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Original Article

Smart Analytical Methods for Detecting Contaminants in Food Products: A Technological Rise toward Food Safety

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Abstract

Food product safety and quality are difficult challenges to address in the context of a modern, globalized, industrialized food supply chain. With growing concerns over contamination arising from harmful chemical residues, pathogenic microorganisms, heavy metals, allergens, and physical particles, the global demand for rapid, reliable, portable, and on-site detection solutions – in an increasingly rich data environment – is constantly increasing. Laboratory-based methods, including gas chromatography (GC), high-performance liquid chromatography (HPLC), and atomic absorption spectroscopy (AAS), remain the gold standard, but often require higher costs, lengthy sample preparation, and longer reporting times. This study provides insights into the transformative role of smart analytical approaches to revolutionizing food safety analyses. Technologies such as Surface-Enhanced Raman Spectroscopy (SERS), near-infrared (NIR) spectroscopy, electrochemical biosensors, lab-on-a-chip (LOC) instruments, and platforms that utilize Artificial Intelligence (AI) have been presented as new alternatives. These techniques allow for real-time monitoring, have high sensitivity and low sample preparation, and are portable/convenient.This paper presents a series of case studies and real-life applications of smart systems are being used for the early detection of spoilage, adulteration, and pathogens, especially in average-perishables, grains, and high-perishable foods (such as oils and dairy), and presents the development of continuous tracking and monitoring using IoT-based systems to guarantee traceability and accountability from producers to consumers. In reviewing traditional versus smart methods, this study highlights the overall impact of area of cost, speed, and sustainability. Finally, emerging technologies, nanomaterials, wearable sensors, and blockchain integration are noted as future references in food safety. In conclusion, the deployment of smart analytical solutions provides an advantage for building more resilient, dynamic, and health-based food systems worldwide.

Keywords: *Types of Food Contaminants and Associated Health Risks, Overview of Smart Analytical Methods, Case Studies, Future Directions and Emerging Technologies, Comparative Analysis.*

Introduction

1. Food is more than a fundamental human requirement, but is also one of the most influential determinants of the health, economy, and social stability of our planet. However, food contamination, whether accidental or intentional, can have severe implications. Contaminants such as pesticides, heavy metals, mycotoxins, antibiotics, pathogenic microorganisms, and micro plastics can compromise food quality and safety.
2. Traditional analytical approaches, such as gas chromatography (GC), high-performance liquid chromatography (HPLC), and atomic absorption spectroscopy (AAS), although reliable measurements, are often cost inhibitive, require trained personnel, and cannot be used to detect food contamination onsite or in real time. Because of these limitations, smart analytical methods have been developed, including complex systems that provide rapid, sensitive, portable, and automated detection of food contamination using a broad variety of contaminants.

Types of Food Contaminants and Associated Health Risks

1. **Biological Contaminants:**
   Biological contaminants are the primary cause of foodborne illnesses worldwide.

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Biological contaminants include a range of pathogens, including bacterial pathogens (Salmonella spp., Escherichia coli O157, Listeria monocytogenes, Campylobacter jejuni, viruses (norovirus, hepatitis A), parasites (Toxoplasma gondii, Cryptosporidium spp.), and toxins produced by fungi (aflatoxins, ochratoxin A, deoxynivalenol). Health impacts range from mild gastrointestinal discomfort to grave illnesses, including hemolytic uremic syndrome, meningitis, and even death, particularly in sensitive populations, including children, the elderly, pregnant women, and patients with compromised immune systems (Scallan et al., 2011).

2. **Chemical Contaminants:**
   Chemical contaminants in food include pesticide residues, veterinary drug residues, heavy metal residues (lead, mercury, cadmium, and arsenic), industrial contaminants (dioxins and polychlorinated biphenyls), and contaminants of processing (acrylamide and heterocyclic amines). Chemical contaminants are known to produce both acute toxicity and a range of chronic health effects, including neurodevelopmental disorders, disruption of reproductive development, carcinogenicity, and reproductive toxicity (Rather et al., 2017). Although many chemicals do not pose toxic risks at sub-toxic levels, when consumers are repeatedly exposed to these chemicals over a long period of time, they can produce significant cumulative public health concerns.
3. **Physical contamination:**
   Physical contaminants include objects that are not product components but originate from outside the food product during processing or packaging. Physically contaminated foods include glass, metal, plastic, stones, and bones. Although not always the case, most physical contaminants are visible to the naked eye. Severe health issues may arise from Som crisps and even contorted perc, including, but not limited to, dental problems, laceration, choking, and internal injury (Wallace et al., 2016).
4. **Contaminants from allergens:**
   Food allergens can be a serious safety issue when they are present in the product(s) through cross-contaminants. Major food allergens are peanuts, tree nuts, milk, eggs, fish, shellfish, and wheat. It is not uncommon for susceptible consumers to react to life-threatening anaphylaxis rather than minor skin irritation (Sicherer & Sampson, 2018).

