol. 1, 2024, pp. 23–27. Fern International Publication, Pune. ISBN: 978-81-971359-8-9.
6. National Association of Colleges and Employers (NACE). (2021). *The Skills Employers Want*. NACE.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Advances in Circular Economy Frameworks for Textile Waste Management and Next-Generation Bio-Based Fibers

Dr. Manju Indrakumar Donode (Kathane)
CHB [Department of Textile], S. Chandra Mahila Mahavidyalaya, Amgaon District-Gondia (MS)

Manuscript ID: BN-2026-030946

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 240-242

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22929607
DOI link: https://doi.org/10.5281/zenodo.22929607

Abstract:
The global textile and apparel industry produces over 92 million tons of solid waste annually, contributing significantly to landfill congestion, microplastic pollution, and atmospheric emissions. Traditional linear economic models—characterized by high-volume production, rapid consumption, and premature disposal—are fundamentally unsustainable given finite natural resources and ecological degradation. This paper evaluates modern circular economy frameworks designed to decouple textile production from virgin resource extraction. We systematically compare current mechanical and chemical textile recycling technologies, focusing on energy metrics, fiber degradation, and process scalability for complex fabric blends (e.g., cotton-polyester). Furthermore, this study explores next-generation bio-based fibers derived from agricultural waste, fungal mycelium networks, and microbial cellulose as viable alternatives to petroleum-derived synthetic polymers. Integrating life cycle assessment (LCA) indicators with policy tools like Extended Producer Responsibility (EPR), this work outlines a comprehensive strategic roadmap toward closed-loop textile ecosystems.

Keywords: *Circular Economy, Textile Recycling, Bio-Based Fibers, Depolymerization, Life Cycle Assessment, Sustainable Apparel*

Introduction

1 Background and Context

The modern textile industry is an essential component of the global economy, yet it remains one of the world's highest resource-intensive and polluting sectors. Driven by the proliferation of fast fashion, global fiber production has more than doubled over the past two decades, surpassing 110 million metric tons per year. The predominant operational paradigm remains overwhelmingly linear: primary resources are extracted, processed into low-cost garments, and rapidly discarded. It is estimated that less than 1% of post-consumer garments are recycled back into high-value textile applications.

2 Problem Statement

Linear textile systems generate extensive environmental externalities across their lifecycle. Upstream processes consume vast quantities of water, land, pesticides, and non-renewable petrochemicals. Downstream, synthetic fibers such as polyester, nylon, and acrylic release non-biodegradable microplastics during laundering and end up in municipal landfills or waste-to-energy incineration facilities, releasing toxic effluents and greenhouse gases.

3 Research Objectives

This study aims to address these critical systemic challenges through the following objectives:

- Evaluate circular economy frameworks tailored specifically for the textile and apparel sectors.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
anju Indrakumar Donode (Kathane), CHB [Department of Textile], S. Chandra Mahila Mahavidyalaya, Amgaon District-Gondia (MS)
Email: manjukathane071@gmail.com

How to cite this article:
Donode (Kathane), M. I. (2026). Advances in Circular Economy Frameworks for Textile Waste Management and Next-Generation Bio-Based Fibers. Bulletin of Nexus Journal, 3(9(II)), 240–242. https://doi.org/10.5281/zenodo.22929607

Quick Response Code:

Website: https://bnir.us

- Perform a comparative technological assessment of mechanical versus chemical recycling methodologies.
- Analyze the material properties, manufacturing feasibility, and sustainability profile of emerging bio-based fibers.
- Examine the role of life cycle assessment (LCA) parameters and regulatory policies in scaling closed-loop textile supply chains.

Circular Economy Frameworks in Textiles

1 The Value-Retention Model

A circular economy in textiles replaces end-of-life disposal with material loops that maintain products, components, and raw materials at their highest utility and economic value. The framework relies on three fundamental principles:

- Elimination of waste and pollution by design.
- Circulation of products and materials at their highest value.
- Regeneration of natural ecosystems.

2 Operational Pathways for Circularity

- **Design for Circularity (DfC):** Prioritizing mono-material fabric constructions, non-toxic dye formulations, and modular garment design to simplify disassembly and material processing.
- **Product-as-a-Service (PaaS):** Shifting from product ownership models to subscription, rental, and take-back programs that incentivize durability and maintenance.
- **Closed-Loop Recycling:** Converting post-industrial and post-consumer textile waste directly back into high-grade spinning fiber without functional downcycling.

Table 1. Structural Comparison: Linear vs. Circular Textile Systems

Performance Indicator	Traditional Linear Model	Circular Economy Model
Primary Feedstock	Petrochemicals & Virgin Cultivated Cotton	Recycled Polymers & Waste Biomass
Material Lifecycle	Short-term usage; Single-use mindset	Extended usage via repair, resale, & loop closure
End-of-Life Handling	Landfilling (73%), Incineration (12%)	Closed-loop recycling (>80% targeted recovery)
Carbon Intensity	High Scope 1, 2, and 3 footprint	Reduced up to 60% through material recirculation

Technological Evaluation of Textile Recycling Pathways

1 Mechanical Recycling

Mechanical recycling involves mechanical processing—shredding, pulling, garnetting, and carding—to reduce fabric back into staple fiber state. While mechanically simple and energy-efficient, the process subjects fibers to severe shear stress, cutting staple lengths significantly. Consequently, mechanically recycled cotton or wool fibers exhibit lower tensile strength and must typically be blended with virgin fibers to produce commercially viable yarn.

2 Chemical Recycling and Polymer Depolymerization

Chemical recycling processes convert synthetic and natural polymer matrices through chemical reactions, solvent extraction, or enzymatic breakdown into constituent building blocks.

- **Solvent Dissolution:** Cellulose is dissolved in organic solvents (e.g., ionic liquids) without altering its molecular structure, regenerating continuous filament yarns equivalent in quality to primary cellulosic fiber.
- **Chemical Depolymerization:** Breaks synthetic polymers like PET down to basic monomers (e.g., DMT and EG). The monomers are re-polymerized into virgin-equivalent recycled polyester (rPET).

Table 2. Technical Evaluation of Textile Recycling Technologies

Technology Type	Input Fiber Scope	Output Integrity	Current Scalability
Mechanical Shredding	Pure cotton, wool, pure synthetics	Reduced staple length & lower tenacity	High (Commercialized)
Solvent Dissolution	Cotton-polyester blends, cellulosics	Virgin-equivalent regenerated fiber	Medium (Scaling up)
Chemical Depolymerization	Pure polyester, nylon 6/6, blends	Virgin-grade polymer monomers	Pilot / Industrial scale

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Next-Generation Bio-Based Fibers

1 Agricultural Residue Fibers

To reduce dependence on resource-heavy virgin crops like conventional cotton, next-generation cellulose extraction utilizes non-food agricultural waste streams:

- **Pineapple Leaf Fiber (PALF):** Derived from post-harvest leaves, offering high tensile strength, fine denier, and natural luster.
- **Banana Pseudostem Fiber:** Extracted from agricultural stalks post-harvest, yielding lignocellulosic fibers with excellent breathability and moisture-wicking properties.

2 Mycelium and Microbial Cellulose

- **Mycelium Leather Substitutes:** Fungal vegetative structures grown on organic waste. Cross-linked hyphal networks are tanned using non-toxic agents to form durable, biodegradable alternatives to animal leather.
- **Bacterial Cellulose (BC):** Produced through aerobic fermentation by strains such as Komagataeibacter xylinus, offering high crystallinity and fine nanofibrillar structure.

Environmental Metrics and Life Cycle Assessment (LCA)

Comparative Life Cycle Assessment (LCA) data demonstrates significant ecological gains when transitioning from traditional virgin fibers to circular and bio-based inputs:

- **Global Warming Potential (GWP):** Recycled polyester (rPET) reduces greenhouse gas emissions by 30% to 60% compared to fossil-derived PET polymers.
- **Water Consumption:** Replacing virgin cultivated cotton with agricultural residue fibers yields water savings of up to 90–98%.
- **Eutrophication & Ecotoxicity:** Eliminating synthetic pesticides and agrochemicals via organic waste biomass mitigates aquatic acidification and soil toxicity.

Policy Drivers, Regulatory Frameworks, and Industry Challenges

The global shift toward circular textiles is increasingly driven by legislative mechanisms including Extended Producer Responsibility (EPR), Digital Product Passports (DPP) for supply chain transparency, and Eco-design directives mandating minimum recycled content. However, industrial implementation challenges persist, particularly in blended fabric separation, capital cost of Near-Infrared (NIR) automated sorting, and achieving economic price parity with virgin petroleum polymers.

Conclusion and Future Outlook

Transitioning the global textile industry toward a circular economy model requires a structural paradigm shift across product design, material innovation, recycling technology, and policy support. While mechanical recycling provides immediate, accessible pathways for post-industrial scrap, advanced chemical recycling and depolymerization technologies are critical to process complex post-consumer blend waste streams at virgin-level quality. Simultaneously, scaling next-generation bio-based fibers derived from agricultural waste, mycelium, and microbial matrices offers a sustainable method to diversify fiber inputs away from fossil fuels.

Acknowledgement

The author expresses sincere gratitude to the management and Principal of S. Chandra Mahila Mahavidyalaya, Amgaon, District Gondia (M.S.) for providing the necessary support, encouragement, and academic environment for carrying out this research work.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Damayanti, D., & Wu, H. S. (2021). Strategic possibility pathways for recycling post-consumer textile waste. Polymers, 13(9), 1470.
2. Development: The Transformative Role of. Royal International Global Journal of Advance and Applied Research, 3(7(III)), 129-131
3. Dr. Kamlesh Ravikumar Patil (2026Sustainable Development and Artificial Intelligence Integration: Opportunities, Challenges, And Future Directions Journal of Research & Development, 18(4(XVIII)),90-93
4. Ellen MacArthur Foundation. (2017). A New Textiles Economy: Redesigning Fashion's Future.
5. European Environment Agency (EEA). (2022). Textiles and the Environment: The Role of Design in Europe's Circular Economy.
6. Kamlesh Ravikumar Patil (2026) Integrating Knowledge for Innovation, Sustainability and Global
7. Patil, Kam. (2023). Understanding deviant behaviors in library use: Patterns, implications, and interventions. LIBRARY SCHOLAR: International Peer-Reviewed Journal of Library Science.
8. Sandin, G., & Peters, G. M. (2018). Environmental impact of textile reuse and recycling–A review. Journal of Cleaner Production, 184, 353-365.
9. Shirvanimoghaddam, K., et al. (2020). Towards a green and sustainable future: Recycling and upcycling of price-competitive textile waste. Journal of Cleaner Production, 268, 122206.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

AI-Driven Development of Smart Chemical Sensors for Rapid Detection of Environmental Pollution

Pushpa Kailas Kondare
Department of Chemistry, Shripatrao Chaougule Arts & Science College Malwadi-Kotoli, Shivaji University, Kolhapur, Maharashtra, India

