International Journal of Research in Engineering and Management Sciences (IJREMS)
E-ISSN: 3107-7439

Research Article
VOL.: 2, Issue: 5, May 2026

Nanomaterial-Based Sensors For Environmental Monitoring: A Review

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ABSTRACT:

Environmental monitoring has become a major focus for nanomaterial sensors due to their high sensitivity, selectivity, and flexibility in detecting pollutants and contaminants. These sensors exploit the distinctive characteristics of nanomaterials such as metal nanoparticles, carbon-based nanomaterials, metal-organic frameworks (MOFs), quantum dots, and nanocomposites to improve sensing performance in air, water, soil, and biological systems. This paper examines the various nanomaterials used in sensors, their sensing mechanisms, and their applications in environmental monitoring with emphasis on real-time, portable, and low-cost sensors. It also includes challenges related to sensitivity, stability, scalability, and environmental compatibility, as well as recent developments and future prospects in nanomaterial-based sensor technologies. The potential of integrating nanomaterials with the Internet of Things (IoT) for smart, connected monitoring is also discussed.

Keywords: Nanomaterials, Environmental monitoring, Sensors, Metal nanoparticles, Carbon nanotubes, Graphene, Metal-Organic Frameworks (MOFs), Quantum dots, Electrochemical sensors

Received Date: 7 May 2026**; Accepted Date:** 17 May 2026**; Published Date:** 24 May 2026.

1. Introduction

This review highlights the significance of nanomaterial-based sensors in addressing the growing need for environmental sensing, given that conventional techniques cannot comprehensively detect a wide range of contaminants (Willner & Vikesland, 2018, p. 1). The distinctive features of nanomaterials, such as a high surface-to-volume ratio, remarkable electrical conductivity, and adjustable optical properties, enable the development of highly sensitive, specific, and fast sensors for various environmental contaminants (Su et al., 2012). These nano-sensors, as nanoscale transducers, can identify and detect chemical, mechanical and physical stimuli, followed by the production of an electrical or optical signal (Asghar et al., 2024, p. 14). This novel technique enables the rapid detection and mitigation of potential risks, thereby preventing environmental degradation and

DOI: https://doi.org/10.65477/ijrems.v2.i5.03

resource wastage (Neelalochana et al., 2025). In particular, the incorporation of various nanoparticles and nanostructures into analytical devices can drive significant progress in developing miniaturized, ultrasensitive, and inexpensive methods for in situ environmental monitoring (Andreescu et al., 2008). These new-generation nanomaterial-based biosensors offer many advantages over conventional sensors, including high sensitivity, selectivity, and cost-effectiveness in detecting contaminants such as heavy metals, organic pollutants, and atmospheric particles (Darwish et al., 2024, p. 4028; Sharma et al., 2024).

2. Nanomaterials Used in Sensors

The combination of nanotechnology with analytical techniques offers great potential for developing miniaturized, fast, and highly sensitive environmental monitoring systems (Andreescu et al., 2008; Willner & Vikesland, 2018). This combination enables the monitoring of a broad spectrum of pollutants, even at very low concentrations, thus improving the accuracy of environmental monitoring (Darwish et al., 2024). This is enabled in particular by the use of various nanomaterials, such as metal nanoparticles, carbon-based nanomaterials, metal-organic frameworks, quantum dots, and nanocomposites, among others, which have specific properties that can be used to develop sensors (Neelalochana et al., 2025; Su et al., 2012). Such sensors offer greater convenience, selectivity, sensitivity, and reproducibility in environmental monitoring, overcoming issues associated with conventional methods, such as the inability to detect low analyte concentrations and interference from other species (Errachid et al., 2022). These developments are important in light of the growing global challenges related to environmental pollution, resource scarcity, and global warming, which need to be addressed through advanced sensor and monitoring technologies for real-time environmental monitoring (Kaur et al., 2024). Nanomaterial-based nanosensors, in particular, are extremely efficient at identifying and sensing chemical, mechanical and physical events at the nanoscale, transducing the electrical and optical signals for the accurate detection and treatment of environmental pollutants (Asghar et al., 2024).

