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Application of Nanocomposite-Based Nanosensors for Rapid Detection of Heavy Metal Contamination in Aquaculture: A Review

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ABSTRACT

Heavy metal contamination in aquaculture systems poses significant health risks to both aquatic organisms and human consumers. Traditional detection methods for heavy metals, including atomic absorption spectroscopy and inductively coupled plasma mass spectrometry, although highly sensitive, are expensive, time-consuming, and require sophisticated laboratory infrastructure. Recent advances in nanotechnology have introduced innovative approaches for environmental monitoring, particularly using nanosensors based on nanocomposite materials. These nanosensors offer remarkable advantages such as high sensitivity, rapid response, portability, and the ability for on-site real-time detection of multiple heavy metal ions. Nanocomposites, which combine the unique properties of various nanomaterials like graphene, carbon nanotubes, metal-organic frameworks, and metal nanoparticles, enhance the functional performance of sensing devices. They enable improved electrical conductivity, chemical stability, surface area, and selective binding capabilities crucial for detecting trace levels of heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) in aquaculture water systems. This paper reviews the latest developments from 2022 onwards regarding nanocomposite-based nanosensors tailored for heavy metal detection in aquaculture. Emphasis is placed on different fabrication techniques, sensing mechanisms (electrochemical, optical, and piezoelectric), analytical performance metrics (limit of detection, response time, selectivity, and stability), and field-deployment potential. Challenges related to sensor fouling, matrix interferences, regulatory standards, and sensor miniaturization are critically discussed. Moreover, future perspectives for integrating nanosensor technologies into smart aquaculture management platforms using wireless data transmission and artificial intelligence (AI) are also addressed. The goal is to highlight the transformative potential of nanocomposite-based nanosensors for ensuring water quality and food safety in modern aquaculture practices while identifying research gaps and opportunities for innovation. By providing a comprehensive overview, this article aims to guide future efforts toward the development of more robust, sensitive, and sustainable nanosensing solutions for heavy metal monitoring in aquatic environments.

KEYWORDS: *Nanocomposite; Nanosensor; Heavy metal contamination; Aquaculture; Rapid detection; Environmental monitoring*

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1. Introduction

Aquaculture has emerged as one of the fastest-growing food production sectors globally, providing a significant proportion of the world's protein intake. However, the intensification of aquaculture activities has also led to heightened environmental concerns, particularly regarding water contamination by heavy metals [1]. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are non-biodegradable, persist in aquatic environments, and bioaccumulate in aquatic organisms, thereby posing serious health risks to both aquatic species and humans [2]. *Table 1* summarizes common heavy metals in aquaculture, their sources, and associated human health effects.

Traditional methods for detecting heavy metal contamination, including atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and anodic stripping voltammetry (ASV), offer high sensitivity and accuracy. Nevertheless, these techniques often require elaborate sample preparation, expensive instrumentation, trained personnel, and centralized laboratories [3]. Furthermore, operational challenges such as the need for frequent calibration and sensitivity to matrix effects in complex water samples from aquaculture farms can limit their practicality for routine, on-site monitoring [4]. As aquaculture systems are often situated in remote or rural locations, the need for portable, cost-effective, rapid, and highly sensitive on-site detection methods has become increasingly urgent.

Recent developments in nanotechnology have provided promising alternatives through the design of nanosensors. These nanosensors, especially those based on nanocomposite materials, offer significant advantages over conventional techniques, including rapid response, high sensitivity and selectivity, low detection limits, and the ability to conduct real-time monitoring in situ [5]. The unique optical, electrical, and catalytic properties of engineered nanomaterials are the foundation of these advanced sensing platforms [6]. Nanocomposite-based nanosensors combine the advantageous properties of various nanomaterials such as graphene, carbon nanotubes (CNTs), metal-organic frameworks (MOFs), and metallic nanoparticles to create hybrid structures that exhibit superior physicochemical properties ideal for sensing applications [7].

The structural diversity of nanocomposite materials used in electrochemical sensors enables enhanced sensitivity and selectivity through synergistic effects of their components, as illustrated in Fig. 1 [8, 9].

The application of nanocomposite-based nanosensors in aquaculture environments, particularly for detecting heavy metal ions, has garnered considerable attention from the scientific community. Different types of nanosensors, including electrochemical, optical, and piezoelectric sensors, have been engineered to exploit the unique properties of nanocomposites, achieving unprecedented levels of sensitivity and specificity [10]. These developments not only contribute to environmental protection and food safety but also align with the broader objectives of sustainable aquaculture practices.