Manuscript ID:
BN-2026-030947

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 243-251

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

Abstract
Environmental pollution is a complex and continuously evolving problem that requires rapid, sensitive and decentralized analytical technologies. Conventional analytical techniques such as atomic absorption spectrometry, inductively coupled plasma mass spectrometry, gas chromatography and high-performance liquid chromatography provide high analytical performance but generally require sophisticated instrumentation, laboratory infrastructure, sample preparation and trained personnel. Smart chemical sensors offer an attractive alternative because they can provide rapid measurements with portable and potentially low-cost instrumentation. However, environmental samples contain multiple interfering species, and sensor responses may be nonlinear, unstable or affected by temperature, pH, humidity and sensor ageing. Artificial intelligence (AI), particularly machine learning (ML), provides new opportunities to overcome these limitations by extracting complex patterns from chemical-sensor responses and converting them into qualitative or quantitative information. This paper reviews the development of AI-driven smart chemical sensors for rapid environmental pollution detection, with emphasis on electrochemical sensors, gas-sensor arrays, optical sensors and nanomaterial-based sensing platforms. The application of machine-learning approaches including principal component analysis, support-vector machines, artificial neural networks, random forests and deep-learning models for signal processing, classification, quantification and sensor-drift compensation is discussed. Recent studies demonstrate the integration of deep learning, electrochemical sensing and Internet-of-Things technology for simultaneous detection of heavy metals in water. The paper also proposes an integrated framework combining chemical recognition, signal transduction, AI-based data interpretation, wireless communication and environmental decision support. Major challenges, including limited datasets, matrix effects, sensor drift, model interpretability and field validation, are discussed. AI-enabled chemical sensors have considerable potential to transform environmental monitoring from periodic laboratory analysis toward rapid, portable and intelligent pollution surveillance.

Keywords: *artificial intelligence; machine learning; smart chemical sensors; environmental pollution; electrochemical sensors; heavy metals; sensor arrays; environmental monitoring; Internet of Things; analytical chemistry.*

DOI: 10.5281/zenodo.22929839
DOI link:
https://doi.org/10.5281/zenodo.22929839

Introduction

Environmental pollution has become one of the major challenges associated with industrialization, urbanization, intensive agriculture and increasing energy consumption. Air, water and soil may contain complex mixtures of inorganic and organic contaminants, including heavy metals, pesticides, volatile organic compounds (VOCs), nitrogen oxides, sulfur oxides, particulate matter, pharmaceutical residues and other emerging pollutants. The chemical composition of environmental matrices can vary considerably with location, season and human activity, making continuous and reliable monitoring essential. Air pollution is particularly important because even relatively low concentrations of some pollutants can adversely affect human health.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Pushpa Kailas Kondare, Department of Chemistry, Shripatrao Chaougule Arts & Science College Malwadi-Kotoli, Shivaji University, Kolhapur, Maharashtra, India
Email: pushpakondare@gmail.com

How to cite this article:
Kondare, P. K. (2026). AI-Driven Development of Smart Chemical Sensors for Rapid Detection of Environmental Pollution. Bulletin of Nexus Journal, 3(9(II)), 243–251.
https://doi.org/10.5281/zenodo.22929839

Quick Response Code:

Website: https://bnir.us

The World Health Organization (WHO) has established health-based guideline levels for major pollutants including $PM_{2.5}$, PM_{10}, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. The 2021 WHO guideline value for annual $PM_{2.5}$ exposure is 5 $\mu g\ m^{-3}$, while the corresponding value for annual NO_2 exposure is 10 $\mu g\ m^{-3}$. (NCBI) These stringent guideline levels emphasize the importance of sensitive and reliable analytical methods.

Conventional instrumental techniques remain the reference methods for many environmental analyses. Techniques such as atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), gas chromatography (GC), liquid chromatography (LC) and mass spectrometry provide excellent sensitivity and selectivity. However, they may require expensive instrumentation, centralized laboratories, skilled operators and relatively extensive sample preparation. These limitations make them less convenient for frequent, decentralized or real-time environmental monitoring.

Chemical sensors provide a complementary analytical strategy. A chemical sensor generally consists of a recognition element, a transducer and a signal-processing system. Interaction between the target analyte and the sensing interface generates a measurable response. Advances in nanotechnology have produced sensing materials with high surface area, enhanced conductivity and tunable surface chemistry, improving the sensitivity of many chemical sensors.

Nevertheless, the analytical response of a sensor rarely depends exclusively on the target analyte. Environmental matrices contain numerous potentially interfering compounds, and parameters such as pH, temperature, humidity and ionic strength can affect sensor performance. Sensor ageing and surface fouling can also cause signal drift.

Artificial intelligence provides an important opportunity to address these challenges. Machine-learning algorithms can identify nonlinear relationships between sensor responses and analyte concentrations, classify complex response patterns, compensate for sensor drift and combine information from multiple sensors. Recent reviews have identified ML as an increasingly important tool for improving electrochemical sensor accuracy and stability. (ScienceDirect)

The integration of AI with chemical sensing therefore represents a transition from conventional **signal measurement** toward **intelligent analytical interpretation**.

Smart Chemical Sensors: Concept and Development

A conventional chemical sensor can be represented by the sequence:

Analyte → Recognition → Transduction → Signal → Analytical result

A smart chemical sensor adds an intelligent computational layer:

Analyte → Recognition → Transduction → Signal processing → AI/ML → Prediction → Decision

The distinction is important. A conventional sensor may measure a single signal parameter such as current, potential, absorbance or resistance. A smart sensing system can analyze the complete response pattern and extract multiple analytical characteristics.

For example, an electrochemical measurement may contain information in:

- peak current,
- peak potential,
- peak width,
- peak separation,
- charge-transfer resistance,
- impedance,
- frequency response and
- temporal signal characteristics.

Instead of selecting only one parameter, AI algorithms can potentially exploit several characteristics simultaneously.

This is particularly valuable for multicomponent environmental samples.

Types of Chemical Sensors for Environmental Monitoring

1 Electrochemical Sensors

Electrochemical sensors are particularly attractive for environmental applications because they can be sensitive, relatively inexpensive and amenable to miniaturization.

Major electrochemical techniques include:

- amperometry,
- potentiometry,
- cyclic voltammetry,
- differential-pulse voltammetry,
- square-wave voltammetry and
- electrochemical impedance spectroscopy.

Nanomaterials including graphene, carbon nanotubes, metal nanoparticles, metal oxides and nanocomposites can modify electrode surfaces and improve electron-transfer characteristics.

The combination of electrochemical sensors with machine learning is especially promising because voltametric and impedance measurements can generate high-dimensional datasets. Recent research specifically identifies signal noise, interfering peaks and nonlinear responses as challenges that can benefit from intelligent data analysis. (IAPC Journals)

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

1 Heavy-metal detection

Heavy metals are among the most important targets for environmental chemical sensors. Lead, cadmium, mercury, arsenic and chromium are of particular concern because of their toxicity and persistence.

A notable recent example was reported by Lahari et al. in 2025. The researchers developed an electrochemical system using gold-nanoparticle-modified carbon-thread electrodes for simultaneous detection of Cd^{2+}, Pb^{2+}, Cu^{2+} and Hg^{2+} in water. Differential-pulse voltammetry was combined with a convolutional neural network for analysis of the sensor response, and the system was integrated with IoT technology for remote monitoring. The reported detection limits were 0.99 μM for Cd^{2+}, 0.62 μM for Pb^{2+}, 1.38 μM for Cu^{2+} and 0.72 μM for Hg^{2+} over a reported linear range of 1–100 μM. Real water samples from lakes in Hyderabad, India, were also investigated. (Nature)

This study illustrates the potential of combining:

nanomaterial → electrochemical sensing → deep learning → IoT

within one environmental analytical platform.

AI and Machine Learning in Chemical Sensing

Artificial intelligence can contribute to chemical sensing at several stages of the analytical workflow.

1 Signal preprocessing

Raw chemical-sensor signals frequently contain noise, baseline variation and environmental disturbances. Preprocessing methods can improve the quality of information supplied to the ML model. Common approaches include:

- normalization,
- smoothing,
- baseline correction,
- filtering,
- outlier identification and
- noise reduction.

The purpose is not simply to make the signal visually attractive; preprocessing should retain chemically meaningful information while reducing irrelevant variation.

2 Feature extraction

Feature extraction converts raw sensor signals into analytically useful variables.

For an electrochemical sensor, features may include:

$$= (I_p, E_p, \Delta, E, w, R_{ct}, Z', Z'' \dots)$$

where $I_p$represents peak current, $E_p$represents peak potential, $w$represents peak width and R_{ct}represents charge-transfer resistance.

For gas sensors, useful features may include:

- response magnitude,
- response time,
- recovery time,
- response slope,
- area under the response curve and
- steady-state resistance.

Machine-Learning Algorithms for Smart Sensors

Different algorithms provide different analytical functions.

Algorithm	Major application in smart sensing
PCA	Dimensionality reduction and pattern visualization
Linear/Multiple Regression	Quantitative prediction
SVM	Classification and regression
Random Forest	Classification, regression and feature importance
ANN	Nonlinear quantitative prediction
CNN	Complex signal/pattern classification
Autoencoder	Feature extraction and anomaly detection
Ensemble models	Improved prediction robustness

Principal component analysis (PCA) is particularly useful for exploratory analysis and dimensionality reduction. Supervised models such as support-vector machines and artificial neural networks can subsequently be used for classification or quantitative prediction.

Deep-learning approaches become attractive when sufficiently large datasets are available. The 2025 heavy-metal sensing study described above used a convolutional neural network to process differential-pulse-voltammetric signals for multiplexed metal detection. (Nature)

However, the most sophisticated algorithm is not automatically the best algorithm. A small chemical dataset may be better handled by a simpler model than by a deep neural network. Model selection should therefore be based on dataset size, analytical objective, interpretability and validation performance.

AI-Driven Gas Sensors and Electronic Noses

Gas sensors frequently suffer from cross-sensitivity. A single sensor may respond to several gases, making individual identification difficult.

An alternative approach is to use an array of partially selective sensors.

The basic principle is:

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Gas mixture → sensor array → response pattern → machine learning → identification/quantification

This is the basis of the electronic-nose approach.

Machine-learning methods have been widely investigated for feature extraction, classification, prediction and compensation of gas-sensor drift. A comprehensive review by Ye et al. reported the importance of ML in electronic-nose systems, particularly for feature extraction, modeling and drift compensation. (MDPI)

Environmental applications may include detection or classification of:

- volatile organic compounds,
- industrial emissions,
- fuel vapors,
- combustion products,
- agricultural chemical vapors and
- other gaseous pollution signatures.

Rather than attempting to make every individual sensor perfectly selective, AI can exploit the **collective response pattern** of the sensor array.

This represents an important change in sensor philosophy:

Chemical selectivity can be achieved not only through the recognition material but also through intelligent interpretation of a multidimensional sensor response.

AI for Water-Pollution Monitoring

Water is a chemically complex matrix containing dissolved salts, organic matter, suspended particles, microorganisms and potentially numerous pollutants.

