Protecting Our Food: Onsite Detection of Harmful Organophosphate Pesticides through Nanomaterial

Sidra Altaf[1,*], Tasawar Iqbal[2] and Nadeem Ahmed[2]

[1]Department of Pharmacy, University of Agriculture, Faisalabad, Pakistan
[2]Institute of Physiology and Pharmacology, University of Agriculture, Faisalabad, Pakistan
*Corresponding author: sidra.altaf@uaf.edu.pk

Abstract

Organophosphate (OP) pesticides are extensively employed in agriculture to manage pests and improve crop productiveness. However, the staying power in their residues poses extreme threats to human fitness and the environment due to their neurotoxic properties. Conventional detection techniques, such as gasoline chromatography and mass spectrometry, offer excessive sensitivity however are regularly costly, hard work-in-depth, and require specialized personnel, making them wrong for on-web page meal safety assessments. This bankruptcy delves into the progressive utility of nanomaterial-based sensors as efficient, transportable, and inexpensive solutions for the rapid detection of OP pesticide residues in meals. Nanomaterials such as metallic nanoparticles, carbon nanotubes, and quantum dots possess notable physicochemical characteristics, together with large floor area, superior electric conductivity, and adjustable optical residences, which make contributions to their high sensitivity and selectivity in detecting trace amounts of pesticide residues. The chapter evaluates numerous sorts of sensor systems, including colorimetric, electrochemical, fluorescence-based, and floor-more suitable Raman scattering (SERS) sensors, detailing their working principles, strengths, and limitations. In addition, the latest improvements in the integration of those sensors with microfluidic systems and smartphone-primarily based technologies are discussed, emphasizing their capability for actual-time monitoring and data evaluation in area programs. The bankruptcy additionally considers future guidelines, which include the incorporation of nanomaterial-primarily based sensors with Internet of Things (IoT) frameworks and artificial intelligence to guide clever agricultural practices. Regulatory and environmental implications of the usage of nanomaterials are also addressed. Ultimately, this generation offers a promising pathway for ensuring meal protection and protective public fitness through set-off and effective detection of poisonous pesticide residues.

Keywords: Organophosphate pesticides, Nanomaterials, Onsite detection, Food safety, Electrochemical sensors, Portable sensors

Cite this Article as: Altaf S, Iqbal T and Ahmed N, 2025. Protecting our food: Onsite detection of harmful organophosphate pesticides through nanomaterial. In: Kausar R, Nisa ZU, Jamil M and Bashir I (eds), Integrated Health and Sustainability: Plants, Wildlife, and Genetic Resilience. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 361-368. https://doi.org/10.47278/book.HH/2025.449

A Publication of Unique Scientific Publishers	**Chapter No:** 25-047	**Received:** 12-Jan-2025 **Revised:** 22-Apr-2025 **Accepted:** 31-May-2025

Introduction

Food protection remains a pressing global health concern, as contaminated food can pose full-size threats to public health and food protection. Millions of people around the sector are stricken by foodborne ailments every year, experiencing signs and symptoms that vary from moderate discomfort to extreme, long-term health issues. According to the World Health Organization, those illnesses are because of a huge variety of foodborne contaminants, highlighting the pressing need for effective tracking and preventive techniques (Godwin et al., 2022). Contaminants in meals can come from more than one source, along with organic hazards which includes bacteria, viruses, and parasites, in addition to chemical and environmental pollution. Among those, chemical contaminants are specifically alarming due to their potential to persist at some stage in the food deliver chain and collect in the human body over time, leading to continual fitness results. Common chemical hazards include pesticide residues, toxic heavy metals like mercury and lead, and industrial pollutants. These substances may additionally input the meals system via agricultural activities, food processing, packaging substances, or environmental contamination of soil and water (Osafo et al., 2022). Pesticide residues are most of the maximum concerning chemical contaminants due to the giant utility of insecticides in modern-day agriculture for pest and ailment manipulate. Although these chemical substances play an important function in enhancing crop manufacturing and ensuring meals supply, strains of them can remain in or on food, potentially posing fitness dangers to customers. Studies have related pesticide publicity with diverse fitness problems, along with neurological problems, hormonal imbalances, and certain forms of most cancers. Beyond human fitness, insecticides also can negatively impact the environment by means of harming non-goal organisms and reducing biodiversity. Consequently, the accountable use of pesticides and rigorous tracking in their residues are vital for safeguarding public health and promoting sustainable farming practices worldwide (Raj et al., 2023).

1.2 Organophosphate (OP) Pesticides

Organophosphate (OP) pesticides are a commonly used group of insecticides in agriculture, valued for their performance in pest manipulate and their position in enhancing crop yields. These compounds exert their outcomes through inhibiting acetylcholinesterase (AChE), a critical enzyme that breaks down acetylcholine—a neurotransmitter essential for transmitting indicators inside the frightened device. When AChE is blocked, acetylcholine accumulates at synaptic junctions, resulting in non-stop nerve stimulation. This overstimulation disrupts everyday neural function, leading to neurotoxic effects in both pests and accidental goals, which include people (Fu et al., 2022). The neurotoxicity related to OP insecticides presents extreme fitness worries (Altaf et al., 2021). Short-time period or acute publicity can lead to signs and symptoms together with nausea, complications, dizziness, muscle spasms, trouble respiratory, and in extreme cases, seizures, coma, or loss of life. Long-time period exposure to decreased doses has been connected to continual fitness troubles, which include reminiscence and studying deficits, developmental delays in youngsters, and an expanded likelihood of neurological situations like Parkinson's sickness. Additionally, some research shows a capacity association between extended OP exposure and positive types of cancer (Pant, 2024). Due to the enormous software of organophosphate (OP) pesticides and the hazard of their residues contaminating meals, there's an urgent need for reliable tracking systems. Effective detection strategies that are sensitive, fast, and suitable for onsite use are crucial to discovering residues directly, preventing the distribution of contaminated meals, and protecting public fitness. Recent developments in sensor technology—mainly the ones incorporating nanomaterials—have proven amazing potential in addressing these challenges, presenting revolutionary solutions for enhancing meal safety monitoring (Ogah et al., 2024).