Several recent studies highlight the critical role of nanosensors in heavy metal detection. For instance, electrochemical sensors based on graphene oxide–gold nanoparticle composites have demonstrated exceptional sensitivity for detecting cadmium and lead ions in aquaculture waters [11]. Optical nanosensors utilizing quantum dot-based nanocomposites have shown high

Table 1. Common heavy metals in aquaculture systems.

Heavy Metal	Common Sources in Aquaculture	Associated Human Health Effects
Pb (Lead)	Pipes, paint, industrial discharge	Neurological damage, developmental issues, kidney disease
Cd (Cadmium)	Fertilizers, battery waste, effluents	Renal dysfunction, bone disorders, carcinogenic effects
Hg (Mercury)	Atmospheric deposition, industrial waste	Neurotoxicity, Minamata disease, fetal development effects
As (Arsenic)	Mining runoff, pesticides	Skin cancer, cardiovascular diseases, hepatotoxicity

Summary of commonly encountered heavy metals in aquaculture, their major anthropogenic sources, and associated adverse human health effects resulting from bioaccumulation and chronic exposure [2].

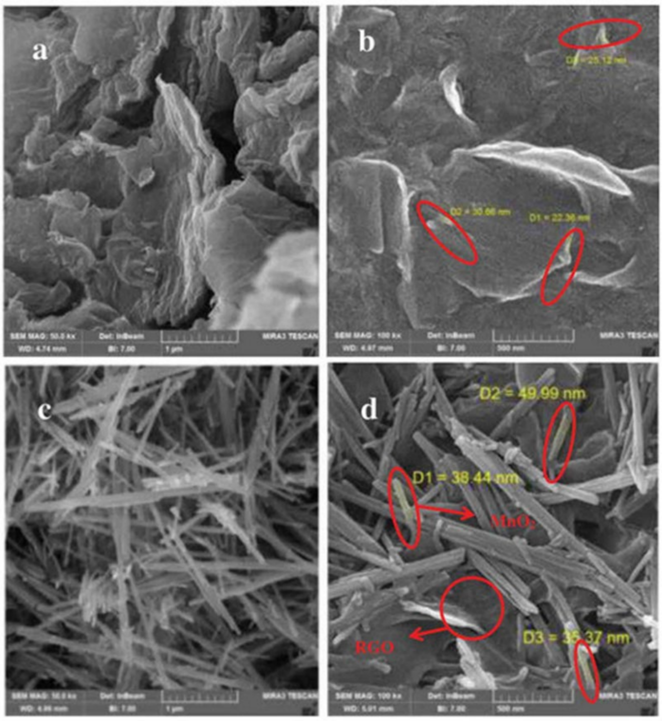

Fig. 1. Morphological characterization of MnO_2/rGO nanocomposites.
FE-SEM images of **(a)** graphene oxide (GO), **(b)** reduced graphene oxide (rGO), **(c)** α-MnO_2, and **(d)** α-MnO_2/rGO nanocomposite. Red-circled regions indicate MnO_2 nanorods distributed on rGO sheets, illustrating the formation of a 2D/1D hybrid structure that enhances electrochemical sensing performance [8, 9].

selectivity towards mercury ions, enabling early-stage contamination alerts [12]. Piezoelectric nanosensors incorporating ZnO nanocomposites have also been successfully employed for real-time detection of arsenic in freshwater systems [13].

Despite these advances, there remain substantial challenges associated with the practical implementation of nanocomposite-based nanosensors in real-world aquaculture settings. Issues such as sensor fouling, environmental interferences, stability over prolonged periods, and the need for calibration remain significant barriers [14]. Furthermore, regulatory frameworks governing the deployment and validation of nanosensors for environmental monitoring are still underdeveloped, necessitating multidisciplinary collaboration between scientists, engineers, policymakers, and industry stakeholders.

Another promising avenue is the integration of nanosensors with wireless data transmission systems and artificial intelligence (AI) algorithms. Such integration would enable the development of smart aquaculture systems capable of continuous, real-time monitoring and predictive analytics for water quality management [15]. Internet of Things (IoT)-enabled nanosensors represent a cutting-edge direction that could revolutionize aquaculture sustainability by providing timely alerts and automated response mechanisms to contamination events.