With a high surface-to-volume ratio and modifiable physicochemical properties, they can be used to achieve superior performance in a wide range of environmental applications including enhanced sensitivity and selectivity of biosensors (Chandran, 2021; Kumar & Bhanjana, 2025). For example, nanosensor-based biosensors have shown unprecedented sensitivity and fast response times for detecting environmental contaminants such as heavy metals and pesticides, with detection limits in the nanomolar to picomolar range (Aguilar-Pérez et al., 2020). This improved selectivity and sensitivity is due to their distinct electrical, thermal, optical, magnetic and electrochemical properties, which can be fine-tuned by controlling their morphology, microstructure, and composition (Sun, 2019).

Table 1: Comparison of Nanomaterial-Based Sensors with Traditional Sensors

This table highlights the advantages and limitations of different nanomaterial-based sensor types for detecting environmental pollutants.

Sensor Type	Nanomaterial Used	Sensing Mechanism	Advantages	Limitations
Electrochemical Sensors	Metal nanoparticles, Graphene	Current/voltage change	High sensitivity, fast response time	Limited long-term stability
Optical Sensors	Quantum dots, Graphene, CNTs	Light absorption/fluorescence	High sensitivity, real-time detection	Potential interference from background noise
Mass-Based Sensors	Nanocomposites, Graphene	Frequency shift	Can detect very low concentrations	Requires stable environment for accuracy
Biosensors	Carbon nanotubes, Graphene	Bioreceptor interaction	Selectivity for biological contaminants	Complex sensor development

Source: Adapted from the comparison of nanomaterial-based and traditional sensor technologies in environmental research articles.

3. Working Principle of Nanomaterial-Based Sensors

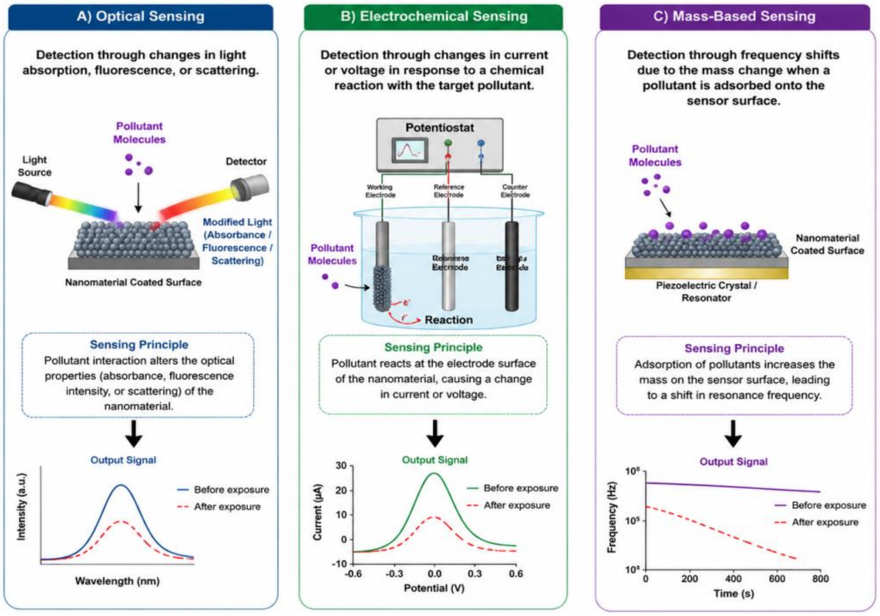
The various types of sensing techniques, involving photonic, electrochemical and gravimetric transducers, have become integral to countless applications, including biomedical and environmental sensing (Cote et al., 2003; Ram et al., 2010). Choosing a particular transduction principle (optical, electrochemical, or mass-based) is important because it affects the assay's dynamic range, resolution, signal-to-noise ratio, and detection limit (Usha et al., 2021).

