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Role of Chemical Sensors in Detecting Food Contaminants and Ensuring Safety: A Review

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ABSTRACT: Food safety is a major public health concern, with contaminants such as pesticides, heavy metals, microbial toxins, and chemical adulterants posing significant risks (Ahmed, Zhang, & Liu, 2022). Chemical sensors offer rapid, reliable, and cost-effective solutions for detecting contaminants, utilizing electrochemical, optical, and biosensing technologies to ensure accurate and real-time monitoring (Chen, Zhang, & Lin, 2020). This review examines advancements in sensor technology, its role in improving food safety, and the challenges hindering commercialization. Additionally, case studies demonstrate the effectiveness of these sensors in detecting common contaminants, highlighting the need for continued innovation and regulatory support to strengthen global food safety measures.

KEYWORDS: Chemical sensors, food safety, contaminants detection, biosensors, electrochemical sensors, optical sensors

I. INTRODUCTION

Food safety remains a global concern, with rising cases of foodborne illnesses and chemical contamination threatening public health and economic stability (Smith & Roberts, 2021). Contaminants such as pesticides, heavy metals, mycotoxins, antibiotics, and industrial pollutants can enter the food chain at various stages, from production to packaging and distribution, necessitating stricter regulations and monitoring techniques (Kim, Park, & Lee, 2022).

Traditional detection methods like chromatography (gas and liquid chromatography) and spectrometry (mass spectrometry, atomic absorption spectrometry) offer high accuracy, but they are costly, labour-intensive, require skilled personnel, and involve complex sample preparation (Lee, Park, & Kim, 2019). Moreover, these techniques lack real-time monitoring, limiting their effectiveness in rapid food safety assessments (Patel, Sharma, & Kaur, 2021)

Chemical sensors provide a fast, reliable, and cost-effective alternative for on-site detection with minimal sample preparation. These sensors function through electrochemical, optical, and biosensing technologies, allowing the identification of a wide range of contaminants (Zhang, Li, & Zhao, 2020). Electrochemical sensors detect changes in electrical properties, optical sensors rely on fluorescence, absorbance, or surface plasmon resonance, and biosensors use biological elements like enzymes, antibodies, or DNA to improve sensitivity and selectivity.

Technological advancements in nanotechnology, material science, and artificial intelligence (AI) have significantly enhanced sensor performance. Nanomaterials such as graphene, quantum dots, and gold nanoparticles have improved sensor sensitivity, stability, and detection limits. Additionally, AI and IoT integration enables real-time monitoring, automated data analysis, and efficient food quality control (Wang, Liu, & Sun, 2022).

Beyond laboratory and industrial use, smart food packaging equipped with embedded sensors offers continuous monitoring of freshness, spoilage, and contamination, improving traceability across the food supply chain. This innovation empowers consumers with real-time safety information, reinforcing global food safety efforts (Patel & Mehta, 2022).



This review explores chemical sensor technology, its applications in food safety, recent technological advancements, and future potential developments, highlighting their role in revolutionizing food monitoring and addressing key challenges in global food security.

II. SCOPE & OBJECTIVES

- To Provide an overview of chemical sensors, explaining their working principles for detecting food contaminants (Zhang & Zhao, 2023).
- To Examine various food contaminants, including pesticides, heavy metals, microbial toxins, and chemical adulterants (Luo & Jiang, 2021).
- To Highlight recent advancements in chemical sensor technology for food safety applications (Wang, Liu, & Sun, 2022).
- To Discuss real-world case studies showcasing the effectiveness of chemical sensors in detecting food contamination (Singh, Patel, & Kumar, 2021).
- To Address challenges in commercialization and propose future directions for integrating chemical sensors into food safety regulations (Smith & Roberts, 2021).

III. TYPES OF CHEMICAL SENSORS IN FOOD SAFETY

- **Electrochemical Sensors:** Measure electrical signals to detect pesticides and heavy metals in food. Nanomaterial-based sensors improve sensitivity and selectivity (Ahmed, Zhang, & Liu, 2022).
- **Optical Sensors:** Use fluorescence, absorbance, and Raman spectroscopy to identify contaminants like mycotoxins, antibiotics, and adulterants. SERS technology enhances trace-level detection (Kim, Park, & Lee, 2022).
- **Biosensors:** Utilize enzymes, antibodies, or DNA to detect foodborne pathogens and toxins, with advancements in DNA-based biosensors and immunosensors improving detection accuracy (Lee, Park, & Kim, 2019)
- **Gas Sensors:** Identify volatile organic compounds (VOCs) from spoilage, oxidation, or contamination using MOS sensors and electronic noses (e-noses) for food freshness monitoring (Patel, Sharma, & Kaur, 2021).
- **Colorimetric Sensors:** Offer simple, cost-effective detection through color changes, with paper-based sensors enabling on-site identification of pathogens and contaminants (Kumar et al., 2020).
- **Nanomaterial-Based Sensors:** Graphene, gold nanoparticles, and quantum dots enhance sensor performance, providing high sensitivity, stability, and real-time monitoring (Luo & Jiang, 2021).
- **Wearable & Smart Packaging Sensors:** Integrated into smart packaging and wearable devices, enabling continuous monitoring of food quality, freshness, and contamination in real time (Patel & Mehta, 2022).