The field of nanocomposite-based nanosensors is evolving rapidly, with continuous innovations in material design, fabrication techniques, and sensing mechanisms. New approaches, such as molecular imprinting on nanocomposite surfaces and the use of biomimetic recognition elements, have significantly enhanced the selectivity and sensitivity of sensors [16]. Advances in 3D printing and microfabrication technologies are also contributing to the miniaturization and customization of nanosensing devices, expanding their applicability across diverse aquatic environments. However, the environmental fate and potential ecotoxicity of these synthetic nanomaterials upon deployment require careful life-cycle assessment to ensure sustainable technological development [17, 18].

In light of these considerations, this review aims to systematically examine the latest developments in nanocomposite-based nanosensors for the rapid detection of heavy metal contamination in aquaculture. We will explore different types of nanocomposites employed, the various sensing mechanisms utilized, the performance metrics achieved, and the challenges and future perspectives in this domain. By providing an in-depth and critical analysis of the current state of research, this paper seeks to underscore the transformative potential of nanocomposite-based nanosensors in ensuring the sustainability and safety of aquaculture practices worldwide.

2. Nanocomposite Materials and Sensing Mechanisms

2.1 Nanocomposite Materials for Heavy Metal Detection

The selection of appropriate nanocomposite materials is crucial for the performance of nanosensors designed to detect heavy metals in aquaculture environments. Nanocomposites used for this purpose typically combine conductive, catalytic, and selective recognition properties.

Carbon-based nanocomposites, such as graphene oxide (GO) and carbon nanotube (CNT) hybrids, have gained significant popularity due to their exceptional electrical conductivity, large surface area, and ease of functionalization [19]. For instance, reduced graphene oxide (rGO) combined with gold nanoparticles (AuNPs) has been employed for the sensitive detection of cadmium and lead ions [11]. Similarly, CNT-based nanocomposites decorated with metal oxides (e.g., ZnO, TiO_2) have been widely explored for enhancing electrochemical sensing performances [20]. Fig. 2 shows a graphene-CNT hybrid, which provides a highly conductive and flexible matrix for advanced sensor applications [21].

Metal-organic frameworks (MOFs), a class of highly porous crystalline materials composed