Important targets include:

- heavy metals,
- nitrate,
- phosphate,
- pesticides,
- phenolic compounds,
- pharmaceutical residues and
- industrial organic contaminants.

A smart water-monitoring system could combine chemical sensors with measurements of:

- pH,
- conductivity,
- temperature,
- dissolved oxygen,
- turbidity and
- oxidation-reduction potential.

The AI model could then integrate these variables with the chemical sensor response.

A conceptual multivariate model may be represented as:

$$C_i = f(S_1, S_2, \dots, S_n, p, H, T, \kappa DO)$$

where $C_i$represents the predicted concentration of contaminant i, $S_1 - S_n$represent sensor responses, Trepresents temperature, κrepresents conductivity and DOrepresents dissolved oxygen.

Such an approach may improve robustness because environmental variables that influence sensor response are included in the prediction model.

AI for Soil-Pollution Monitoring

Soil contamination presents an additional challenge because soil is highly heterogeneous.

Important contaminants include:

- Pb,
- Cd,
- Hg,
- As,
- Cr,
- pesticides,
- petroleum hydrocarbons and
- persistent organic pollutants.

Portable chemical sensors combined with AI could facilitate measurements at multiple geographical locations.

When sensor measurements are associated with geographical coordinates, the system can potentially generate spatial pollution maps.

A future monitoring architecture could therefore combine:

Chemical sensor + AI + GPS + GIS

Such systems could be useful for identifying contamination hotspots and supporting environmental management.

Sensor Drift and Matrix Effects

Sensor drift is one of the major barriers to long-term environmental deployment.

A sensor that produces response R_1under laboratory conditions may produce a different response $R_2$to the same analyte after prolonged operation.

Possible causes include:

- electrode fouling,
- surface degradation,
- humidity,
- temperature,
- material ageing,
- changes in matrix composition and
- changes in sensor sensitivity.

Machine learning can potentially identify temporal patterns and compensate for drift. Drift compensation has been an important research direction in electronic-nose systems. (PubMed Central (PMC))

Similarly, matrix effects can be incorporated into multivariate models.

However, AI should not be viewed as a magic correction mechanism. If the training dataset does not adequately represent the real environment, the model may fail when deployed outside the laboratory.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

This makes **representative training data** one of the most important requirements for intelligent chemical sensing.

Proposed AI-Driven Smart Chemical Sensor Framework

Based on the developments discussed above, a generalized smart environmental sensing architecture can be proposed.

Stage 1: Chemical recognition

The pollutant interacts with:

- nanomaterials,
- molecularly imprinted polymers,
- enzymes,
- aptamers,
- selective receptors or
- metal-organic materials.

↓

Stage 2: Signal transduction

The chemical interaction is converted into:

- current,
- potential,
- impedance,
- resistance,
- absorbance,
- fluorescence or another measurable signal.

↓

Stage 3: Signal processing

Noise reduction and normalization are performed.

↓

Stage 4: AI analysis

Machine-learning or deep-learning algorithms perform:

- classification,
- regression,
- feature extraction,
- anomaly detection or
- sensor-drift correction.

↓

Stage 5: Connectivity

The processed information is transferred through IoT or wireless communication.

↓

Stage 6: Environmental decision

The final system generates:

- contaminant concentration,
- pollution category,
- warning signal,
- geographical pollution map or
- early-warning information.

Proposed architecture

Environmental sample

↓

Smart chemical sensor

↓

Signal acquisition

↓

Preprocessing

↓

Feature extraction

↓

AI/ML model

↓

Pollutant identification & quantification

↓

IoT/Cloud/Edge platform

↓

Environmental monitoring dashboard

↓

Early warning & decision support

Analytical Performance Parameters

For a smart chemical sensor to be useful analytically, AI accuracy alone is insufficient.

Important analytical parameters include:

Sensitivity

The change in sensor response per unit concentration:

$$Sensitivity = \frac{\Delta Response}{\Delta Concentration}$$

Limit of detection

The minimum concentration that can be reliably distinguished from the analytical background.

A commonly used approximation is:

$$LOD = \frac{3\sigma}{m}$$

where σrepresents the standard deviation of the blank or low-level response and $m$is the calibration slope.

Selectivity

The ability to detect the target analyte in the presence of potentially interfering species.

Accuracy

Agreement between measured/predicted and reference values.

Precision

Reproducibility of repeated measurements.

Recovery

For environmental samples:

$$Recovery(\%) = \frac{Measured\ concentration}{Expected\ concentration} \times 100$$

AI model performance

For regression models, commonly reported metrics include:

$$R^2,\ RMSE,\ MAE$$

For classification:

$$Accuracy,\ Precision,\ Recall,\ F1-score$$

Importantly, these metrics should be calculated using appropriate validation data rather than only the training dataset.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Comparison of Conventional and AI-Enabled Chemical Sensors

Parameter	Conventional sensor system	AI-enabled smart sensor
Signal interpretation	Often rule/calibration based	Data-driven
Multianalyte analysis	Difficult	More feasible
Nonlinear response	Difficult to model	ML can model nonlinear relationships
Interference	Often problematic	Potentially compensated using multivariate models
Sensor drift	Requires recalibration	Potential drift compensation
Data integration	Limited	Multisensory integration possible
Remote monitoring	Additional hardware required	Easily integrated with IoT
Real-time decision support	Limited	Possible
Model transparency	Generally high	Depends on algorithm
Dataset requirement	Relatively low	Potentially high

The principal advantage of AI is therefore not simply increased numerical accuracy. Its broader value lies in the ability to integrate **multiple chemical signals and environmental variables into one analytical decision system**.

Integration with Internet of Things

The Internet of Things can extend smart chemical sensors beyond individual measurements.

A typical system may contain:

Sensor node → Microcontroller → Edge AI → Wireless communication → Cloud/database → User interface

IoT integration has already been demonstrated in recent heavy-metal sensing research. The 2025 multiplexed heavy-metal platform combined electrochemical sensing, CNN-based analysis and IoT connectivity, demonstrating the feasibility of remote environmental monitoring. (Nature)

Edge computing is particularly attractive because preliminary analysis can be performed near the sensor.

This can reduce:

- communication latency,
- data transmission,
- energy requirements and
- dependence on continuous cloud connectivity.

Advantages of AI-Driven Smart Chemical Sensors

The integration of AI with chemical sensing offers several potential advantages.

1 Rapid analysis

Portable sensors can provide measurements without requiring every sample to be transported to a central laboratory.

2 Multianalyte detection

AI can analyze response patterns from sensor arrays and distinguish multiple contaminants.

3 Improved signal interpretation

Complex nonlinear signals can be analyzed using ML models.

4 Sensor-drift compensation

Machine-learning approaches can help identify and correct temporal changes.

5 Remote monitoring

IoT connectivity allows measurements to be transmitted to remote users.

6 Reduced analytical infrastructure

Portable systems may reduce dependence on centralized laboratory facilities.

7 Continuous surveillances

Sensor networks can provide repeated measurements rather than isolated sampling events.

8 Early-warning systems

AI can identify abnormal patterns before pollution reaches more severe levels.

Major Challenges

Despite considerable progress, several challenges must be addressed.

1 Data scarcity

AI models require sufficient and representative training data. Chemical-sensor datasets are often much smaller than datasets used in conventional AI applications.

2 Overfitting

A model may produce excellent training performance while failing on unknown samples.

3 Matrix effects

Real environmental samples are significantly more complicated than synthetic laboratory solutions.

4 Sensor drift

Long-term changes can reduce prediction accuracy.

5 Lack of standardized datasets

Differences in sensor fabrication, experimental conditions and preprocessing make comparison between studies difficult.

6 Explainability

Black-box predictions may be difficult to justify in environmental regulatory applications.

7 Field validation

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Many sensor systems demonstrate promising laboratory performance but require more extensive validation under real environmental conditions.

8 Cybersecurity and data integrity

IoT-connected environmental monitoring systems also introduce concerns regarding data security and reliable communication.

These limitations indicate that future studies should report not only model accuracy but also **external validation, robustness, calibration transfer and long-term field performance**.

Future Perspectives

The next stage of AI-driven chemical sensing should move beyond simply connecting a sensor to a machine-learning algorithm.

1 Explainable AI

Environmental decisions should ideally be supported by interpretable models. Feature-importance analysis and explainable-AI methods can help identify which sensor responses contributed most strongly to a prediction.

2 Physics-informed machine learning

Combining chemical principles with data-driven models may improve model generalization when experimental datasets are limited.

3 Sensor fusion

Combining chemical sensors with pH, temperature, conductivity, humidity and other measurements could provide more reliable environmental predictions.

4 Edge AI

AI algorithms embedded directly within sensor nodes could allow rapid local decisions.

5 Self-calibrating sensors

Future systems could continuously identify changes in sensitivity and update their calibration.

6 Sustainable sensing materials

Future chemical sensors should increasingly use environmentally benign, low-cost and energy-efficient materials.

7 Digital environmental monitoring

The integration of sensor networks, AI, GIS and IoT could enable real-time environmental pollution maps.

These developments could shift environmental monitoring from periodic sampling toward continuous and intelligent surveillance.

Relevance to Sustainable Development and Viksit Bharat 2047

AI-driven smart chemical sensors have potential relevance to India's environmental monitoring requirements because they can support decentralized and relatively low-cost analytical measurements.

A distributed network of smart sensors could potentially be deployed nearby:

- industrial areas,
- agricultural regions,
- rivers and lakes,
- wastewater discharge points,
- urban traffic corridors and
- landfill sites.

Data from these networks could be analyzed using AI and incorporated into environmental monitoring platforms.

Such technologies are consistent with the broader objectives of sustainable development because rapid detection can support early intervention rather than relying solely on retrospective laboratory analysis.

For India, the development of indigenous smart sensing platforms could additionally contribute to:

- affordable environmental analysis,
- decentralized monitoring,
- technology-driven pollution management,
- development of analytical instrumentation,
- AI-enabled scientific innovation and
- sustainable technological development.

The concept therefore sits naturally at the intersection of **analytical chemistry, artificial intelligence, environmental science and smart technology**.

Conclusion

AI-driven smart chemical sensors represent an important emerging direction in environmental analytical chemistry. Conventional chemical sensors provide the essential interface between environmental contaminants and measurable signals, while artificial intelligence provides a computational framework for interpreting increasingly complex sensor responses.

Electrochemical sensors, gas-sensor arrays, optical sensors and nanomaterial-based platforms can be integrated with machine-learning algorithms for pollutant classification, quantitative prediction, interference management and sensor-drift compensation. Recent experimental work has demonstrated the feasibility of combining nanomaterial-modified electrochemical sensors, deep learning and IoT technologies for simultaneous detection of multiple heavy metals in real water samples. (Nature)

The development of these systems can therefore be represented by the progression:

Conventional sensor → Smart sensor → AI-enabled sensor → Connected sensor network → Intelligent environmental monitoring system

However, successful field deployment will require more than high laboratory accuracy. Representative datasets, rigorous validation, sensor stability, matrix-effect correction, explainable models and standardized performance evaluation are essential.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

The future of environmental monitoring is likely to involve the convergence of **advanced chemical sensing, artificial intelligence, nanotechnology, IoT and analytical chemistry**. Properly designed AI-enabled chemical sensors could provide rapid, portable and decentralized tools for pollution surveillance and early warning, supporting sustainable environmental management and the development of technologically advanced environmental-monitoring infrastructure.