IV. COMMON FOOD CONTAMINANTS AND DETECTION METHODS

- **Pesticides:** Electrochemical sensors and biosensors detect organophosphates and carbamates, with recent advancements in enzyme-based biosensors and nanomaterial-modified electrodes for improved selectivity.
- **Heavy Metals:** Nanomaterial-based sensors efficiently identify lead, mercury, and arsenic, utilizing graphene oxide and gold nanoparticles for enhanced sensitivity and real-time monitoring.
- **Microbial Toxins:** Optical biosensors enable aflatoxin and mycotoxin detection, with aptamer-based biosensors offering rapid and highly selective toxin identification.
- **Chemical Adulterants:** Surface-Enhanced Raman Spectroscopy (SERS) sensors help detect melamine and formalin in dairy and seafood, with portable SERS devices enabling on-site testing.
- **Antibiotic Residues:** Electrochemical and optical biosensors track tetracyclines, sulphonamides, and β -lactams in food products, with molecularly imprinted polymers (MIPs) enhancing specificity.
- **Foodborne Pathogens:** Biosensors incorporating DNA, antibodies, and enzymatic reactions detect Salmonella, E. coli, and Listeria, with emerging graphene-based and smartphone-integrated solutions enabling rapid detection.



- **Food Fraud and Mislabelling:** Spectroscopic and electrochemical sensors uncover mislabelled meat, diluted juices, and counterfeit spices, with Isotope Ratio Mass Spectrometry (IRMS) and paper-based sensors aiding fraud detection.
- **Microplastics and Nanoplastics:** Advanced spectroscopic and fluorescence-based sensors identify microplastics in bottled water, seafood, and salt, with quantum dot-based fluorescence sensors improving detection accuracy.

V. CASE STUDIES

5.1 Electrochemical Sensors for Pesticide Detection

Zhang et al. (2020) conducted a study on an electrochemical sensor utilizing graphene oxide for the swift detection of organophosphate pesticides in vegetables. The sensor demonstrated high sensitivity and selectivity, delivering accurate results within minutes (Zhang, Li, & Zhao, 2020).

5.2 Biosensors for Aflatoxin Detection in Dairy Products

Lee et al. (2019) conducted a study developing a biosensor utilizing aptamer-based recognition for detecting aflatoxins in milk samples. The sensor demonstrated high accuracy and enabled real-time monitoring, enhancing food safety detection capabilities (Lee, Park, & Kim, 2019).

5.3 Heavy Metal Detection in Seafood Using Nanomaterial-Based Sensors

Singh et al. (2021) conducted a case study on a nano-enabled electrochemical sensor designed for mercury detection in fish samples. The sensor exhibited high precision, effectively meeting regulatory safety standards for food safety monitoring (Singh, Patel, & Kumar, 2021).

5.4 SERS-Based Sensor for Detecting Melamine in Infant Formula

Chen et al. (2022) conducted a study using Surface-Enhanced Raman Spectroscopy (SERS) to identify melamine adulteration in infant formula. The sensor exhibited high specificity and enabled rapid detection, helping mitigate the risks of food fraud and contamination.

5.5 Smart Packaging Sensor for Real-Time Meat Freshness Monitoring

Patel et al. (2023) conducted a case study on an intelligent packaging sensor designed to change colour in response to ammonia and biogenic amine levels in packaged meat. This real-time indicator enabled consumers to easily evaluate meat freshness and quality before purchase, enhancing food safety awareness.

5.6 Paper-Based Colorimetric Sensor for Adulterant Detection in Honey

Kumar et al. (2020) developed a low-cost paper-based sensor designed to detect sugar syrup adulteration in honey samples. The sensor offered a quick, on-the-spot colour change, enabling easy purity assessment and improving food authenticity verification.

VI. DISCUSSIONS

- **Advantages of Chemical Sensors:** High sensitivity, real-time analysis, portability, and cost-effectiveness.
- **Challenges:** Sensor stability, reproducibility, interference from complex food matrices, and lack of standardization in regulatory frameworks.
- **Commercialization Prospects:** Advances in nanotechnology and artificial intelligence can enhance sensor performance, but further validation is needed for large-scale adoption (Smith & Roberts, 2021).

VII. PROSPECTS

- **IoT and AI Integration:** Smart sensor networks enable automated food quality monitoring, enhancing efficiency and real-time detection (Zhang & Zhao, 2023).
- **Miniaturization & Wearable Sensors:** Development of handheld and wearable chemical sensors allows for on-the-go food safety analysis (Patel & Mehta, 2022).
- **Multi-Analyte Sensors:** Advanced sensors capable of detecting multiple contaminants simultaneously, improving comprehensive food safety assessments (Wang, Liu, & Sun, 2022).
- **Policy & Regulatory Advancements:** Establishing international standards for chemical sensor validation, ensuring reliability in food safety applications.



VIII. CONCLUSION

Chemical sensors are revolutionizing food safety by providing rapid, sensitive, and cost-effective detection of contaminants. Despite significant advancements, challenges such as scalability, accuracy, and regulatory approval remain. Future research should focus on integrating sensors with AI and IoT for automated monitoring and real-time analysis. Smart packaging and wearable sensors hold promise for continuous food quality assessment. Sustainable, eco-friendly sensor materials should be prioritized to minimize environmental impact. Establishing standardized regulatory frameworks will be crucial for widespread adoption. Expanding sensor applications beyond contamination detection to include freshness and nutritional analysis can further enhance food safety and quality (Zhang & Zhao, 2023). Collaborative efforts between academia, industry, and regulatory bodies will drive innovation and ensure global food security.

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