1.3 Need for Onsite Detection

Conventional analytical strategies like Gas Chromatography-Mass Spectrometry (GC-MS) and High-Performance Liquid Chromatography (HPLC) are broadly identified for their excessive sensitivity and accuracy in detecting organophosphate pesticide residues. These strategies permit the correct measurement of even hint stages of contaminants. However, they require superior, steeply-priced gadgets, complex sample practice processes, and professional technicians, restricting their use to nicely geared-up laboratories. Their high operational charges and prolonged evaluation instances make them impractical for speedy screening, particularly in area or onsite environments (Bhattu et al., 2022). With growing emphasis on meal safety, there is an increasing need for detection technologies that are rapid, transportable, and within your means. Such methods allow spark-off choice-making to save our contaminated merchandise from getting into the food supply. Onsite detection equipment provides real-time evaluation, minimizes the hazard of sample degradation all through transportation, and guides non-stop monitoring at key points along with farms, processing facilities, and distribution facilities (Zhang et al., 2022). Nanomaterials have received huge attention as a capacity answer to the subject of pesticide detection. Owing to their distinctive physicochemical characteristics, they can significantly enhance the sensitivity and specificity of sensors, whilst also enabling the layout of compact, cost-effective, and clean-to-use detection systems. Incorporating nanomaterials into sensing technologies permits the improvement of dependable onsite devices that can quickly discover and deal with organophosphate pesticide infection, thereby enhancing meal safety and shielding public health (Huang et al., 2022).

1.4 Organophosphates

Organophosphates (OPs) are artificial chemical substances appreciably applied in agriculture for his or her effectiveness in managing insect and pest infestations. They feature with the aid of inhibiting acetylcholinesterase, a crucial enzyme in the fearful device. This inhibition results in the buildup of acetylcholine, which overstimulates nerve cells, in the end, inflicting paralysis and loss of life in bugs. Commonly used OPs encompass chlorpyrifos, malathion, and parathion. While those pesticides contribute to extended agricultural productiveness, they also pose critical dangers to human health and the environment. Short-term publicity can cause signs and symptoms including dizziness, headaches, nausea, and, in excessive instances, breathing misery or maybe death. Long-time period exposure, especially in youngsters, has been associated with developmental delays and diverse neurological disorders (Raj & Krishnan, 2023). Because of their high toxicity, using organophosphates is tightly regulated in many countries, with a growing emphasis on safer options and included pest management practices. Nevertheless, these pesticides are nonetheless typically used in lots of growing regions because of their affordability and effectiveness (Fu et al., 2022).

1.5 Mechanism of action Organophosphate

Organophosphates (OPs) induce toxicity by and large by way of disrupting the normal feature of acetylcholinesterase (AChE), an enzyme crucial for correct nerve signaling. Under ordinary situations, AChE breaks down the neurotransmitter acetylcholine (ACh) within synapses, assisting to terminate nerve impulses and alter signal transmission. When OPs inhibit AChE hobby, acetylcholine accumulates excessively at nerve synapses, causing extended activation of cholinergic receptors—each muscarinic and nicotinic (Iqbal et al.,2024). This overstimulation of the frightened system can lead to more than a few signs, such as muscle twitching, weakness, excessive salivation, sweating, narrowing of the airlines (bronchoconstriction), and, in severe cases, paralysis and respiratory failure because of impaired neuromuscular function (Aroniadou-Anderjaska et al., 2023).

2. Principles of Onsite Detection

2.1 Key Criteria for Onsite Analytical Devices

Onsite analytical tools for detecting organophosphate (OP) insecticides need to fulfill positive performance criteria to be reliable in actual-global programs. High sensitivity is important to discover even minimal ranges of OP residues that could threaten health, even as strong selectivity is essential to as it should be become aware of these insecticides amid numerous ability interferences discovered in complicated food samples. These functions ensure accurate monitoring, even when infection is low. Additionally, the device ought to be portable to facilitate use in a variety of places along with farms, markets, and food processing facilities. Ease of use is also critical, permitting people without specialized know-how to function the gadgets efficiently (Sun et al., 2021). A fast response time is important for permitting instantaneous selection-making, supporting to save you contaminated merchandise from entering the market. Efficient detection now not most effective minimizes food waste but additionally helps timely adherence to regulatory standards. Additionally, requiring minimum sample coaching simplifies the trying out system by removing complicated laboratory approaches, making an allowance for quicker analysis immediately in the subject. Together, those capabilities improve the practicality of sizable onsite tracking, reinforcing efforts to make certain meals protection and defend public health. Ultimately, a powerful onsite detection device should stability accuracy, speed, affordability, and simplicity of use to efficaciously address the increasing undertaking of pesticide contamination within the worldwide meals supply (Vegesna et al., 2024).