Acknowledgement
The author expresses sincere gratitude to the Principal, Head of the Department of Chemistry, and all faculty members of Shripatrao Chaougule Arts & Science College, Malwadi-Kotoli, Shivaji University, Kolhapur, Maharashtra, for their continuous encouragement, guidance, and academic support throughout the preparation of this research work.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Ye, Z., Li, Y., Liu, Y., Wang, L. & Li, Q. Recent progress in smart electronic nose technologies enabled with machine learning methods. *Sensors*, **21**, 7620 (2021). (MDPI)
2. Mohd Nashruddin, S. N. A. B., Salleh, F. H. M. & Yunus, R. M. Artificial intelligence-powered electrochemical sensor: Recent advances, challenges, and prospects. *Heliyon*, **10** (2024). (PubMed Central (PMC))
3. Application of machine learning to improve the accuracy of electrochemical sensors: A review. *Trends in Analytical Chemistry*, **193**, 118469 (2025). (ScienceDirect)
4. Lahari, S. A. et al. IoT integrated and deep learning assisted electrochemical sensor for multiplexed heavy metal sensing in water samples. *npj Clean Water*, **8**, 10 (2025). (Nature)
5. A narrative review of machine learning integrated electrochemical sensors for smart environmental monitoring. *Journal of Electrochemical Science and Engineering* (2026). (IAPC Journals)
6. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: WHO (2021). (World Health Organization)
7. World Health Organization. *WHO Global Air Quality Guidelines: Executive Summary*. Geneva: WHO (2021). (World Health Organization)
8. World Health Organization. Recommended 2021 air-quality guideline levels and interim targets. *WHO Global Air Quality Guidelines* (2021). (NCBI)
9. Wagh, P. (2026). Artificial intelligence–driven sensor systems for heavy metal pollution monitoring: emerging applications and future directions. *Discover Applied Sciences*, **8**, 646. DOI: 10.1007/s42452-026-08670-6.
10. This is an **excellent reference for your paper** because it directly covers AI, sensors, heavy metals, environmental monitoring, IoT and challenges such as interpretability and field deployment.
11. Ijaz, U., Ali, M., Ahmad, I., Hamza, S. A., & Kim, H.-D. (2025). A comprehensive review of electronic nose systems: design, sensors, and future directions. *Chemical Engineering Journal*, **524**, 169482. DOI: 10.1016/j.cej.2025.169482.
12. This is particularly useful for your sections on **gas sensors, VOCs, sensor arrays and AI algorithms**.
13. Melikoglu, M. (2025). The electronic nose: A critical global review of advances in analytical methods and real-world applications. *Microchemical Journal*, **[volume/article details as published]**, 115363. DOI: 10.1016/j.microc.2025.115363.
14. Useful for discussing **data fusion, deep learning, environmental applications and real-world deployment** of electronic noses.
15. [Authors as published]. (2025). Application of machine learning to improve the accuracy of electrochemical sensors: A review. *Trends in Analytical Chemistry*, **193**, 118469. DOI: 10.1016/j.trac.2025.118469.
16. This is one of the **most directly relevant references** for your title because it discusses how ML can improve electrochemical sensor accuracy, stability and interpretation.
17. Mousazadehgavan, M., Hajalifard, Z., Basirifard, M., et al. (2025). The critical role of artificial intelligence in optimizing electrochemical processes for water and wastewater remediation: A state-of-the-art review. *ACS ES&T Water*, **5**(6), 2793–2811. DOI: 10.1021/acsestwater.5c00238.
18. This is useful when connecting your sensor technology with **water pollution, wastewater and AI-based environmental management**.
19. Jasper, I., da Rocha Rodrigues, R., Florencio, J. C., Sauer, H., Hryniewicz, B. M., & Vidotti, M. (2026). Recent advances and emerging strategies of electrochemical sensors for pesticides and toxic metals detection. *Discover Sensors*, **2**, 23.
20. Very useful for your sections on **pesticides and heavy-metal detection using electrochemical sensors**.
21. [Authors as published]. (2025). Electrochemical and photoelectrochemical aptasensors for the detection of environmental pharmaceutical pollutants.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Electrochimica Acta, 146396. DOI: 10.1016/j.electacta.2025.146396.

22. This gives you a reference for **emerging contaminants**, particularly pharmaceutical residues, which can broaden your paper beyond conventional heavy metals.
23. Ye, Z., Li, Y., Liu, Y., Wang, L., & Li, Q. (2021). Recent progress in smart electronic nose technologies enabled with machine learning methods. *Sensors*, **21**, 7620. DOI: 10.3390/s21227620.
24. A particularly good reference for **feature extraction, ML classification and sensor-drift compensation**.
25. [Authors as published]. (2023). Review on algorithm design in electronic noses: Challenges, status, and trends. *Intelligent Computing*, **2**. DOI: 10.34133/icomputing.0012.
26. Useful for explaining why **algorithm selection and model stability** are important in AI-based sensor systems.
27. [Authors as published]. (2022). Handling non-stationarity in E-nose design: A review. *Sensor Review*, **42**(1), 39–61. DOI: 10.1108/SR-02-2021-0038.
28. This is particularly useful for your discussion of **sensor drift and changing environmental conditions**.
29. Kasthuri, S., Devasena, D., & Dharshan, Y. (2025). Recent advancements and applications of electronic nose systems in environmental monitoring and pollution detection: A comprehensive survey. *Journal of Information Systems Engineering and Management*, **10**(7S). DOI: 10.52783/jisem.v10i7s.775.
30. This is directly relevant to your **environmental pollution + electronic nose + AI** discussion.
31. [Authors as published]. (2026). Harnessing the potential of artificial intelligence and 3D-printed electrochemical sensors for environmental analysis. *Current Opinion in Electrochemistry*, **55**, 101772. DOI: 10.1016/j.coelec.2025.101772.
32. This would be a particularly nice **future-perspective reference**, because it connects AI, 3D-printed electrochemical sensors and environmental analysis.
33. [Authors as published]. (2024). Electronic nose for the detection and discrimination of volatile organic compounds: Application, challenges, and perspectives. *Trends in Analytical Chemistry*.
34. Useful for your **VOC detection, gas-sensor arrays, PCA/SVM/ANN/CNN and sensor-drift** sections.
35. Mohd Nashruddin, S. N. A. B., Salleh, F. H. M., & Yunus, R. M. (2024). Artificial intelligence-powered electrochemical sensor: Recent advances, challenges, and prospects. *Heliyon*, **10**, e37964. DOI: 10.1016/j.heliyon.2024.e37964.
36. This is another strong **general AI + electrochemical sensor** reference and should definitely remain in your bibliography.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Artificial Intelligence for Sustainable & Environmentally Benign Chemical Science

Sangramsinh Shahajirao Bhosale
Dept. of Chemistry, Shripatrao Chaugle Arts & Science College Malwadi - Kotoli, Shivaji University Kolhapur

Manuscript ID:
BN-2026-030948

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 252-256

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22929885
DOI link:
https://doi.org/10.5281/zenodo.22929885

Abstract
Green chemistry seeks to prevent pollution at its source by reducing waste, energy demand, hazardous substances, and resource consumption. Artificial intelligence (AI), especially machine learning (ML), can strengthen this approach by learning from chemical and process data, predicting outcomes, screening large chemical spaces, and optimizing experiments. Recent literature identifies applications ranging from catalyst discovery and reaction optimization to CO_2 capture, sustainable polymers, waste management, water treatment, and process control. A 2026 review in Applied Intelligence highlights artificial neural networks, random forests, and Bayesian optimization as important approaches across these areas, while also emphasizing data quality, validation, energy use, and scalability as major concerns. (see References 1–6) This project reviews how AI can support the principles of green chemistry and proposes a practical research framework in which sustainability metrics are included directly in model objectives. The central idea is that an AI system should not merely maximize chemical yield; it should seek a balanced outcome involving yield, selectivity, waste, toxicity, energy, solvent impact, and resource efficiency. The report concludes that AI can become an enabling technology for greener chemistry when models are transparent, experimentally validated, and evaluated against environmental as well as technical performance.
Keywords: *Artificial intelligence, machine learning, green chemistry, sustainable chemistry, reaction optimization, catalysis, green solvents, waste minimization, CO_2 capture, sustainable materials.*

Introduction

Green chemistry is a preventive approach to chemistry that aims to design chemical products and processes so that hazardous substances and waste are reduced or eliminated. Traditional chemical development often relies on repeated laboratory experiments, which can consume significant quantities of reagents, solvents, energy, and time. AI provides a complementary route: computational models can analyze large datasets before experiments are performed, identify promising candidates, and suggest efficient operating conditions. Recent research shows that AI and data science are being applied to reaction optimization, new material discovery, process automation, and real-time environmental monitoring. A 2025/2026 open-access review describes AI as a tool for predicting chemical behavior and optimizing processes while noting persistent barriers such as insufficient high-quality data, limited interpretability, and weak cross-disciplinary integration. (see References 1–6) The combination is particularly attractive because green chemistry is inherently multi-objective. A reaction can have high yield but still be environmentally undesirable if it uses a toxic solvent, a rare catalyst, excessive energy, or produces difficult-to-treat waste. AI can help formulate and solve such multi-objective problems by combining chemical performance with sustainability indicators.

***Creative Commons** (CC BY-NC-SA 4.0)*
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sangramsinh Shahajirao Bhosale, Dept. of Chemistry, Shripatrao Chaugle Arts & Science College Malwadi - Kotoli, Shivaji University Kolhapur
Email: sangramsinhbhosale99@gmail.com

How to cite this article:
Bhosale, S. S. (2026). Artificial Intelligence for Sustainable & Environmentally Benign Chemical Science. Bulletin of Nexus Journal, 3(9(II)), 252–256. https://doi.org/10.5281/zenodo.22929885

Quick Response Code:

Website: https://bnir.us

Problem Statement

Chemical research and manufacturing face a dual challenge: producing useful chemicals efficiently while reducing environmental burden. Experimental trial-and-error can be slow and resource intensive, and conventional optimization may focus primarily on yield or cost. There is therefore a need for computational methods that can predict chemical outcomes and identify operating conditions that simultaneously satisfy performance and green-chemistry objectives. The research problem addressed in this project is: How can AI be integrated into chemical research to improve reaction efficiency while reducing waste, energy use, hazardous inputs, and environmental impact?

Aim And Objectives

Aim: To study the role of AI in advancing green chemistry and develop a conceptual framework for AI-assisted sustainable chemical research.