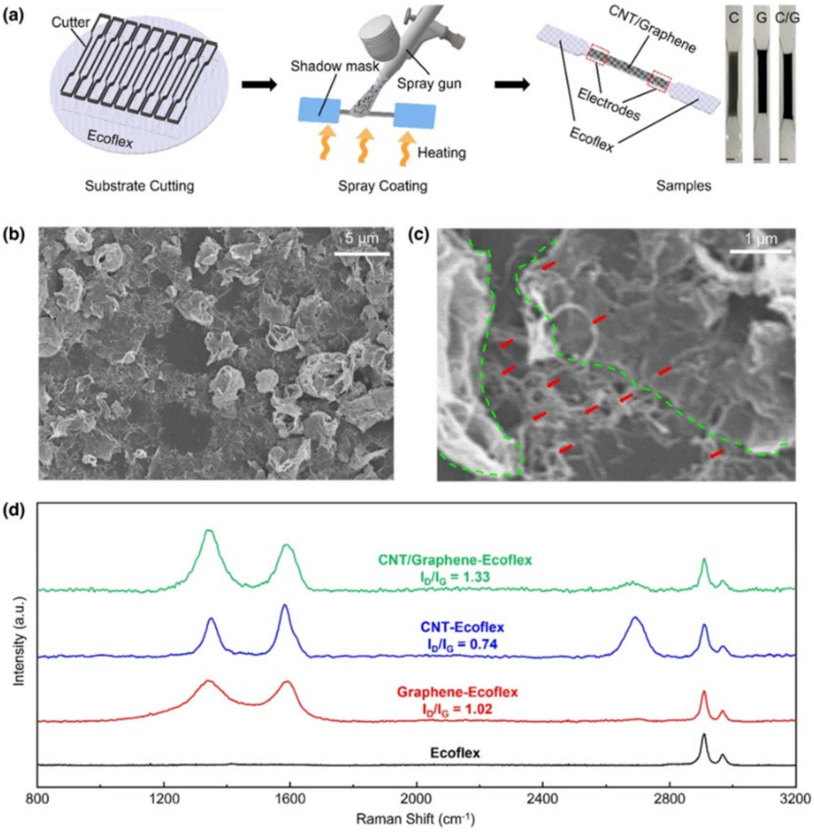

Fig. 2. Structure and characterization of a graphene–CNT hybrid sensor.
(a) Schematic illustration of the fabrication process of a MWCNT/graphene hybrid sensor on an Ecoflex substrate; **(b)** SEM image of the randomly distributed hybrid film; **(c)** magnified view highlighting CNTs bridging adjacent graphene sheets; and **(d)** Raman spectra confirming the formation of a percolating 1D–2D nanocarbon network with enhanced mechanical and electrical properties [21].

Table 2. Nanocomposite materials used for heavy metal detection.

Nanocomposite Type	Components	Key Properties	Target Ions	References
rGO–AuNP	Reduced graphene oxide, gold NPs	High conductivity, biocompatibility	Cd^{2+}, Pb^{2+}	[19, 11]
CNT–ZnO/TiO_2	Carbon nanotubes, metal oxides	Large surface area, stability	Pb^{2+}, Cu^{2+}	[20]
MOF–Graphene	MOFs, graphene sheets	High porosity, selective adsorption	Hg^{2+}, As^{3+}	[22]
PANI–AuNP	Polyaniline, gold nanoparticles	Flexible, stable in water environments	Cd^{2+}, Pb^{2+}	[24]

Overview of representative nanocomposite types applied in heavy metal sensing, including their constituent materials, key physicochemical properties, and target metal ions relevant to aquaculture monitoring.

of metal ions coordinated to organic ligands, are another promising category. MOF-based nanocomposites exhibit extraordinary adsorption capacities for heavy metals and have been integrated with nanomaterials like graphene or quantum dots (QDs) to fabricate highly sensitive optical and electrochemical sensors [22]. The design flexibility of MOFs allows for tailoring pore size and surface chemistry to selectively trap specific metal ions [23].

Polymer-based nanocomposites, where conducting polymers such as polyaniline (PANI) or polypyrrole (PPy) are combined with nanoparticles, are also widely studied. These systems offer excellent flexibility, processability, and environmental stability, making them suitable for in-field applications in aquaculture [24]. Hybrid sensing systems that combine different transduction mechanisms (e.g., electrochemical-optical) are also emerging to provide redundant and more reliable data [25]. Table 2 summarizes commonly used nanocomposite types for heavy metal detection, highlighting their components, key properties, and target ions.

2.2 Fabrication Techniques for Nanocomposite-Based Nanosensors

Several fabrication techniques have been developed for assembling nanocomposites into functional nanosensors:

- Electrode Modification: For electrochemical sensors, modifying electrodes with nanocomposite films is a common approach. Drop-casting, spin-coating, and electrochemical deposition are typical techniques. For example, a screen-printed carbon electrode (SPCE) modified with a GO-AuNP composite was successfully utilized for detecting Pb^{2+} and Cd^{2+} in aquaculture water with detection limits below 1 ppb [26].
- Layer-by-Layer (LbL) Assembly: This technique allows for precise control over film thickness and composition. It involves the sequential adsorption of oppositely charged polyelectrolytes and nanomaterials to create multilayered nanocomposite films [27].
- Sol–Gel Processing: The sol–gel method is often used to synthesize metal oxide–based nanocomposites. It enables the incorporation of nanoparticles into a porous matrix, which enhances the adsorption and sensing of heavy metal ions [28].
- Electrospinning: Electrospinning can fabricate nanofibers embedded with nanocomposites, providing a high surface area-to-volume ratio that is advantageous for sensor sensitivity [29].
- 3D Printing: Emerging studies have explored the use of 3D printing to fabricate customizable nanocomposite-based sensor platforms for aquaculture monitoring. This technique offers rapid prototyping and scalability [30].