2.2 Challenges in Onsite Detection of Organophosphates

Despite notable advancements in sensor technology, several key challenges continue to hinder the widespread adoption of onsite detection systems for organophosphate pesticides. Environmental factors such as changes in temperature, humidity, and the presence of chemically similar substances can significantly impact sensor accuracy. These conditions may result in false positive or negative readings, reducing the reliability of the data and limiting confidence in the technology. Another ongoing concern is the long-term stability of sensors. Many nanomaterial-based devices are prone to degradation over time or with repeated use, which can compromise their detection performance. Incorporating self-correcting capabilities or environmental repayment algorithms into detection devices can in addition decorate their accuracy and reliability. Successfully addressing those troubles is critical for developing dependable, discipline-equipped sensors that allow proactive meal protection measures and help ensure compliance with regulatory standards (Hossain et al., 2024). Table 1 elaborates advantages relevant to onsite detection of organophosphate pesticides in food.

Table 1: Advantages relevant to onsite detection of organophosphate pesticides in food

Sr. No.	Nanomaterial Type	Detection Method	Target Pesticide(s)	Key Features/Advantages	References
1	Gold Nanoparticles	Colorimetric	Chlorpyrifos, Malathion	Visual detection, easy to use, rapid response	(Sahu et al., 2023)
2	Carbon Nanotubes (CNTs)	Electrochemical	Parathion, Diazinon	High sensitivity, good conductivity	(Lohrasbi-Nejad, 2022)
3	Graphene Oxide	Electrochemical	Multiple OP pesticides	Large surface area, enhanced electron transfer	(Yan et al., 2020)
4	Quantum Dots	Fluorescence	Chlorpyrifos	Strong fluorescence, tunable emission	(Ghosh et al., 2021)
5	Silver Nanoparticles	Surface-Enhanced Raman Scattering (SERS)	Malathion, Parathion	Signal enhancement, molecular fingerprinting	(Afroozeh, 2024)
6	Zinc Oxide Nanoparticles	Electrochemical	Diazinon	Low cost, good stability	(Lohrasbi-Nejad, 2022)
7	Magnetic Nanoparticles	Magnetic Separation + Detection	Multiple OP pesticides	Easy sample pre-concentration	(El-Deen & Hussain, 2023)
8	Polymer Nanocomposites	Electrochemical	Chlorpyrifos	High selectivity due to functionalization	(Huang et al., 2024)
9	Titanium Dioxide NPs	Photoelectrochemical	Various OPs	High stability, photocatalytic properties	(Meshesha et al., 2022)
10	Carbon Dots	Fluorescence	Parathion	Biocompatible, low toxicity	(Gaviria et al., 2022)
11	Silicon Nanowires	Electrochemical	Chlorpyrifos	High surface-to-volume ratio	(Mahmoudpour et al., 2022)
12	MoS2 Nanosheets	Electrochemical	Malathion	Excellent electrical properties	(Wang et al., 2024)
13	Paper-based Nanocomposites	Colorimetric / Electrochemical	Various OPs	Portable, disposable, low cost	(Caratelli et al., 2022)
14	Aptamer-Functionalized Nanoparticles	Electrochemical / Fluorescence	Specific OPs	High specificity and binding affinity	(Mahmoudpour et al., 2021)
15	Enzyme-Nanomaterial Hybrid	Electrochemical	Organophosphates	Enhanced sensitivity due to enzyme catalysis	(Suresh et al., 2023)

3. Role of Nanomaterials in Detection

3.1 Introduction to Nanomaterials

Nanomaterials, characterized by way of having at least one size between 1 and 100 nanometers, have become crucial in enhancing sensor technology for detecting organophosphate insecticides. They are generally categorized based totally on their composition and structural features. Carbon-based totally nanomaterials, together with carbon nanotubes (CNTs) and graphene, are prized for his or her fantastic electrical conductivity and mechanical durability. Metal-based nanomaterials, inclusive of nanoparticles of gold and silver, are valued for his or her adjustable optical properties and sturdy catalytic capabilities. Polymeric nanomaterials, like dendrimers and nano-gels, provide benefits in biocompatibility and can be tailored with numerous surface functionalities (Aggarwal et al., 2025). The different physicochemical characteristics of those nanomaterials lead them to particularly effective for sensor applications. Their excessive surface region-to-volume ratio will increase interactions with goal analytes, substantially enhancing detection sensitivity. Due to their nanoscale size, they can penetrate tiny spaces and bind correctly to precise molecules which includes organophosphate insecticides, even within complex meals matrices. Additionally, their optical, electronic, and magnetic houses can be finely tuned, permitting the introduction of adaptable detection systems tailor-made to unique sensing necessities. Together, these features permit nanomaterial-based sensors to appropriately pick out trace quantities of dangerous insecticides, facilitating speedy, dependable, and transportable meals safety checking out (Mallela, 2024).

3.2 Functionalization and Surface Modification

Surface functionalization is prime to improving the selectivity and binding affinity of nanomaterials closer to organophosphate insecticides. This procedure entails modifying the nanomaterial surfaces with particular chemical corporations or organic reputation factors that selectively engage with goal pesticide molecules. By customizing the floor chemistry, nanomaterials may be engineered into distinctly selective sensing structures capable of detecting organophosphates even in complicated sample matrices (Mehta et al., 2024). A broadly used approach is bio-conjugation, in which biomolecules including enzymes, antibodies, or aptamers are connected to the nanomaterial floor. These biomolecules act as recognition factors that in particular bind to organophosphate compounds or their metabolites. For instance, acetylcholinesterase (AChE) may be immobilized on nanoparticles to discover organophosphates through enzyme inhibition, wherein the pesticide's presence blocks the enzyme's interest and triggers a measurable sign trade (Urmi et al., 2024). This functionalization now not best complements specificity for correct detection but also improves sensor balance and reaction time. These enhancements are specifically essential for onsite packages, where speedy and dependable effects are essential. Through floor change and bio-conjugation, nanomaterials grow to be effective, high-overall performance sensors for actual-time monitoring of pesticide infection in meals and environmental samples (Khalid et al., 2024).