Objectives:

- Review major AI/ML methods relevant to green chemistry.
- Examine AI applications in reaction optimization, catalysis, solvent selection, sustainable materials, CO_2 capture/utilization, and waste management.
- Identify sustainability metrics that can be integrated into AI optimization. • Analyze benefits, limitations, data requirements, and validation needs.
- Propose a practical AI-assisted workflow for greener chemical experimentation.
- Suggest future directions for autonomous and data-driven sustainable chemistry.

Methodology

This project is designed as a literature-based research review and conceptual framework study. Recent peer-reviewed literature was examined to identify recurring AI techniques, application areas, benefits, and deployment challenges. The framework emphasizes evidence-backed use of machine learning rather than treating AI as a substitute for experimental chemistry. Proposed workflow: • Step 1 — Define the chemical problem and sustainability target. • Step 2 — Collect experimental, process, material, and environmental-impact data. • Step 3 — Clean data, standardize units, record metadata, and address missing values. • Step 4 — Generate chemical/process descriptors and sustainability indicators. • Step 5 — Train and compare suitable models such as random forests, neural networks, Gaussian-process models, or Bayesian optimization. • Step 6 — Use multi-objective optimization to balance yield, selectivity, energy, waste, toxicity, and resource use. • Step 7 — Experimentally validate predictions and feed new results back into the model. • Step 8 — Report uncertainty, interpretability, reproducibility, and environmental impact.

Major Applications of AI in Green Chemistry

1 Reaction Optimization

Machine learning can learn relationships between reaction conditions—such as temperature, time, solvent, catalyst loading, concentration, and reagent ratios—and outcomes such as yield or selectivity. Bayesian optimization and active learning can reduce the number of experiments needed by choosing informative experiments instead of testing conditions randomly. AI-driven reaction optimization is therefore well suited to minimizing experimental waste while reaching a target performance.

2 Catalyst Discovery and Design

Catalysts can lower activation barriers and reduce energy requirements, but identifying effective catalysts experimentally can be expensive. AI can screen candidate materials and molecular structures, learn structure–property relationships, and prioritize candidates for laboratory testing.

Recent reviews describe ML-supported virtual screening as a way to reduce the number of physical experiments required during catalyst discovery. (see References 1–6)

3 Green Solvent Selection

Solvent choice strongly affects toxicity, volatility, energy demand, waste generation, and worker safety. AI models can rank or predict solvent performance for a specific reaction and combine chemical compatibility with environmental descriptors. A green-solvent recommendation system could therefore optimize both reaction performance and solvent sustainability.

4 Sustainable Materials and Polymers

AI can accelerate the discovery of materials with desired mechanical, thermal, optical, catalytic, or separation properties. When sustainability descriptors are included, models can also prioritize lower-impact feedstocks, recyclability, durability, and reduced hazardous content. This supports materials-by-design approaches in which environmental performance is considered at the same time as technical performance.

5 CO_2 Capture and Conversion

AI can support the selection of sorbents, membranes, catalysts, and operating conditions for carbon capture and conversion. Models can evaluate large chemical spaces and help identify combinations that improve capture capacity, selectivity, regeneration efficiency, or energy

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

performance. Recent literature specifically identifies CO_2 capture and conversion as an active AI-for-green-chemistry application. (see References 1–6)

6 Waste Management and Water Treatment

AI can model pollutant removal, optimize treatment conditions, detect contamination, and support membrane or adsorption-process design. In chemical engineering, wastewater treatment and membrane technologies are among the most prominent areas of AI-for-sustainability research. (see References 1–6)

7 Process Optimization and Environmental Monitoring

At industrial scale, AI can monitor process variables, detect abnormal operation, predict equipment performance, and optimize energy and material flows. Real-time models can also assist environmental monitoring by detecting changes in emissions or water quality. Such applications connect green chemistry with sustainable chemical engineering and operational efficiency.

AI Methods Relevant to Green Chemistry

The appropriate method depends on the data volume, chemical problem, and need for interpretability.

AI/ML method	Potential green-chemistry use	Key advantage
Random Forest	Reaction/property prediction; solvent or catalyst ranking	rankingRobust and relatively interpretable
Artificial Neural Network	Nonlinear reaction/process modeling	Captures complex relationships
Bayesian Optimization	Selecting next experiments	Efficient optimization with fewer trials
Gaussian Process	Small-data optimization with uncertainty	Useful uncertainty estimates
Clustering	Grouping chemicals/materials/process states	Finds patterns without labels
Natural Language Processing	Mining chemical literature and patents	Extracts knowledge from text
Computer Vision	Monitoring color, crystals, defects, or experiments	Automates visual measurements

Sustainability Metrics for Ai Optimization

A key research recommendation is to avoid defining success only by chemical yield. AI systems intended for green chemistry should consider a vector of sustainability metrics. Useful indicators include:

- Atom economy: how efficiently reactant atoms are incorporated into the desired product.
- E-factor: mass of waste generated relative to product mass.
- Process mass intensity (PMI): total mass of materials used per mass of product.
- Energy intensity: energy required per unit of product.
- Solvent impact: toxicity, volatility, persistence, and quantity.
- Hazard/toxicity: risks associated with reactants, intermediates, products, and by-products.
- Carbon footprint: greenhouse-gas emissions across the relevant process boundary.
- Resource criticality: dependence on scarce or non-renewable elements and feedstocks.

A multi-objective AI model can search for solutions that provide a reasonable compromise among these metrics. This is important because improving one metric can unintentionally worsen another; for example, a higher yield may require a more energy-intensive temperature or a less desirable solvent.

Proposed Research Framework

The proposed project architecture is an iterative AI–Experiment–Feedback loop: Input data → Data preprocessing → Chemical descriptors + sustainability descriptors → AI model → Multi-objective optimization → Recommended experiment → Laboratory validation → New data → Model update The system should record not only successful experiments but also failures and unexpected outcomes. Experimental metadata—instrument, operator, batch, scale, purity, analytical method, temperature control, and solvent grade—should be captured where possible. This improves reproducibility and reduces hidden sources of model bias. The model should also report uncertainty. A prediction with high uncertainty should generally trigger additional experimental validation rather than being treated as a reliable fact. This is especially important when models are applied outside the chemical or process space represented in their training data.

Benefits of AI for Green Chemistry

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

• Reduces the number of physical experiments needed for optimization.
• Accelerates discovery of catalysts, materials, solvents, and reaction conditions.
• Supports simultaneous optimization of chemical performance and environmental impact.
• Helps identify patterns in large and complex chemical datasets.
• Enables real-time monitoring and predictive process control.
• Can support safer-by-design chemical development.
• Facilitates integration of automation, robotics, and self-driving laboratories.
• May reduce raw-material, solvent, energy, and waste requirements when deployed appropriately.

Challenges And Limitations

AI is not automatically green. Training and operating computational models can consume energy, and a model may recommend a chemically efficient process that shifts environmental burden elsewhere. Therefore, environmental claims must be evaluated using a defined system boundary.
• Data quality: inconsistent, sparse, biased, or poorly documented datasets can produce unreliable models.
• Interpretability: black-box predictions can be difficult for chemists to trust or validate mechanistically.
• Generalization: performance can deteriorate when models encounter new substrates, instruments, scales, or laboratories.
• Experimental validation: computational predictions must be tested in the laboratory before being treated as chemical knowledge.

• Reproducibility: model versions, preprocessing, descriptors, and experimental metadata should be documented.
• Computational footprint: AI itself has energy and hardware costs.
• Goal misalignment: optimizing yield alone can conflict with green chemistry objectives.
• Scale-up: conditions that work in a small laboratory reactor may not remain optimal at industrial scale.

Future Scope

The field is moving toward automated and autonomous chemical research. Future systems may combine AI models, robotic liquid handling, analytical instruments, process sensors, and closed-loop optimization. Recent reviews also identify quantum-computing/AI combinations, open data platforms, sustainable materials informatics, and automated laboratories as important emerging directions. (see References 1–6)

A particularly promising direction is green-by-design AI, in which environmental constraints are incorporated from the beginning rather than evaluated after a chemical process has already been optimized. Another important direction is cross-laboratory validation, where models are tested using independent data from different instruments, laboratories, and scales.

For academic research, a manageable experimental project could focus on a single reaction family and compare conventional one-factor-at-a-time optimization with Bayesian optimization. The study could measure the number of experiments required, final yield, energy consumption, solvent quantity, waste generation, and an aggregate greenness score.

Conclusion

Artificial intelligence has significant potential to support the transition toward greener and more sustainable chemistry. Its greatest value is not simply predicting chemical outcomes, but helping researchers search large design spaces while explicitly considering environmental objectives. Current literature demonstrates applications in reaction optimization, catalysis, sustainable materials, CO_2 capture and conversion, waste management, water treatment, and chemical-process optimization. (see References 1–6) However, AI should be treated as an enabling scientific tool rather than an automatic guarantee of sustainability. High-quality data, transparent models, uncertainty estimation, experimental validation, and life-cycle thinking are essential. A successful AI-for-green-chemistry system should optimize what matters to green chemistry: prevention of waste and hazards, efficient use of resources, lower energy
demand, safer chemicals, and sustainable production. Overall, the integration of AI with green chemistry provides a strong research direction for students and researchers because it combines computational science, chemistry, environmental sustainability, and experimental validation in one interdisciplinary framework.

Acknowledgement

I express my sincere gratitude to my teachers, mentors, and the Department of Chemistry for their continuous guidance, encouragement, and valuable support during the preparation of this research project. Their academic insights and constructive suggestions greatly contributed to the successful completion of this work.

Financial support and sponsorship

Nil.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Elkhatat, A., & Al-Muhtaseb, S. A. (2026). Harnessing Artificial Intelligence (AI) for a greener future: a review of AI advancements in green chemistry, chemical processes and sustainable materials. Applied Intelligence, 56, 306. DOI: 10.1007/s10489-026-07326-7. (see References 1–6)
2. Yadav, S., Chandra, H., Tiwari, K. S., et al. (2026). A review on the role of artificial intelligence and data science in green and sustainable chemistry: current trends and futuristic pathways. Discover Chemical Engineering, 6, 1. DOI: 10.1007/s43938-025-00104-w. (see References 1–6)
3. Ali, M., Mahmood, T., & Khan, F. (2026). Review of artificial intelligence applications in sustainable chemical engineering. Discover Sustainability, 7, 1181. (see References 1–6)
4. Role of artificial intelligence in the chemical industry transition to a sustainable, circular, and net-zero future. Current Opinion in Chemical Engineering, 51 (2026), 101234. DOI: 10.1016/j.coche.2026.101234. (see References 1–6)
5. Artificial intelligence-enabled electrosynthesis of chemicals: from sustainable synthesis to smart laboratory. Chemical Catalysis (2026), 101747. DOI: 10.1016/j.checat.2026.101747. (see References 1–6)
6. Synthetic organic chemistry driven by artificial intelligence. Nature Reviews Chemistry (2019). DOI: 10.1038/s41570-019-0124-0. (see References 1–6)

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Social Realism and the Representation of Marginalized Lives: A Comparative Study of Munshi Premchand and Mulk Raj Anand

Sushant Thakur
Assistant professor, Department: - English, Veerangna Masak Devi Nag Govt Model College Jawanga Geedam

Manuscript ID:
BN-2026-030949

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 257-262

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22929938
DOI link:
https://doi.org/10.5281/zenodo.22929938

Abstract

Indian literature has played a significant role in representing the realities of socially and economically marginalized communities. Among the writers who used literature as a medium for social criticism, Munshi Premchand and Mulk Raj Anand occupy important positions. Although they wrote in different linguistic and literary contexts, both authors were deeply concerned with poverty, caste discrimination, exploitation, and the unequal structures of Indian society. This paper comparatively examines the nature of social realism in selected works of Premchand and Mulk Raj Anand. Premchand's Godaan, Sadgati, and Kafan reveal the harsh realities of rural poverty, caste hierarchy, and agrarian exploitation, while Anand's Untouchable, Coolie, and Two Leaves and a Bud focus on untouchability, labour exploitation, colonial oppression, and the suffering of marginalized individuals. The study argues that both writers transformed ordinary and disadvantaged people into central figures of literary representation. However, their approaches to realism differ in emphasis and technique. Premchand presents social injustice largely through the collective experience of rural society and moral contradictions, whereas Anand frequently concentrates on the immediate experiences of individual victims of oppressive social structures. Through a comparative reading, the paper demonstrates that their writings not only document social realities but also question the systems responsible for human suffering. Their contribution remains important for understanding the development of social realism and socially committed literature in India.