2.3 Sensing Mechanisms

Nanocomposite-based nanosensors utilize various sensing mechanisms to detect heavy metals:

- Electrochemical Sensing: Electrochemical detection remains the most widely used due to its high sensitivity and quantitative output. Techniques such as differential pulse voltammetry (DPV), square wave anodic

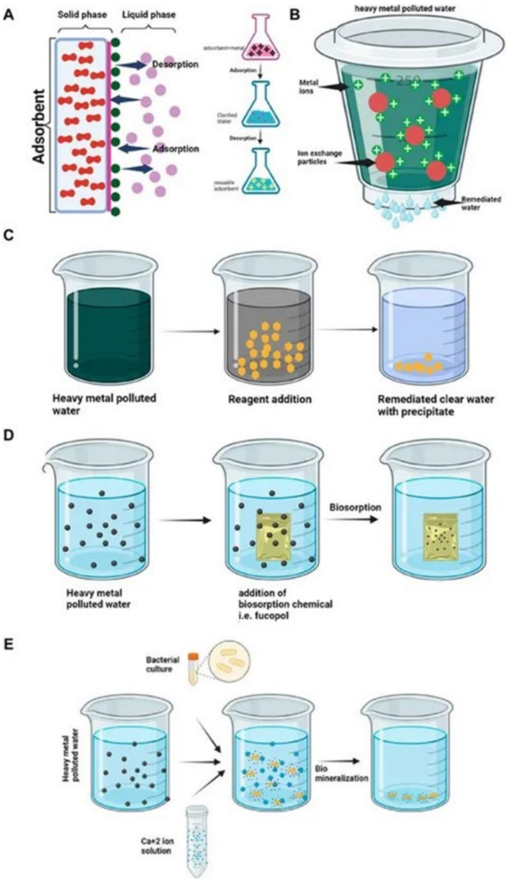

Fig. 3. Mechanisms involved in heavy metal removal from aquatic systems.
Schematic representation of major mechanisms including **(A)** adsorption, **(B)** ion exchange, **(C)** precipitation, **(D)** biosorption, and **(E)** biomineralization, which are commonly leveraged or mimicked by engineered nanomaterials in aquatic remediation and sensing applications [36].

stripping voltammetry (SWASV), and electrochemical impedance spectroscopy (EIS) are common [31]. Nanocomposites enhance electron transfer kinetics and provide binding sites for heavy metal ions, improving sensitivity and selectivity [32].

- Optical Sensing: Optical sensors, including fluorescence, colorimetric, and surface plasmon resonance (SPR)-based sensors, exploit changes in optical properties upon heavy metal binding. For instance, quantum dot–graphene oxide nanocomposites have been used to detect Hg^{2+} ions through fluorescence quenching [33].
- Piezoelectric Sensing: Piezoelectric sensors, particularly quartz crystal microbalance (QCM) devices coated with nanocomposite films, detect mass changes upon heavy metal adsorption, providing label-free and real-time monitoring [34].
- Field-Effect Transistor (FET)-Based Sensing: FET sensors incorporate nanocomposites into the gate region, and the binding of heavy metals modulates the charge carrier mobility, leading to detectable changes in current [35].

Fig. 3 illustrates various mechanisms for the removal of heavy metals in aquatic systems, including adsorption, ion exchange, and precipitation, which are often leveraged or mimicked by nanocomposite sensors [36].

3. Performance Evaluation and Field Deployment Potential

This section synthesizes performance data and field-testing outcomes reported in the literature for various nanocomposite-based nanosensors, critically evaluating their potential for aquaculture application.

3.1 Reported Analytical Performance

Literature surveys indicate that nanocomposite-based nanosensors consistently achieve high sensitivity and low detection limits for heavy metals. Table 3 compiles the reported performance of different nanosensor types, showcasing their capabilities in detecting trace levels of contaminants relevant to aquaculture.

As shown in Table 3, detection limits often fall within the sub-ppb to low ppb range, which is sufficient to meet the stringent regulatory limits set by organizations like the WHO and the European Union for water bodies [37]. A critical comparison with conventional techniques, as summarized in Table 4, highlights the key advantages of nanosensors, particularly their rapid response time and portability, despite the potentially superior absolute sensitivity of laboratory-based instruments like ICP-MS [38, 39].

The performance of these sensors is heavily influenced by the properties of the constituent nanomaterials. For instance, the high surface area of graphene oxide [42] and the stability of ZnO nanorods [43] are frequently cited as key factors contributing to enhanced sensor efficiency. Innovative nanocomposite designs continue to push the boundaries of sensitivity and selectivity for aquatic monitoring [44].