4. Nanomaterial-Based Detection Techniques

4.1 Colorimetric Sensors

Colorimetric sensors are most of the only and maximum accessible detection methods, relying on a seen coloration change to signal the presence of a target substance, inclusive of organophosphate insecticides. This approach permits short, instrument-free detection, making it nicely suited for onsite and field packages. The detection mechanism is based totally on adjustments within the optical houses of nanomaterials whilst they interact with unique analytes (Khalid et al., 2024).

Gold nanoparticles (AuNPs) are usually used in colorimetric sensors because of their sturdy floor plasmon resonance, which offers them an exceptional red color while nicely dispersed. When exposed to organophosphate insecticides, those nanoparticles may combine or undergo surface adjustments, inflicting a visible color shift from pink to blue or pink, absolutely indicating infection. Likewise, quantum dots—semiconductor nanocrystals with adjustable fluorescence and coloration houses—can also be used for the visible detection of pesticides. These sensors help qualitative or semi-quantitative analysis depending on the intensity of the color alternate. Their ease of use, affordability, and fast reaction make them particularly precious in settings in which laboratory facilities are unavailable or wherein short screening is essential to ensure food protection (Che Sulaiman et al., 2020).

4.2 Electrochemical Sensors

Electrochemical sensors offer an incredibly sensitive and powerful approach for detecting organophosphate insecticides by way of measuring adjustments in electric indicators as a result of redox reactions or enzyme inhibition. Their portability, brief reaction instances, and coffee power intake make them perfect for onsite applications. To raise their performance, these sensors regularly contain nanomaterials inclusive of graphene, carbon nanotubes (CNTs), and metal oxides, which beautify the electrode's surface area and electric conductivity. This improves electron switch efficiency and increases sensitivity to low tiers of pesticide residues (Lazarević-Pašti, 2023). Electrochemical sensors are typically divided into categories: enzyme-primarily based and enzyme-loose. Enzyme-based totally sensors typically use acetylcholinesterase (AChE), an enzyme whose hobby is inhibited by way of organophosphate insecticides. When immobilized on a nanomaterial-changed electrode, the volume of enzyme inhibition correlates with pesticide concentration, resulting in a measurable signal alternate. Conversely, enzyme-free sensors discover pesticides through direct electrochemical interactions with the nanomaterial floor, removing the want for biological elements and improving balance and shelf existence. Both kinds aim to offer accurate, speedy, and affordable detection, making them nicely applicable for area diagnostics and recurring monitoring of food protection (Kaur & Singh, 2020).

4.3 Fluorescence and Photoluminescence-Based Sensors

Fluorescence and photoluminescence-based sensors make the most of the light-emitting traits of nanomaterials including quantum dots and fluorescent Nano dots to detect organophosphate insecticides with excessive sensitivity and specificity. These nanomaterials emit light upon excitation at precise wavelengths, and interactions with the target pesticide cause detectable adjustments in their optical signals (Mahajan & Patil, 2022). Detection commonly is predicated on quenching consequences or Forester resonance power switch (FRET). In quenching, the presence of insecticides diminishes or suppresses the fluorescence intensity. In FRET-based total sensors, strength is transferred from a donor fluorophore to an acceptor molecule best while they are near—an event prompted with the aid of pesticide binding. Both mechanisms bring about measurable adjustments in emission intensity or wavelength, which may be without delay correlated to pesticide attention (Kaur et al., 2020). These sensors provide fast and pretty sensitive detection, regularly able to figure out insecticides at Nano molar or maybe Pico molar concentrations, making them properly appropriate for tracing low-degree infection in meals and environmental samples. Their capacity for actual-time evaluation, blended with compatibility with transportable fluorescence devices, supports their use in onsite and discipline tracking applications (Fauzi et al., 2021).

4.4 Surface-Enhanced Raman Scattering (SERS)

Surface-Enhanced Raman Scattering (SERS) is a fairly touchy analytical approach that amplifies the in any other case weak Raman indicators of molecules by means of utilizing steel nanostructures, generally composed of silver or gold nanoparticles. These nanostructures generate localized floor Plasmon resonances, which notably enhance the surrounding electromagnetic field, ensuing in a marked enhancement of the Raman indicators from close by molecules (Goel et al., 2024). In the context of detecting organophosphate insecticides, SERS proves especially effective via revealing the precise vibrational spectra—basically molecular fingerprints—of these chemicals. Because every pesticide produces an exceptional Raman spectrum, SERS facilitates precise identification, even at very low concentrations, regularly down to components according to billion (ppb) stages or lower (Moldovan et al., 2021).

This approach is especially wonderful for onsite detection, because it merges awesome sensitivity with molecular-degree selectivity, thereby minimizing the chances of fake positives. SERS may be performed with portable Raman spectrometers, making it sensible to be used in agricultural fields or meal protection inspections. Through fast and reliable detection of pesticide residues, SERS performs a critical function in making sure meals safety and permitting activated, knowledgeable choices in environmental and health tracking (Liu et al., 2022).