Keywords: *Social realism, Premchand, Mulk Raj Anand, marginalization, caste, poverty, exploitation, Indian literature*

Introduction

Literature often provides an important space for examining realities that remain ignored or suppressed in official histories and dominant social narratives. The experiences of peasants, labourers, lower-caste communities, and economically disadvantaged people have frequently entered public consciousness through literary representation. In the Indian context, the early twentieth century was marked by colonial domination, economic inequality, rigid social hierarchies, and widespread poverty. These conditions created a strong need for literature that could move beyond romantic imagination and engage directly with social life. Social realism emerged as an important literary approach through which writers represented ordinary people and exposed the structures responsible for their suffering.

A comparison between Premchand and Anand is particularly meaningful because both writers shared a commitment to representing social realities, although they approached those realities differently. Premchand's realism is strongly connected with rural India, agrarian life, and the complicated relationships among caste, land, poverty, and traditional social institutions.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Sushant Thakur, Assistant professor, Department: - English, Veerangna Masak Devi Nag Govt Model College Jawanga Geedam
Email: sushant.2521@gmail.com

How to cite this article:
Thakur, S. (2026). Social Realism and the Representation of Marginalized Lives: A Comparative Study of Munshi Premchand and Mulk Raj Anand. Bulletin of Nexus Journal, 3(9(II)), 257-262.
https://doi.org/10.5281/zenodo.22929938

Quick Response Code:

Website: https://bnir.us

His works often present society as a broad network in which individuals are shaped by economic and cultural forces. Anand, in contrast, frequently constructs his narratives around the direct experiences of marginalized individuals. His characters encounter discrimination and exploitation in immediate and visible forms, allowing the reader to confront the psychological as well as social consequences of oppression. The present study examines social realism in selected works of the two writers, with particular attention to *Godaan*, *Sadgati*, and *Kafan* by Premchand and *Untouchable*, *Coolie*, and *Two Leaves and a Bud* by Mulk Raj Anand. The comparison focuses on the representation of poverty, caste, exploitation, marginalized lives, and the writers' attitudes towards social reform. The purpose is not merely to identify similarities and differences between the two authors, but to understand how their literary methods shaped two important forms of Indian social realism.

Objectives of the Study

The present study has the following objectives:

1. To examine the major features of social realism in the selected works of Munshi Premchand and Mulk Raj Anand.
2. To compare their representation of poverty, caste discrimination, exploitation, and marginalized communities.
3. To analyse the similarities and differences in their approaches to social reality and human suffering.
4. To evaluate their contribution to the development of socially committed literature in India.

Research Methodology

This study adopts a qualitative and comparative literary approach. It is primarily based on the close reading and textual analysis of selected works by Munshi Premchand and Mulk Raj Anand. The selected texts have been examined through common comparative parameters, including poverty, caste hierarchy, economic exploitation, marginalization, characterization, and social reform. The study also uses relevant critical perspectives on realism and Indian literature to understand the broader literary context of the two writers. Rather than treating the works as separate examples of social fiction, the paper places them in dialogue with one another. This comparative method makes it possible to identify both shared concerns and significant differences in their treatment of social reality. The analysis is limited to selected representative texts and does not attempt to cover the complete literary output of either writer. The purpose is to develop a focused comparison of how Premchand and Anand use fiction to represent marginalized lives and question unequal social structures.

Premchand and the Realism of Rural India

Munshi Premchand occupies a central position in the development of modern Indian fiction because of his sustained engagement with ordinary people and their social realities. His writings moved away from idealized representations of society and directed attention towards peasants, labourers, women, and marginalized communities. Poverty in Premchand's fiction is not merely a personal condition; it is closely connected with social institutions, economic inequality, and unequal relations of power.

In *Godaan*, Premchand presents the complex world of rural India through the life of Hori, a poor peasant whose desire for social respect and economic security remains largely unfulfilled. Hori's struggle represents more than individual misfortune. His life is shaped by debt, agrarian exploitation, social expectations, and the authority of powerful groups within the village. The novel demonstrates how poverty can become a continuing cycle in which the poor remain trapped despite constant labour and sacrifice. Premchand's realism is particularly effective because he does not present rural life as either completely harmonious or entirely hopeless. Instead, he reveals its contradictions, including community bonds, traditional values, exploitation, and human resilience.

The issue of caste becomes particularly sharp in *Sadgati*. The story exposes the cruelty of a social order in which human dignity is denied on the basis of caste. The suffering of Dukhi reflects the unequal relationship between marginalized communities and socially dominant groups. Premchand's treatment of caste is significant because the story avoids presenting discrimination as an isolated act of personal cruelty. Instead, the injustice emerges from a larger social system that normalizes inequality.

Kafan offers another dimension of Premchand's social realism. Through the characters of Ghisu and Madhav, the story raises uncomfortable questions about extreme poverty, social neglect, and the erosion of conventional moral expectations. Their behaviour cannot be understood simply through moral judgment. Premchand places their actions within a larger environment of deprivation and marginalization. The story therefore challenges the reader to consider how prolonged poverty can affect human relationships, responsibility, and emotional responses.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Premchand's realism is rooted in his understanding of society as an interconnected structure. Economic exploitation, caste hierarchy, tradition, and social expectations repeatedly influence the lives of his characters. His fiction does not offer easy solutions, yet it consistently encourages readers to recognize the human cost of social inequality. Through ordinary characters and familiar social situations, Premchand transformed rural life into a powerful subject of literary and social analysis.

Mulk Raj Anand and the Representation of Marginalized Lives

Mulk Raj Anand occupies an important place in Indian English literature for bringing the lives of socially excluded and economically vulnerable people into the centre of the novel. His fiction emerged in the context of colonial India, where caste discrimination, poverty, class inequality, and colonial economic structures shaped the lives of millions. Anand's social realism is therefore marked by a strong concern with the dignity of the individual. Instead of presenting marginalized people merely as background figures, he makes their experiences central to the narrative.

His novel *Untouchable* provides one of the clearest examples of this approach. The novel follows Bakha, a young sanitation worker who experiences the humiliations associated with untouchability during a single day. Anand's narrative exposes how caste operates through everyday social interactions. Bakha's exclusion is not limited to economic disadvantage; it affects his movement, social relationships, self-respect, and understanding of himself. The significance of the novel lies in its attempt to make the reader experience the social world from the perspective of someone placed at the margins of the caste hierarchy. Anand thereby transforms an abstract social problem into an intensely human experience.

The representation of poverty becomes broader in *Coolie*. Munoo, the young protagonist, moves through different environments in search of livelihood and security. His experiences reveal the vulnerability of poor workers within unequal economic structures. Anand presents poverty as a condition produced not simply by individual failure but by a social and economic system in which disadvantaged people possess very little control over their circumstances. Munoo's movement from one workplace to another also allows Anand to portray different forms of exploitation and class relations.

Two Leaves and a Bud extends this concern into the world of plantation labour under colonial rule. The novel depicts workers whose lives are controlled by economic and institutional forces. Colonial authority and the plantation system combine to create conditions in which labourers have limited power over their own lives. Through this setting, Anand connects individual suffering with larger structures of colonial exploitation. His realism thus moves beyond the representation of poverty itself and asks why certain groups are systematically denied dignity and power.

A distinctive feature of Anand's fiction is his attention to the psychological consequences of oppression. His marginalized characters are not simply victims; they possess desires, aspirations, frustrations, and a sense of dignity. Bakha, for example, desires recognition and a life free from the restrictions imposed by caste. Similarly, Munoo's search for a better life reflects the aspirations of a young person caught within an unequal economic order. By presenting these characters as complex human beings, Anand challenges literary traditions that reduce marginalized people to stereotypes.

Anand's social realism is also strongly connected with his commitment to social change. His narratives expose injustice with the intention of provoking ethical reflection. The reader is encouraged to question the legitimacy of institutions and practices that produce suffering. In this respect, Anand's fiction combines realism with protest. His novels do not merely reproduce social conditions; they invite readers to examine the moral consequences of those conditions.

Comparative Analysis of Premchand and Mulk Raj Anand

Poverty and Economic Exploitation

Poverty is one of the strongest points of connection between Premchand and Anand. Neither writer treats poverty simply as an unfortunate condition experienced by isolated individuals. Instead, poverty is presented as the consequence of larger social and economic arrangements.

In Premchand's *Godaan*, poverty is closely associated with agrarian life. Hori's dependence on land, debt, social obligations, and economically powerful groups demonstrates how the rural poor can become trapped within a cycle of indebtedness. Poverty also affects social status and personal dignity. Hori's economic difficulties cannot therefore be separated from the social expectations surrounding him.

Anand approaches economic deprivation through a somewhat different framework. In *Coolie*, Munoo's experiences expose the insecurity of labour and the vulnerability of people who have little economic power. In *Two Leaves and a Bud*, plantation workers are subjected to a system in which their labour sustains an economic structure from which they receive limited benefit. Anand consequently gives

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

greater emphasis to labour relations and the interaction between economic exploitation and colonial authority.

The difference is significant. Premchand's poverty is predominantly rooted in agrarian and traditional social structures, whereas Anand more frequently connects poverty with labour, class relations, and colonial economic institutions. Yet both writers reach a similar conclusion: poverty is not merely an individual's failure but a condition shaped by unequal structures.

Caste and Social Hierarchy

Caste is another major area of comparison. Premchand's *Sadgati* provides a direct critique of caste-based inequality. Dukhi's treatment demonstrates how caste can determine access to dignity, labour, social interaction, and recognition. The story exposes the contradiction between religious and social ideals and the actual treatment of marginalized people.