3.2 Selectivity and Real Sample Analysis

A crucial metric for aquaculture application is sensor selectivity in complex water matrices. Studies consistently demonstrate that tailored surface functionalization of nanocomposites can impart high specificity towards target metal ions. For example, sensors functionalized with thiol groups show preferential binding to Hg^{2+}, while phosphate groups enhance affinity for Pb^{2+} and Cd^{2+} [45]. Selectivity tests often involve challenging the sensor with common interferents like Na^+, K^+, Mg^{2+}, Ca^{2+}, Zn^{2+}, and Fe^{3+}, with many reported sensors maintaining robust performance [11, 33]. Advanced materials, including those functionalized with specific biomolecules or ionophores, are key to achieving this high specificity in complex matrices [46].

When applied to real water samples from aquaculture farms, nanocomposite-based nanosensors generally show excellent agreement with standard methods like ICP-MS, with reported relative errors often below 10% and recovery rates between 90-110% [26, 47]. This validates their reliability for monitoring in authentic, complex environments with minimal sample pretreatment.

3.3 Case Studies and Field Deployment

Several case studies underscore the practical potential of these technologies. As summarized

Table 3. Analytical performance of nanocomposite-based nanosensors.

Nanosensor Type	Nanocomposite Material	Target Metal	Detection Limit (μg/L)	Reference
Electrochemical	Graphene oxide–AuNPs	Pb^{2+}	0.5	[27]
Colorimetric	$Fe_3O_4@SiO_2$–APTMS	Hg^{2+}	1.2	[29]
Fluorescent	Carbon QDs–ZnO	Cd^{2+}	0.8	[28]
Piezoelectric	(QCM) ZnO Nanorods	As^{3+}	0.9	[13]

Comparison of reported detection limits and sensing performance of various nanocomposite-based nanosensors for heavy metal detection in aquatic and aquaculture environments.

Table 4. Comparison between nanosensors and conventional analytical techniques.

Technique	Detection Time (min)	Sensitivity	Selectivity	Portability	Reference
Nanocomposite Nanosensor	< 10 – 30	High	High to Medium	High	[32]
Atomic Absorption	~ 30	High	Medium	low	[40]
ICP-MS	~ 45	Very High	High	Low	[41]

Comparative evaluation of nanocomposite-based nanosensors and traditional laboratory-based methods in terms of detection time, sensitivity, selectivity, portability, and practical applicability.

in Table 5, successful deployments have been documented in various countries.

Field testing often involves integrating sensors into portable, ruggedized units with wireless data transmission (e.g., Bluetooth, LoRa) for remote monitoring [51]. Some systems have been successfully tested over periods of several weeks, demonstrating the ability to track contamination trends and identify pollution sources, such as spikes following rainfall events [47, 52]. Fig. 4 provides a schematic overview of the integrated workflow for developing and deploying nanosensors in an aquaculture setting, from material synthesis to data-driven decision-making.

Fig. 4. Schematic workflow for the development, deployment, and application of nanocomposite-based nanosensors in smart aquaculture. The process involves (1) Nanocomposite Synthesis & Sensor Fabrication, (2) Lab-based Characterization & Calibration, (3) Field Deployment in aquaculture ponds with integrated wireless systems, (4) Data Transmission to a central platform/cloud, and (5) Data Analysis & Decision Support using AI algorithms for real-time alerts and management actions.

4. Discussion: Challenges, Synthesis, and Future Outlook

4.1 Critical Analysis of Technological Maturity and Challenges

While the reported performance of nanocomposite-based nanosensors is impressive, a critical gap remains between laboratory success and widespread commercial deployment in aquaculture. The key challenges, summarized in Table 6, require urgent attention.

Beyond these technical hurdles, significant regulatory and environmental concerns persist. The regulatory landscape for environmental

Table 5. Field applications of nanocomposite-based nanosensors in aquaculture.

Country	Metal Detected	Nanosensor Type	Result Summary	Reference
Iran	Cd^{2+}	ZnO-CNT Hybrid Sensor	Successful monitoring in carp culture tanks	[48]
China	Pb^{2+}	Electrochemical (Graphene-Au)	Effective detection in tilapia farms	[49]
India	Hg^{2+}	Colorimetric (Fe_3O_4@SiO_2)	Trace detection in shrimp aquaculture	[50]
USA	Cd^{2+}	Fluorescent (QDs-ZnO)	Real-time monitoring demonstrated successful	[43]

Summary of selected case studies demonstrating the application of nanocomposite-based nanosensors for heavy metal monitoring in real aquaculture settings across different countries.