4.5 Paper-Based Microfluidic Devices

Paper-based microfluidic gadgets provide a sensible and efficient technique for onsite detection of organophosphate pesticides, way to their lightweight, low-value, and disposable layout. These devices are fabricated with the usage of patterned paper that channels small volumes of liquid through micro-scale pathways via capillary action, disposing of the want for outside pumps or sophisticated devices (Parato, 2023). To improve detection overall performance, nanomaterials including gold nanoparticles, carbon nanotubes, or quantum dots are included in the microchannel. These materials interact with pesticide molecules, producing measurable responses—along with visible coloration shifts, fluorescence, or electrochemical indicators—relying on the detection method hired. Their ease of use, minimum sample coaching, and fast reaction time make them ideal for field programs (Fattahi & Hasanzadeh, 2022). A super innovation in this era is the incorporation of smartphones for signal detection and evaluation. Mobile apps and built-in sensors can capture and interpret changes inside the sign, taking into account quantitative evaluation and real-time outcomes (Rao et al., 2022).

5. Case Studies and Recent Advances

5.1 Specific Examples of OP Detection

Recent developments in nanotechnology have caused the development of advanced strategies for detecting unique organophosphate insecticides which include chlorpyrifos, malathion, and parathion. One powerful strategy employs gold nanoparticle-based colorimetric assays for chlorpyrifos detection, where substantial color shifts can be visible with the naked eye. This method presents a sincere and low-priced solution for monitoring pesticide residues without the need for stylish instrumentation (Kumaravel et al., 2024). In the case of malathion, electrochemical sensors using graphene-greater electrodes have emerged as an incredibly touchy alternative. Graphene's extremely good electrical conductivity and massive surface vicinity substantially improve electron transfer and facilitate more potent interactions with pesticide molecules, resulting in specific and dependable detection (Saliya et al., 2025). For parathion, quantum dot-based fluorescence sensors have been designed. These sensors function via a fluorescence quenching mechanism, wherein the presence of parathion reduces the emitted fluorescence intensity. This permits for an instant, selective detection even at very low concentrations. Together, those nanomaterial-driven sensing methods provide powerful gear for actual-time monitoring of toxic pesticide residues, contributing to safer meal structures and advanced environmental fitness. Ongoing studies and innovation are anticipated to similarly optimize their performance and make their own sensible programs (Ganesan & Nagaraaj, 2020).

5.2 Field Deployments and Pilot Studies

Nanomaterial-based discipline sensors had been correctly tested in various agricultural settings and neighborhood markets for the detection of pesticide residues in produce and soil. A key instance entails the usage of paper-based microfluidic strips paired with smartphone digital camera evaluation, enabling rapid, on-site trying out of fruits and greens. This technique presents on-the-spot results without the want for laboratory infrastructure, drastically enhancing the accessibility and performance of pesticide screening (Mirres et al., 2022). These real-time sensing technologies equip farmers and food safety personnel with timely, actionable insights that assist save you the distribution of infected merchandise, thereby improving food protection. By supplying low-value, transportable, and clean-to-use detection equipment, those systems guide a shift from traditional, centralized pesticide trying out to more decentralized, community-pushed monitoring (Olufemi et al., 2024). This evolution allows for quicker responses, reduces checking out delays, and broadens the attain of surveillance efforts across the agricultural price chain. Overall, these improvements spotlight the valuable contribution of nanotechnology to sustainable agriculture and public fitness by permitting more powerful control of pesticide residues (Patil et al., 2023).

5.3 Comparative Analysis

When evaluating nanomaterial-primarily based techniques for pesticide detection, each sensitivity and specificity range depending on the form of nanomaterial and the underlying detection approach. Electrochemical sensors are a few of the maximum touchy, regularly able to identifying pesticide residues at parts-per-billion (ppb) stages, making them perfect for excessive-precision analysis. On the opposite hand, colorimetric assays offer greater simplicity and simplicity of interpretation via seen color adjustments, although they typically exhibit slightly decrease sensitivity. Fluorescence-based sensors strike a stability between sensitivity and simplicity of use, however, they regularly require fundamental devices or controlled lights conditions to function reliably. In phrases of value-effectiveness, paper-primarily based structures and colorimetric strips are the most not pricey, which makes them perfect for use in low-useful resource environments or for huge field deployment (Bagyalakshmi et al., 2022).

6. Future Perspectives and Challenges

The mixture of nanomaterial-primarily based sensors with Internet of Things (IoT) and synthetic intelligence (AI) technologies holds incredible promise for transforming clever agriculture by permitting automatic pesticide monitoring. These included systems improve the precision and performance of residue detection, contributing to better meals protection and environmental sustainability. However, several regulatory and standardization hurdles remain. Challenges including tool certification, reproducibility of effects, and steady nice control of nanotechnology-based total sensors ought to be addressed before big-scale deployment (Nath, 2024). Additionally, worries surrounding the environmental impact and capability toxicity of nanomaterials underscore the importance of undertaking comprehensive health and ecological safety critiques. To mitigate dangers, it is vital to implement strong regulatory frameworks and encourage accountable development. Equally vital is growing public cognizance and user engagement. Outreach tasks and focused schooling packages can help stakeholders—from farmers to meals inspectors—undertake and efficiently use that technology. Ultimately, a multidisciplinary and inclusive technique is prime to unlocking the whole capacity of nanotechnology in agriculture, promoting more secure food manufacturing, and fostering lengthy-time period sustainability in farming practices (Kumar, 2025).