Anand's *Untouchable* similarly places caste discrimination at the centre of the narrative. Bakha's experiences reveal the everyday operation of untouchability. What makes Anand's treatment distinctive is his sustained focus on the consciousness of the marginalized individual. The reader is encouraged to understand discrimination not only as a social practice but also as an experience that affects self-respect and identity.

Both writers therefore reject the normalization of caste hierarchy. However, Premchand often presents caste within the broader social structure of the village, whereas Anand concentrates more intensely on the individual's experience of exclusion.

Representation of Marginalized Characters.

Both writers give literary visibility to people who were frequently absent from conventional representations of Indian society. Peasants, labourers, sanitation workers, and socially disadvantaged communities become central rather than peripheral figures.

Premchand's characters are often embedded within a larger social community. Hori's story, for instance, cannot be separated from the village, its institutions, customs, economic relationships, and social expectations. His individual struggle becomes representative of the difficulties faced by the rural poor.

Anand frequently narrows the narrative focus to an individual character whose experiences reveal the larger system. Bakha and Munoo are particularly important examples. Their personal experiences allow Anand to make social oppression emotionally immediate.

Thus, both writers humanize marginalized communities, but they employ different narrative scales. **Premchand frequently moves from the individual towards the social structure, while Anand often moves from the individual's experience towards a critique of the wider structure.**

Social Realism and Literary Technique

The realism of both writers depends upon their engagement with ordinary life. They avoid presenting society through idealized images and instead foreground conflict, deprivation, discrimination, and social contradiction.

Premchand's realism is particularly effective in his depiction of rural institutions and everyday relationships. His fiction often contains several social groups interacting within the same narrative space, allowing the reader to observe how power operates through community structures.

Anand's realism tends to be more direct and individual-centred. His narratives frequently place the reader close to the consciousness of marginalized characters. This psychological proximity intensifies the experience of discrimination and exploitation.

Their differences can therefore be understood as differences of emphasis rather than opposing literary philosophies. Premchand's realism is predominantly social and structural in its rural orientation, while Anand's realism combines social criticism with a pronounced psychological and individual perspective.

Humanism and Social Reform

Despite their differences, the deepest connection between Premchand and Anand lies in their humanistic concern. Both writers ask the reader to look beyond social labels and recognize the humanity of people who are denied dignity.

Premchand's criticism often emerges through irony, tragedy, social contradiction, and the consequences of poverty. His stories encourage readers to question customs and institutions that produce suffering.

Anand's criticism is generally more openly confrontational. His novels frequently place the injustice of caste, class, and colonial exploitation before the reader and encourage a moral response.

Their literature consequently performs two related functions: it **represents social reality and challenges the reader to reconsider that reality**. Neither writer treats literature as detached entertainment. Their fiction carries an ethical concern for social justice.

Major Similarities and Differences

The comparative reading reveals several important similarities. Both Premchand and Anand:

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

- focus on ordinary and marginalized people;
- expose poverty and exploitation;
- criticize caste-based discrimination;
- challenge unequal social structures;
- emphasize human dignity;
- use realism as a means of social criticism; and
- connect literature with the possibility of social awareness and reform.

At the same time, important differences emerge. Premchand's fictional world is strongly associated with **rural India, agrarian relations, caste structures, and traditional social institutions**. Anand's fiction gives greater prominence to **individual consciousness, labour relations, urban and industrial settings, and colonial structures of power**. Premchand often creates a broad social canvas, while Anand frequently intensifies the reader's engagement with an individual marginalized protagonist.

These differences make the comparison productive rather than repetitive. The two writers approach similar questions from different literary and social locations, allowing their works to illuminate different dimensions of Indian social reality.

Findings and Discussion

The comparative analysis establishes that social realism in Premchand and Mulk Raj Anand is grounded in a shared concern for people who remain disadvantaged within unequal social structures. Both writers shift literary attention away from privileged or idealized characters and towards peasants, labourers, sanitation workers, and other marginalized individuals. Their fiction consequently challenges the assumption that the lives of ordinary people are insignificant subjects for serious literature.

One of the principal findings is that **poverty is represented as a structural problem rather than merely an individual failure**. Premchand's *Godaan* connects poverty with indebtedness, agrarian dependence, social obligations, and unequal rural power relations. Anand's *Coolie* and *Two Leaves and a Bud*, on the other hand, reveal the vulnerability of workers within exploitative labour systems. Although their settings differ, both writers demonstrate that economic deprivation restricts individual freedom and dignity. Poverty in their fiction is therefore inseparable from the social institutions within which people live.

The second important finding concerns **caste and social exclusion**. Premchand's *Sadgati* and Anand's *Untouchable* expose the destructive consequences of caste hierarchy. Both writers demonstrate that caste is not simply a theoretical social category; it affects every day behaviour, labour, human relationships, and access to dignity. Anand's concentration on Bakha's experience makes the psychological impact of untouchability especially immediate, while Premchand places caste discrimination within the wider structure of village society.

A third finding is the difference in the **scale of representation** adopted by the two writers. Premchand generally constructs a broader social landscape in which individual characters are connected with family, village, caste, economic relations, and traditional institutions. Anand frequently concentrates on the individual consciousness of a marginalized protagonist. This difference does not indicate a fundamental disagreement between the writers. Rather, it demonstrates two complementary ways of representing oppression: Premchand often reveals the system through its social relationships, while Anand makes the reader encounter the system through the immediate experience of the individual.

The study also finds a significant difference in their treatment of **colonialism and economic power**. Premchand's major concern in the selected works is the complex interaction between rural poverty, caste, social customs, and economic exploitation. Anand more explicitly connects social suffering with colonial institutions and labour relations. His fiction therefore extends the question of marginalization from traditional social hierarchy to the structures of colonial capitalism.

Their works demonstrate that poverty, caste discrimination, and exploitation are sustained through social relationships and institutions. Their realism consequently possesses both an aesthetic and an ethical dimension.

Conclusion

The comparative study of Munshi Premchand and Mulk Raj Anand demonstrates the significant role of social realism in representing marginalized lives in Indian literature. Although the two writers worked in different linguistic and literary contexts, their fiction is united by a serious concern with poverty, caste discrimination, exploitation, and human dignity.

The major difference between the two writers is therefore one of emphasis rather than purpose. **Premchand generally develops a broad social vision rooted in rural and agrarian India, while Anand frequently approaches social injustice through the individual experience of caste and class oppression within a colonial environment.** Yet both writers ultimately question the structures that normalize inequality.

The comparative study thus concludes that Premchand and Anand represent two closely related but distinct modes of Indian social realism.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Premchand's expansive representation of rural society and Anand's focused portrayal of marginalized individuals together demonstrate the capacity of Indian literature to transform social experience into critical reflection. Their works remain valuable not only as literary texts but also as powerful engagements with the ethical and social realities of their time.

Acknowledgement
The author expresses sincere gratitude to the Principal and colleagues of Veerangna Masak Devi Nag Government Model College, Jawanga Geedam, for their encouragement, support, and academic guidance during the preparation of this research paper.
The author is deeply thankful to scholars, researchers, and literary critics whose valuable works on Munshi Premchand, Mulk Raj Anand, social realism, and Indian literature provided important insights and references for this study.

Financial support and sponsorship
Nil.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

References
1. Anand, M. R. (1935). *Untouchable*. Wishart Books.
2. Anand, M. R. (1936). *Coolie*. Lawrence & Wishart.
3. Anand, M. R. (1937). *Two leaves and a bud*. Wishart Books.
4. Anand, M. R. (2007). *The lost years: A memoir*. Penguin Books.
5. Asaduddin, M. (Ed.). (2018). *The complete short stories* (Vols. 1–4). Penguin Classics.
6. Lal, P., & Ratan, J. (Trans.). (1957). *The gift of a cow* (M. Premchand). Jaico Publishing House.
7. Premchand. (1936). *Godaan*. Saraswati Press.
8. Premchand. (2018). *The complete short stories* (M. Asaduddin, Ed.). Penguin Classics.
9. Premchand. (2020). *Godaan*. Hind Pocket Books.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

Bulletin of Nexus
Multidisciplinary International Research Journal, Double-Blind Peer Reviewed, Open Access Journal
ISSN : 3065-7865 / Volume-3, Issue-9(II), September 2026

Original Article

Potential of Vertical Farming as a Sustainable Livelihood Diversification Strategy for Small and Marginal Farmers in Beed District of Maharashtra

Pardeshi Poonam Dashrath[1], Dr. Meenal Annachhatre[2]
[1]Research Scholar, Department of Economics, Savitribai Phule Pune University, Pune
[2]Research Guide, Department of Economics, Savitribai Phule Pune University, Pune

Manuscript ID:
BN-2026-030950

ISSN: 3065-7865

Volume 3

Issue 9(II)

September 2026

Pp. 263-266

Submitted: 09 Aug 2026

Revised: 19 Aug 2026

Accepted: 14 Sept. 2026

Published: 30 Sept. 2026

DOI: 10.5281/zenodo.22929976
DOI link: https://doi.org/10.5281/zenodo.22929976

Abstract

Beed district of Maharashtra is characterized by recurring water scarcity, climatic variability, and limited livelihood opportunities, which particularly affect small and marginal farmers. Against this backdrop, the present study examines the potential of vertical farming as a sustainable livelihood diversification strategy for farming households in the district. The study is based on secondary data collected from government reports, research publications, policy documents, and relevant literature. It evaluates the potential of vertical farming in terms of efficient utilization of land and water resources, crop diversification, income generation, and livelihood resilience. The study also identifies key constraints, including high initial investment, technical requirements, energy costs, and limited market access. The findings suggest that, with appropriate technological, financial, institutional, and market support, vertical farming can complement conventional agricultural practices and provide an alternative avenue for enhancing income security and livelihood sustainability among small and marginal farmers in Beed district.

Key Words: *Vertical farming, Small and Marginal farmers, Landholding, Sustainable Livelihoods*

Introduction

Farming in Maharashtra's Beed district becomes more challenging. In order to raise crops like cotton and soybeans, the majority of farmers in this area have very limited land holdings and depend on merely rainfall. However, extended dry periods, unsuccessful monsoons, and recurrent droughts have become commonplace, causing crop destruction and financial hardship for people. With no other source of income, many young people are forced to leave their villages, and farmer distress continues to rise. There is an urgent need to find innovative ways to make money from the same little plot of land without requiring more water or risk.

Vertical farming provides an effective yet simple solution. Farmers can use less water and space by growing crops in layers on shelves, walls, or stacked trays rather than just on the ground. This method allows them to grow high-value vegetables, leafy greens, or herbs all year round, even in dry conditions. Studies show that such systems can increase harvests by 40-60% while using almost half the water compared to traditional farming. For a small farmer in Beed, this means turning a tiny plot into a steady source of income, reducing dependence on uncertain rains, and growing food that sells well in local markets.

The purpose of the study is to find out how small and marginal farmers in the Beed district might use vertical farming as a sustainable means of diversifying their sources of income.

***Creative Commons** (CC BY-NC-SA 4.0)*

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License, which allows others to remix, tweak, and build upon the work noncommercially, as long as appropriate credit is given and the new creations ae licensed under the identical terms.