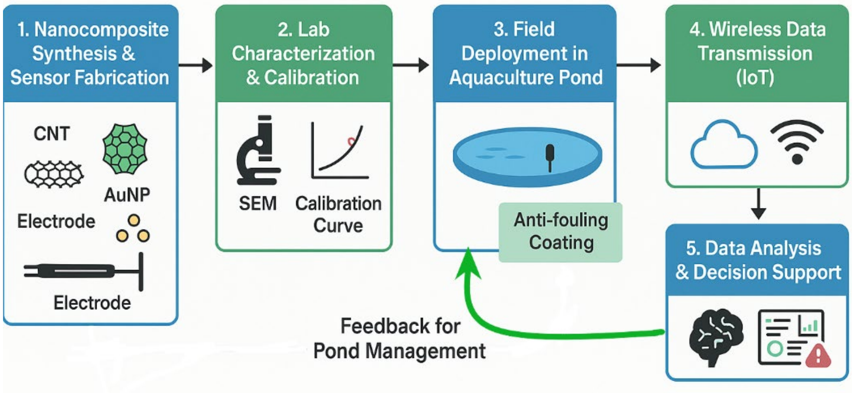

Fig. 4. Integrated workflow of nanocomposite-based nanosensors in smart aquaculture.
Conceptual schematic illustrating the sequential stages of nanocomposite synthesis and sensor fabrication, laboratory characterization and calibration, field deployment in aquaculture ponds, wireless data transmission, and AI-assisted data analysis for real-time water quality management and decision support.

Table 6. Major challenges in nanosensor deployment for aquaculture monitoring.

Challenge	Description	Impact	Potential Mitigation Strategies	Reference
Biofouling	Accumulation of organisms (algae, bacteria) on sensor surfaces, reducing sensitivity and accuracy.	High	High Development of antifouling coatings (e.g., PEG, zwitterionic polymers), periodic cleaning, or ultrasonic self-cleaning mechanisms.	[53]
Matrix Effects	Variability in water chemistry (pH, salinity, dissolved organic matter) can interfere with sensor response.	Medium	Incorporation of robust calibration methods, use of internal standards, and designing sensors with built-in compensation.	[54]
Long-Term Stability	Degradation of nanocomposite materials or leaching of nanoparticles over time, affecting reliability.	High	Encapsulation strategies, use of more stable and inert matrix materials, and long-term durability testing.	[55]
Scalability & Reproducibility	Batch-to-batch variability in nanocomposite synthesis hinders mass production of consistent sensors.	High	High Development of standardized, scalable fabrication protocols (e.g., continuous flow synthesis) and rigorous quality control.	[56]

Overview of key technical and operational challenges associated with real-time deployment of nanosensors in aquaculture systems, along with their impacts and potential mitigation strategies.

Table 7. Advantages and limitations of selected nanocomposite materials.

Sensor Material	Advantages	Challenges for Aquaculture Application	Reference
Graphene Oxide	High conductivity, large surface area, flexible design	Prone to aggregation in ionic solutions, potential long-term environmental persistence	[11, 42]
Chitosan-based	Biocompatibility, biodegradability, low-cost	cost Limited stability and swelling in saltwater, moderate conductivity	[62]
CNT-metal hybrids	Very high sensitivity, tunable electronic response	Cost, potential cytotoxicity, complex functionalization	[20, 63]
MOF-based	Extremely high porosity, designable pore chemistry	Stability in water, scalability of synthesis, cost	[22, 64]

Comparison of commonly used nanocomposite materials for aquaculture sensing, highlighting their principal advantages and material-specific challenges affecting long-term performance.

nanosensors is underdeveloped, lacking standardized validation protocols and certification processes [57]. Furthermore, the potential ecotoxicity of nanomaterials upon leaching into the environment warrants a thorough life-cycle assessment (LCA) of these devices [58, 17, 18]. Future research must prioritize the development of biodegradable or easily recoverable nanocomposites to minimize ecological risks [59]. Interdisciplinary collaboration is essential to navigate the environmental impacts and policy challenges associated with deploying nanotechnology at scale [60].

4.2 Comparative Advantages and Material-Specific Challenges

The advantages of nanocomposite-based sensors are clear when compared to both traditional lab techniques and simple colorimetric kits. They offer a compelling combination of sensitivity, speed, and portability. However, the choice of nanocomposite material involves trade-offs, as outlined in Table 7. A comprehensive review of nanocomposite-based sensors highlights both the remarkable progress and the persistent challenges in detecting heavy metals in water [61].