7. Conclusion

This chapter emphasizes the urgent need for fast, sensitive, and on-website detection of risky organophosphate pesticides to guard meal safety and public health. Nanomaterial-primarily based sensors provide clean advantages over conventional laboratory strategies, way to their unique physicochemical houses. These include portability, value performance, and the capability to deliver actual-time consequences. A range of nanomaterials—which include gold nanoparticles, carbon nanotubes, and quantum dots—have proven notable sensitivity and specificity in figuring out even trace tiers of pesticide residues. Such advancements spotlight the transformative function of nanotechnology in enhancing food safety surveillance, especially in agricultural fields and market environments where timely detection is crucial. To unlock the entire capability of those improvements, collaborative efforts across disciplines—including materials technology, chemistry, biology, and agriculture—are essential. Continued development in sensor engineering, at the side of the status quo of regulatory requirements and environmental chance tests, may be key to broader implementation. Ultimately, combining nanotechnology with digital innovations along with IoT and AI can revolutionize pesticide monitoring structures, main to safer meals manufacturing and stepping forward global public fitness effects.

References

Afroozeh, A. (2024). A review of developed surface-enhanced Raman spectroscopy (SERS)-based sensors for the detection of common hazardous substances in the agricultural industry. *Plasmonics*, 1–19.

Aggarwal, A., Bose, D., Monteiro, D., Meyers, K., Kapadia, N., & Asha, T. (2025). Nanomaterials for enhanced detection of some organophosphate and organochlorine pesticides: a comprehensive review of recent advances. *Journal of Nanoparticle Research*, *27*(4), 1–34.

Altaf, S., Muhammad, F., Aslam, B., & Faisal, M. N. (2021). Cell membrane enveloped polymeric nanosponge for detoxification of chlorpyrifos poison: In vitro and in vivo studies. *Human & Experimental Toxicology*, 40(8), 1286–1295.

Aroniadou-Anderjaska, V., Figueiredo, T. H., de Araujo Furtado, M., Pidoplichko, V. I., & Braga, M. F. M. (2023). Mechanisms of organophosphate toxicity and the role of acetylcholinesterase inhibition. *Toxics*, *11*(10), 866.

Bagyalakshmi, S., Sivakami, A., Pal, K., Sarankumar, R., & Mahendran, C. (2022). Manufacturing of electrochemical sensors via carbon nanomaterials novel applications: a systematic review. *Journal of Nanoparticle Research*, *24*(10), 201.

Bhattu, M., Kathuria, D., Billing, B. K., & Verma, M. (2022). Chromatographic techniques for the analysis of organophosphate pesticides with their extraction approach: a review (2015–2020). *Analytical Methods*, *14*(4), 322–358.

Caratelli, V., Di Meo, E., Colozza, N., Fabiani, L., Fiore, L., Moscone, D., & Arduini, F. (2022). Nanomaterials and paper-based electrochemical devices: merging strategies for fostering sustainable detection of biomarkers. *Journal of Materials Chemistry B*, *10*(44), 9021–9039.

Che Sulaiman, I. S., Chieng, B. W., Osman, M. J., Ong, K. K., Rashid, J. I. A., Wan Yunus, W. M. Z., Noor, S. A. M., Kasim, N. A. M., Halim, N. A., & Mohamad, A. (2020). A review on colorimetric methods for determination of organophosphate pesticides using gold and silver nanoparticles. *Microchimica Acta*, *187*(2). https://doi.org/10.1007/S00604-019-3893-8

El-Deen, A. K., & Hussain, C. M. (2023). Recent developments in green magnetic nanoparticles for extraction and preconcentration of pollutants from environmental samples. *Trends in Environmental Analytical Chemistry*, *39*, e00211.

Fattahi, Z., & Hasanzadeh, M. (2022). Nanotechnology-assisted microfluidic systems for chemical sensing, biosensing, and bioanalysis. *TrAC Trends in Analytical Chemistry*, *152*, 116637.

Fauzi, N. I. M., Fen, Y. W., Omar, N. A. S., & Hashim, H. S. (2021). Recent advances on detection of insecticides using optical sensors. *Sensors*, *21*(11), 3856.

Fu, H., Tan, P., Wang, R., Li, S., Liu, H., Yang, Y., & Wu, Z. (2022). Advances in organophosphorus pesticides pollution: Current status and challenges in ecotoxicological, sustainable agriculture, and degradation strategies. *Journal of Hazardous Materials*, *424*, 127494.

Ganesan, M., & Nagaraaj, P. (2020). Quantum dots as nanosensors for detection of toxics: a literature review. *Analytical Methods*, *12*(35), 4254–4275.

Gaviria, M. I., Barrientos, K., Arango, J. P., Cano, J. B., & Peñuela, G. A. (2022). Highly sensitive fluorescent biosensor based on acetylcholinesterase and carbon dots–graphene oxide quenching test for analytical and commercial organophosphate pesticide detection. *Frontiers in Environmental Science*, *10*, 825112.

Ghosh, S., Gul, A. R., Park, C. Y., Kim, M. W., Xu, P., Baek, S. H., Bhamore, J. R., Kailasa, S. K., & Park, T. J. (2021). Facile synthesis of carbon dots from Tagetes erecta as a precursor for determination of chlorpyrifos via fluorescence turn-off and quinalphos via fluorescence turn-on mechanisms. *Chemosphere*, *279*, 130515.