Overview of Smart Analytical Methods

1. Surface-Enhanced Raman Spectroscopy (SERS)
   SERS increases the Raman scattering of molecules adsorbed on roughened metal surfaces (or nanoparticles) to provide a powerful non-destructive method for trace contaminants in food products, including pesticides and food dyes. Additionally, SERS can be utilized in field formats because of its portability and limited sample preparation.
2. **Near-Infrared Spectroscopy (NIR)**
   NIR spectroscopy uses electromagnetic radiation in the range of 780–2500 nm (near-infrared). It is most commonly used for non-destructive testing of moisture, fat, and protein content in food products. Consequently, unwanted adulterants, including urea, can also be detected in milk.
3. **Electrochemical Biosensors**
   Electrochemical biosensors use biological recognition elements (e.g., antibodies, enzymes and DNA) in conjunction with electrochemical transducers. They are designed to detect glucose, aflatoxins, pathogens, and antibiotics in food. They are inexpensive, sensitive, and miniaturized.
4. **Lab-on-a-Chip (LOC)**
   LOC systems have microfluidic chips that reduce laboratory laboratory procedures. LOC systems have a much smaller sample size and can simultaneously identify multiple contaminants in smaller sample volumes. In addition, LOC systems provide results very quickly, frequently requiring very little reagent usage.
5. **Artificial Intelligence (AI) and Machine Learning (ML)**
   AI has a profound effect on boosting the ability of food safety monitoring programs and standards with predictive modelling, pattern recognition, and data analytic capabilities. Various machine learning algorithms can also easily analyze spectral data or images to classify contaminant types and spoilage, and offer evaluations related to freshness.
6. **Devices based on the Internet of Things (IoT)**
   IoT platforms are used in combination with sensors, cloud computing, and mobile applications to enable real-time remote food monitoring throughout the supply chain. Smart packaging using RFID tags and sensors can potentially demonstrate the effects of temperature variations, gas emissions, and pH (pH representing spoilage).

Methodology

This study employed an analytical and descriptive research design and secondary data obtained from industry reports, patents, case studies in general, and peer-reviewed research publications. The focus of this study is as follows:

- Bringing together for smart methods to detect and assess their merits, disadvantages, and main principles.
- Contrasting smart methods with traditional methods with respect to cost, mobility, speed, and sensitivity.
- Identifying existing commercial devices and practical examples.

Case Studies: Successful Applications of Intelligent Detection Methods

1. **Rapid Pathogen Identification in Fresh Produce**
   A major outbreak of E. coli O157 in leafy greens prompted a production company to implement an electrochemical biosensor system for preharvest testing. The system allowed real-time harvesting decisions by reducing the detection time from 48 h to 45 min. Over a two-year period, this implementation avoided an estimated $2.3 million in potential recalls and related brand damages.
2. **Grain Storage Mycotoxin Monitoring**
   A grain cooperative used machine learning algorithms in conjunction with NIR spectroscopy to continuously check stored grains for mycotoxin development.
3. **Identification and Detection of Food Adulteration in Rich Items**
   An expert food retailer guarantees the purity of premium olive oils at receiving points using an on-demand SERS system. The technology determined cases of superior oil adulteration in 7% of deliveries that would have gone unnoticed by the traditional methods of quality control. . By avoiding fraud and protecting the reputation of the brand, the system was paid for in four months (Temiz et al., 2020).

New Future Directions and Technologies

1. **Nanotechnology-enhanced recognition**: Continued development of new nanomaterials that have recently been emerging, such as quantum dots, carbon nanotubes, and metal-organic frameworks, will continue to improve system sensitivity and selectivity.
2. **Inclusion of IoT:** The possibility that IoT adds to the mechanical collection and analysis of data and real-time monitoring of supply chains can be achieved with smart analytical devices and IoT infrastructure. Networked sensors can monitor their surroundings, understand particles, and set off immediate reactions. In addition, this connectivity enables block chain-based traceability to promote responsibility and willingness (Li et al., 2020).
3. **Wearable and Implantable Sensors for Continuous Monitoring:** Emerging wearable technologies for food safety workers include smart gloves with embedded sensors capable of detecting surface contamination, and digital reality systems that overlay testing data onto actual items. There are numerous wearable and implantable sensors for continuous monitoring. Research on implantable sensors that can track internal conditions and microbiological status without compromising packaging integrity continues to advance for the long-term storage of edible goods (Gao et al., 2021)

Comparative Analysis: Traditional vs. Smart Methods

With growing concerns regarding food safety, it is vital to evaluate how modern smart analytical methods outperform traditional techniques. The following is a comparative overview:

Parameter	Traditional Methods	Smart Analytical Methods
Detection Time	Hours to days (e.g., HPLC, GC, culture methods)	Seconds to minutes (e.g., biosensors, NIR, SERS)
Sensitivity	Very high (detects trace amounts)	High to very high (ppb/ppm level)
Portability	Limited; lab-based instruments	High; portable devices and handheld scanners
User Expertise	Requires trained personnel	Can be operated by semiskilled users or consumers
Sample Preparation	Extensive (extraction, filtration, dilution)	Minimal or no preparation needed
On-site Applicability	Rare; mostly off-site laboratory analysis	High; many tools are designed for field or onsite use
Automation	Manual and time-intensive	AI-integrated, real-time data processing and alerts
Cost (per test)	High (due to chemicals, equipment, and labor)	Low to moderate (once device is installed)
Real-Time Monitoring	Not feasible	Possible with IoT and sensor integration
Environmental Impact	Uses chemicals, generates waste	Low impact; eco-friendly designs and reusable components

Literature Review

As food products and their ingredients become increasingly contaminated and polluted, food safety has become a serious global issue. Traditional analytical approaches can be accurate, but they take time, have large sample preparation requirements, and use centralized laboratories to assess food product authenticity. Smart packaging systems with sensors are increasingly used to monitor the quality of food products in real time with respect to contamination or decay. These smart approaches can even help food safety monitoring and quality assurance across the supply chain, supporting better health, transparency, and sustainable food practices across the food system.

Conclusion

Smart analytical methods are establishing a new paradigm in the field of food safety and contaminant detection. It provides rapid, accurate, and non-invasive solutions to conventional approaches that empower consumers, regulators, and producers. As the global food system becomes more complex, smart tools will continue to play a vital role in protecting health, maintaining transparency, and promoting sustainable food practices.

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Conflicts of interest

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

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