4.3 Integration with Digital Technologies and Smart Aquaculture

The true transformative potential of nanosensors lies in their integration into digital agriculture frameworks. The confluence of IoT, AI, and nanosensors can enable "Smart Aquaculture" [15, 51, 65]. Real-time data from deployed sensor networks can be streamed to cloud platforms where machine learning algorithms can predict contamination events based on historical and real-time trends, allowing for preemptive action [66]. Furthermore, the rise of smartphone-based readout systems, where colorimetric or fluorescent signals are quantified using a phone's camera and a dedicated app, dramatically lowers the technical and cost barriers for end-users [67]. Comprehensive economic assessments are crucial to validate the cost-benefit advantage and encourage adoption of these integrated systems in commercial aquaculture operations [68]. The successful deployment of nanomaterials in water purification and sensing provides a strong foundation for these integrated monitoring solutions [69].

4.4 Future Research Directions

Based on the critical assessment of the current state-of-the-art, the following future research directions are proposed to advance the field:

1. Multi-analyte Sensing Platforms: Future efforts should focus on developing single sensor platforms capable of simultaneously detecting a panel of contaminants, including heavy metals, antibiotics, pesticides, and pathogens, to provide a comprehensive water quality diagnosis [70].
2. Advanced Antifouling Strategies: Research into novel bio-inspired and nanostructured antifouling coatings that are effective and environmentally benign is crucial for long-term deployment.
3. Eco-Design and Green Nanomaterials: A paradigm shift towards using sustainable, biodegradable, or recyclable nanomaterials (e.g., derived from cellulose, chitosan) should be encouraged to address environmental safety concerns [59].
4. Self-Powered Sensors: Exploring energy-harvesting technologies, such as triboelectric nanogenerators (TENGs) powered by water movement, could enable autonomous, battery-free sensor operation in remote locations [71].
5. Standardization and Regulatory Science: Collaborative efforts between researchers, industry, and regulators are needed to establish standardized performance evaluation protocols and clear regulatory pathways for the approval of nanosensing devices [57].
6. Exploration of Emerging Nanomaterials: The sensing community should continue to explore the potential of newer 2D materials (e.g., MXenes, phosphorene) and their heterostructures with traditional nanocomposites for achieving unprecedented sensitivity and specificity [72].
7. Continuous research and critical reviews are vital to track the development of nanocomposite-based sensors for environmental contaminants and steer future innovations [73, 74].
8. The use of nanocomposites for both detection and remediation represents a powerful synergistic approach to managing water quality [75].

5. Conclusion and Future Perspectives

This review has synthesized recent advancements in nanocomposite-based nanosensors for the rapid detection of heavy metal contamination in aquaculture. The integration of nanomaterials such as graphene derivatives, carbon nanotubes, metal-organic frameworks, and metallic nanoparticles into composite structures has demonstrably led to sensing platforms with exceptional sensitivity (often in the sub-ppb range), rapid response times, and high selectivity. These attributes make them promising candidates to overcome the limitations of traditional, lab-bound analytical methods.

The potential impact on aquaculture is significant. The ability to perform frequent, on-site, and real-time monitoring can enable a shift from reactive to proactive management of water quality. This directly contributes to enhanced biosecurity, reduced economic losses from contamination events, and ensured seafood safety, aligning with the goals of sustainable and precision aquaculture [76, 65].

However, the path to widespread commercialization is fraught with challenges.

Issues of sensor fouling, long-term stability in harsh aquatic environments, reproducibility in large-scale manufacturing, and unresolved environmental and regulatory concerns represent significant hurdles. Addressing these requires a multidisciplinary approach, combining expertise from materials science, sensor engineering, aquaculture biology, and regulatory science.

Future progress in this field will likely be driven by several key trends: the development of multi-analyte and multifunctional sensors [77], the integration with AI-powered data analytics for predictive monitoring, the adoption of eco-friendly materials, and the creation of self-powered, autonomous sensing systems. By focusing on these strategic directions and fostering collaboration across disciplines, the full potential of nanocomposite-based nanosensors can be realized, ultimately contributing to the resilience and sustainability of global aquaculture production.

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