Godwin, E. J. O., Chandrasekaran, V., Smah, A. C., & Faith, E. O. (2022). Emerging infectious food system related zoonotic foodborne disease–A threat to global food safety and nutrition security. In *Foodborne Pathogens-Recent Advances in Control and Detection*. IntechOpen.

Goel, R., Chakraborty, S., Awasthi, V., Bhardwaj, V., & Dubey, S. K. (2024). Exploring the various aspects of Surface enhanced Raman spectroscopy (SERS) with focus on the recent progress: SERS-active substrate, SERS-instrumentation, SERS-application. *Sensors and Actuators A: Physical*, 115555.

Hossain, N., Rimon, M. I. H., Mimona, M. A., Mobarak, M. H., Ghosh, J., Islam, M. A., & Al Mahmud, M. Z. (2024). Prospects and challenges of sensor materials: A comprehensive review. *E-Prime-Advances in Electrical Engineering, Electronics and Energy*, 100496.

Huang, Y., Zhai, J., Liu, L., Shang, Z., Zhang, X., Huang, H., Shen, B., & Chen, G. (2022). Recent developments on nanomaterial probes for detection of pesticide residues: A review. *Analytica Chimica Acta*, *1215*, 339974.

Huang, Y., Zhao, S., Wang, Q., Xu, W., & Huang, W. (2024). A highly sensitive electrochemical sensor based on surface molecularly imprinted polymers and graphene carbon nanotubes for highly selective detection of chlorpyrifos. *Polymers for Advanced Technologies*, *35*(6), e6462.

Iqbal, M. U., Altaf, S., Naeem, M. A., Aufy, M., Alfuraydi, A. A., Iqbal, T., Hussein, A. M., Maksoud, M. A. A., & Malik, A. (2024). Amelioration of Organophosphate Poisoning Using Red Blood Cell Membrane-Cloaked Oil Nano-Sponge. *Journal of Biological Regulators and Homeostatic Agents*, 5753–5767. https://doi.org/10.23812/J.BIOL.REGUL.HOMEOST.AGENTS.20243808.462

Kaur, A., Kaur, P., & Ahuja, S. (2020). Förster resonance energy transfer (FRET) and applications thereof. *Analytical Methods*, *12*(46), 5532–5550.

Kaur, J., & Singh, P. K. (2020). Enzyme-based optical biosensors for organophosphate class of pesticide detection. *Physical Chemistry Chemical Physics*, *22*(27), 15105–15119.

Khalid, W., Zulfiqar, A., Shehzad, T., Haider, S. A., Abid, Z., Altaf, M., Ashraf, R. S., & Shahid, M. (2024). Luminescent and Photonic Materials for Sensing Applications. *Organic and Inorganic Materials Based Sensors*, *3*, 789–813.

Kumar, A. (2025). Engineered nanomaterials and associated threats in the environment risk assessment strategies. In *Biotechnological Interventions in the Removal of Emerging Pollutants* (pp. 515–537). Springer.

Kumaravel, A., Aishwarya, S., & Sathyamoorthi, S. (2024). Emerging technologies for sensitive detection of organophosphate pesticides: a review. *Current Analytical Chemistry*, *20*(6), 383–409.

Lazarević-Pašti, T. (2023). Carbon materials for organophosphate pesticide sensing. *Chemosensors*, *11*(2), 93.

Liu, C., Xu, D., Dong, X., & Huang, Q. (2022). A review: Research progress of SERS-based sensors for agricultural applications. *Trends in Food Science & Technology*, *128*, 90–101.

Lohrasbi-Nejad, A. (2022). Electrochemical strategies for detection of diazinon. *Journal of Electrochemical Science and Engineering*, *12*(6), 1041–1059.

Mahajan, M. R., & Patil, P. O. (2022). Fluorescence and photoluminescence-based totally sensors make the most the light-emitting traits of nanomaterials including quantum dots and fluorescent Nano dots to detect organophosphate insecticides. *Inorganic Chemistry Communications*, *144*, 109883.

Mahmoudpour, M., Ding, S., Lyu, Z., Ebrahimi, G., Du, D., Dolatabadi, J. E. N., Torbati, M., & Lin, Y. (2021). Aptamer functionalized nanomaterials for biomedical applications: Recent advances and new horizons. *Nano Today*, *39*, 101177.

Mahmoudpour, M., Karimzadeh, Z., Ebrahimi, G., Hasanzadeh, M., & Ezzati Nazhad Dolatabadi, J. (2022). Synergizing functional nanomaterials with aptamers based on electrochemical strategies for pesticide detection: current status and perspectives. *Critical Reviews in Analytical Chemistry*, *52*(8), 1818–1845.

Mallela, Y. L. N. K. (2024). 2D Materials' Sensing Mechanisms. In *2D Materials: Sensing Applications* (pp. 217–250). Springer.

Mehta, J., Dhaka, R. K., Dilbaghi, N., Lim, D. K., Hassan, A. A., Kim, K.-H., & Kumar, S. (2024). Recent advancements in adsorptive removal of organophosphate pesticides from aqueous phase using nanomaterials. *Journal of Nanostructure in Chemistry*, *14*(1), 53–70.

Meshesha, M. M., Kannan, K., Chanda, D., Gautam, J., Jang, S. G., & Yang, B. L. (2022). Remarkable photoelectrochemical activity of titanium dioxide nanorod arrays sensitized with transition metal sulfide nanoparticles for solar hydrogen production. *Materials Today Chemistry*, *26*, 101216.