Address for correspondence:
Pardeshi Poonam Dashrath, Research Scholar, Department of Economics, Savitribai Phule Pune University, Pune
Email: poonampardeshi0710@gmail.com

How to cite this article:
Pardeshi, P. D., & Annachhatre, M. (2026). Potential of Vertical Farming as a Sustainable Livelihood Diversification Strategy for Small and Marginal Farmers in Beed District of Maharashtra. Bulletin of Nexus Journal, 3(9(II)), 263–266. https://doi.org/10.5281/zenodo.22929976

Quick Response Code:

Website: https://bnir.us

In context of the district's dry climate and resource limitations, it aims to investigate the feasibility and possible advantages of vertical farming while identifying the technical, financial, and social obstacles that might prevent its adoption. The study also aims to provide suitable institutional interventions, community-based mechanisms, and government support to encourage small and marginal farmers to adopt vertical farming approaches that are accessible, inexpensive, and economically feasible.

Review of Literature

(Sonawane, 2018) The study examines vertical farming as an emerging agricultural technology in response to major challenges such as population growth, declining cultivable land, water scarcity, climate change, labour shortages and urbanization. The study, based on secondary data from research journals, books, websites and reports, explains different vertical farming systems, particularly hydroponics, aeroponics and aquaponics, and discusses their advantages, disadvantages and feasibility in India. The paper highlights that vertical farming can provide high production per unit of land, use substantially less water and soil, enable year-round production, reduce transportation-related losses and support pesticide-free cultivation. However, the study also identifies important limitations, including high initial investment, high energy requirements, the need for skilled labour, technical challenges and questions regarding economic viability and public acceptance. The paper notes that vertical farming had begun to emerge in India through small-scale initiatives and technological enterprises, but concludes that its wider adoption requires greater awareness, technical knowledge, affordability, infrastructure and economic feasibility. (Aditi Saha Roy, 2024) the study explain that vertical farming can help address the growing problems of limited land, water scarcity, climate change, and declining soil fertility. The study discusses hydroponics, aeroponics, aquaponics, and controlled-environment agriculture as important methods of vertical farming. It highlights that these systems can use land more efficiently, reduce water use, support year-round production, and lower the need for chemical pesticides. The study also reveals that hydroponic farming may use nearly 13 times less water than conventional farming while producing considerably higher lettuce yields per unit area. However, the authors point out that high initial investment, electricity and maintenance costs, technical complexity, shortage of skilled workers, and uncertain market prices remain major barriers, particularly in India.

Objectives:

1. To examine the potential of vertical farming as an alternative and supplementary livelihood diversification strategy.
2. To analyse the opportunities and challenges associated with the adoption of vertical farming in the context of Beed district.

Research Methodology

The present study is based entirely on secondary data and adopts a descriptive and analytical research design. The study examines the potential of vertical farming as a sustainable livelihood diversification strategy for small and marginal farmers, with special reference to the agricultural and resource conditions of Beed district, Maharashtra. Secondary data were collected from reliable and relevant published sources, including reports and publications of government and institutional agencies such as the Government of Maharashtra, Maharashtra Agriculture Department, Directorate of Economics and Statistics, NABARD, India Meteorological Department (IMD), Agriculture Census, District Statistical Office, and other relevant government departments. In addition, information was collected from research papers, peer-reviewed journals, institutional reports and recent published literature relating to vertical farming, protected cultivation, sustainable agriculture and rural livelihoods.

Data Analysis

Table 1: Socio-economic vulnerability profile of Beed district

Indicator	Value
Landholders below 2 hectares	83.04%
Rural population share	~80% (20.71 lakh of 25.85 lakh)
Average annual rainfall	666.36 mm
Groundwater depth, summer	12-15 meters
Groundwater decline	-1.38 meters
Farmer suicides, Beed district	269 (2023); 256 (2025) - highest in Marathwada
Marathwada farmer suicides, 5-year total	5,075 (2021-2025); 1,129 in 2025 alone

Source: NABARD district report (2023-24); Census of India (2011); Groundwater Survey and Development Agency, Government of Maharashtra; Divisional Commissioner's office, Chhatrapati Sambhajinagar.

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

The above table highlight the vulnerability of small and marginal farmers in Beed district, where 83.04% of landholders operate holdings of less than two hectares, indicating a highly fragmented landholding structure. This vulnerability is further increased by the district's relatively low and uneven rainfall of 666.36 mm, increasing dependence on limited groundwater resources, with summer groundwater levels reaching 12–15 meters and a reported decline of 1.38 meters in 2023. The high incidence of farmer suicides in Beed and the wider Marathwada region further reflects the economic and livelihood challenges associated with agriculture. Collectively, these conditions demonstrate the need to explore supplementary and alternative livelihood strategies that require limited land and utilize water and other resources efficiently. In this context, vertical farming has potential as a sustainable livelihood diversification strategy for small and marginal farmers, particularly through intensive production on limited land, efficient water utilization, and opportunities for cultivating high-value crops.

Table 2: Resource requirements - vertical farming versus conventional cultivation

Parameter	Vertical Farming	Conventional Farming
Water requirement	70-90% lower	Baseline
Land requirement, equivalent output	95-99% lower	Baseline
Yield per unit area	10-20 times higher	Baseline
Dependence on rainfall	None	Complete

Source: Comparative studies of hydroponic and conventional cultivation (2024); reviews of modern agricultural technology and land-use efficiency (2025).

The comparison presented in the table demonstrates the potential advantages of vertical farming as a livelihood diversification strategy for small and marginal farmers, particularly in resource-constrained regions such as Beed. Compared with conventional farming, vertical farming can require 70–90% less water, 95–99% less land for equivalent output, and can generate 10–20 times higher yield per unit area, while eliminating direct dependence on rainfall. These characteristics are particularly relevant to Beed district, where small and marginal farmers face constraints related to limited landholdings, water scarcity and uncertain rainfall conditions. The findings therefore suggest that vertical farming has the potential to complement conventional agriculture by enabling intensive production with more efficient utilization of land and water resources. However, the practical adoption of vertical farming may depend on factors such as initial investment, technical knowledge, energy requirements, access to markets and institutional support, which need to be considered while assessing its overall suitability for small and marginal farmers.

Opportunities associated with adoption of Vertical Farming in Beed District

Severe water scarcity makes water-efficient methods essential

Beed received only about 50% of its normal monsoon rainfall by early September 2026, with August recording just 25 mm over two rainy days, the sharpest dry spell in five years. Long-term average annual rainfall is only around 750 mm, and the district has faced repeated droughts. Vertical cropping system use 90–95% less water than open-field farming, making them ideal for such conditions.

Small landholdings favour space-intensive farming

In Beed, more than 83% of farmers possess less than two hectares, which restricts the growth of the area. Hydroponic NFT systems may produce 18-25 kg of leafy greens per square meter annually, while traditional fields can only yield 2-4 kg. Vertical farming increases output per square meter. Potential yields for some crops surpassing 200 kg/m² are reported by some optimized greenhouse models.

High-value crops can boost off-season income

With rainfed crops like soybean giving low and unstable returns, vertical farming allows growing high-value crops (spinach, basil, strawberries) during dry months. Small vertical units (50-100 sq. m) can add ₹80,000-₹1,20,000 per year to household income without replacing the main crop.

Supplementary income improves household resilience

For a farmer with only 100 sq. m of usable space, vertical farming could mean 1,800-2,500 kg of produce annually, generating ₹54,000-₹1,12,500 at farm-gate prices of ₹30-45/kg. This extra income can help meet daily expenses, repay loans, or invest in children's education.

Challenges associated with adoption of Vertical Farming in Beed District

High initial cost is the biggest barrier

Even a modest hydroponic or vertical setup for 1,000 sq. ft (about 93 sq. m) requires ₹1.8-2.5 lakh for basic infrastructure like channels, pumps, tanks, and shade nets. Larger commercial units (1 acre) can cost ₹1.7-2.2 crore, with per-square-meter capital costs

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)

ranging from ₹4,200 to ₹5,500. For a marginal farmer in Beed earning less than ₹65,000 per acre annually, this is unaffordable without heavy subsidies.

Lack of technical knowledge and training

Vertical farming requires understanding of nutrient solutions, pH management, pest control in closed systems, and climate regulation skills, but most Beed farmers have never been trained in it. While Krishi Vigyan Kendras (KVKs) and NGOs operate in the district, their focus remains on conventional crops and water conservation, not soilless or layered cultivation.

Unreliable electricity supply

Electricity is necessary for vertical systems to run timers, pumps, and occasionally LED lights. Beed still experiences regular power cuts, particularly in the summer, which can interfere with irrigation schedules and harm delicate crops. This can be resolved by solar-powered systems, but they are more expensive initially.

Weak market linkages for perishable produce

Leafy greens and herbs are highly perishable and need quick sale. Beed lacks dedicated collection centers, cold chains, or tie-ups with urban retailers for such produce. Without assured buyers, farmers may be forced to sell at distress prices or let produce go to waste.

Inconsistency in policy and restricted coverage of subsidies

While schemes like the Mission for Integrated Development of Horticulture (MIDH) offer up to 50% subsidy for protected cultivation, vertical farming is not explicitly included in most state guidelines. This leaves farmers unsure whether they qualify for support, slowing down adoption.

Conclusion

The vertical farming has good potential to provide an additional livelihood option for small and marginal farmers in Beed district, especially because it requires less land and water and is less dependent on rainfall. However, its adoption may be difficult for farmers due to high initial costs, technical requirements, energy needs and limited access to finance. Therefore, proper government support through subsidies, training, shared infrastructure, renewable energy and suitable financial support is important. Overall, vertical farming can be a useful and sustainable option for farmers in Beed, but its actual acceptance and benefits need to be confirmed through a primary field survey.

Acknowledgement

I express my sincere gratitude to my Research Guide, Dr. Meenal Annachhatre, Department of Economics, Savitribai Phule Pune University, Pune, for her valuable guidance, encouragement, and continuous support throughout the preparation of this research study.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

References

1. Aditi Saha Roy, S. D. (2024). Vertical farming: A sustainable agriculture format of the future. International Journal of Research in Agronomy.
2. Sonawane, M. S. (2018). Status of Vertical Farming in India. International Archive of Applied Sciences and Technology.
3. The Tribune. (2023-2024). Reports on Marathwada and Beed district farmer suicides. Retrieved from https://www.tribuneindia.com/
4. Government of Maharashtra, Department of Agriculture. (2011). Agriculture Census Maharashtra state report, 2000-01 and 2010-11. Retrieved from https://www.krishi.maharashtra.gov.in/
5. IMARC Group. (2026). India vertical farming market size and growth. Retrieved from https://www.imarcgroup.com/india-vertical-farming-market
6. Indian Districts Project. (2026). Agriculture: Beed, Maharashtra. Retrieved from https://indiandistricts.in/statistics/maharashtra/beed/agriculture/

© 2026 Bulletin of Nexus| Published by: Royal International Global LLC (USA)