Mirres, A. C. de M., Silva, B. E. P. de M. da, Tessaro, L., Galvan, D., Andrade, J. C. de, Aquino, A., Joshi, N., & Conte-Junior, C. A. (2022). Recent advances in nanomaterial-based biosensors for pesticide detection in foods. *Biosensors*, *12*(8), 572.

Moldovan, R., Iacob, B.-C., Farcău, C., Bodoki, E., & Oprean, R. (2021). Strategies for SERS detection of organochlorine pesticides. *Nanomaterials*, *11*(2), 304.

Nath, S. (2024). Advancements in food quality monitoring: integrating biosensors for precision detection. *Sustainable Food Technology*.

Ogah, C., Oganah-Ikujenyo, B., Onyeaka, H., Ojapah, E., Adeboye, A., & Olaniran, T. (2024). Organophosphate pesticide residues in fruits and vegetables in Nigeria: prevalence, environmental impact, and human health implications. *Environmental Science and Pollution Research*, 1–20.

Olufemi, O. I., Ayeni, O., & Olagoke-Komolafe, O. E. (2024). *Advancing real-time predictive systems for listeria and E. coli detection in meat processing facilities across the USA*.

Osafo, R., Balali, G. I., Amissah-Reynolds, P. K., Gyapong, F., Addy, R., Nyarko, A. A., & Wiafe, P. (2022). Microbial and parasitic contamination of vegetables in developing countries and their food safety guidelines. *Journal of Food Quality*, *2022*(1), 4141914.

Pant, A. B. (2024). *Dictionary of Toxicology*. Springer.

Parato, N. (2023). *Development of a paper-based enzymatic microfluidic biosensor to detect organophosphate pesticides*. Politecnico di Torino.

Patil, S., Aklade, N., & Uikey, A. A. (2023). Revolutionizing vegetable value chains: a comprehensive review of digital technologies and their impact on agricultural transformation. *Current Journal of Applied Science and Technology*, *42*(47), 54–65.

Raj, A., Dubey, A., Malla, M. A., & Kumar, A. (2023). Pesticide pestilence: Global scenario and recent advances in detection and degradation methods. *Journal of Environmental Management*, *338*, 117680.

Raj, R. S., & Krishnan, K. A. (2023). A comprehensive review on the impact of emerging organophosphorous pesticides and their remedial measures: Special focus on acephate. *Environmental Nanotechnology, Monitoring & Management*, *20*, 100813.

Ranjan, A., & Jindal, T. (2022). *Toxicology of organophosphate poisoning*. Springer.

Rao, A. S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M., & Ngo, T. (2022). Real-time monitoring of construction sites: Sensors, methods, and applications. *Automation in Construction*, *136*, 104099.

Sahu, B., Kurrey, R., Deb, M. K., Khalkho, B. R., & Manikpuri, S. (2023). Recognition of malathion pesticides in agricultural samples by using α-CD functionalized gold nanoparticles as a colorimetric sensor. *Talanta*, *259*, 124526.

Saliya, C. S., Mathew, N., Samuel, S., Sunny, E. K., & Abraham, J. (2025). Nanomaterials for sensing pharmaceuticals. In *Smart Nanomaterials for Environmental Applications* (pp. 291–317). Elsevier.

Sun, D.-W., Huang, L., Pu, H., & Ma, J. (2021). Introducing reticular chemistry into agrochemistry. *Chemical Society Reviews*, *50*(2), 1070–1110.

Suresh, R., Rajendran, S., Khoo, K. S., & Soto-Moscoso, M. (2023). Enzyme Immobilized nanomaterials: An electrochemical bio-sensing and biocatalytic degradation properties toward organic pollutants. *Topics in Catalysis*, *66*(9), 691–706.

Urmi, R., Banerjee, P., Singh, M., Singh, R., Chhillar, S., Sharma, N., Chandra, A., Singh, N., & Qamar, I. (2024). Revolutionizing biomedicine: Aptamer-based nanomaterials and nanodevices for therapeutic applications. *Biotechnology Reports*, e00843.

Vegesna, V. V., Adepu, A., & Whig, P. (2024). IT for healthcare and food safety enhancing public health through technology integration. In *Nutrition Controversies and Advances in Autoimmune Disease* (pp. 525–546). IGI Global.

Wang, F., Zhu, Y., Qian, L., Yin, Y., Yuan, Z., Dai, Y., Zhang, T., Yang, D., & Qiu, F. (2024). Lamellar Ti3C2 MXene composite decorated with platinum-doped MoS2 nanosheets as electrochemical sensing functional platform for highly sensitive analysis of organophosphorus pesticides. *Food Chemistry*, *459*, 140379.

Yan, L., Yan, X., Li, H., Zhang, X., Wang, M., Fu, S., Zhang, G., Qian, C., Yang, H., & Han, J. (2020). Reduced graphene oxide nanosheets and gold nanoparticles covalently linked to ferrocene-terminated dendrimer to construct electrochemical sensor with dual signal amplification strategy for ultra-sensitive detection of pesticide in vegetable. *Microchemical Journal*, *157*, 105016.

Zhang, J., Huang, H., Song, G., Huang, K., Luo, Y., Liu, Q., He, X., & Cheng, N. (2022). Intelligent biosensing strategies for rapid detection in food safety: A review. *Biosensors and Bioelectronics*, *202*, 114003.