For example, although electrochemical biosensors are currently the most widely market for metabolite measurements, optical and mass-based sensors have unique advantages for other applications due to the use of different physical properties to generate the signal (Turner, 2013). These sensing mechanisms translate a biological recognition event into a signal via different processes: optical sensors work on changes in light properties, electrochemical sensors on changes in electrical properties and mass-based sensors on changes in mass or mass-induced frequency change (Suma & Adarakatti, 2024). Electrochemical sensors, in particular, are incredibly versatile in operation for real-time monitoring, and can be miniaturized for integration into portable devices; however, they require careful calibration and are prone to interference and drift effects (Rosendo et al., 2023).

4. Environmental Monitoring using Nanomaterial-Based Sensors

The surge in industrialization has demanded advanced environmental monitoring technologies to detect and measure its adverse impact on the environment and human health, prompting the development of improved sensing technologies (Heo et al., 2023). This encompasses chemical sensors that can detect, quantify and continually monitor various inorganic and organic contaminants released into the environment (Inobeme et al., 2024). These modern chemical sensing technologies provide sensitive, selective detection of pollutants and enable real-time monitoring, overcoming the drawbacks of conventional techniques (Ojomo, 2025). This advancement in technology allows the use of these sensors in different environmental media for:

- Air Pollution: Sensing gases such as CO2, NOx, O3, and VOCs.
- Water Quality Monitoring: Sensing metals, pesticides and microorganisms.
- Soil Contamination: Detection of contaminants and soil quality.
- Biological Sensing: Sensing of biological contaminants and pathogens (Gao et al., 2025).



Detection through changes in light absorption, fluorescence, or scattering.

Pollutant interaction alters the optical properties (absorbance, fluorescence intensity, or scattering) of the nanomaterial.

Detection through changes in current or voltage in response to a chemical reaction with the target pollutant.

Pollutant reacts at the electrode surface of the nanomaterial, causing a change in current or voltage.

Detection through frequency shifts due to the mass change when a pollutant is adsorbed onto the sensor surface.

Adsorption of pollutants increases the mass on the sensor surface, leading to a shift in resonance frequency.

Figure 1: Mechanism of Nanomaterial-Based Sensors for Environmental Monitoring.

Source: Authors' conceptualization based on recent literature in nanomaterial-based sensors for environmental monitoring.

Figure 1: Sensing Mechanisms of Environment Monitoring by Nanomaterials. (A) Optical, (B) Electrochemical, (C) Mass-Based. These play an important role in sensing pollutants in the environment, including gases, metals and VOCs.

Electrochemical sensors, in particular, have demonstrated many advantages, such as high sensitivity, low detection limits, and low cost, and are becoming increasingly prominent in this field for environmental monitoring (Kurbanoğlu & Cetin, 2025; Zhang, 2024). This is also enhanced by advances in miniaturization and microfabrication techniques, which enable the development of in situ, mobile devices capable of automated analysis of environmental samples (Hanrahan et al., 2004). These enable the use of small sample volumes and the miniaturisation of the system, resulting in ever more sensitive, sensitive, accurate and reliable chemical sensors for environmental sustainability (Gamboa, 2023; Rahman & Asiri, 2017).

5. Challenges and Limitations

While the potential of nanomaterials in sensor fabrication is significant, there are key challenges in translating laboratory developments into real-world applications (Fadel et al., 2016). One of the primary challenges is optimizing sensitivity and selectivity, particularly for low-concentration analyte detection, and ensuring the sustainability and reproducibility of sensor performance, which are affected by various factors, such as environmental conditions (Kamal, 2018). Cost-related factors, including the high cost of advanced nanomaterials and difficulties in scaling up to produce sensors for large-scale applications, further exacerbate these challenges (Hassan et al., 2023; Virk et al., 2024).

Additionally, environmental considerations, such as the toxicity of certain nanomaterials and the overall sustainability of sensors, require assessment and the development of mitigation strategies for sustainable sensor development (Simpa et al., 2024). Therefore, ongoing research needs to address the selectivity, stability, and long-term durability of nanomaterial-based sensors, and investigate environmentally friendly and economical approaches for the large-scale fabrication of sensors (Asghar et al., 2024). This includes exploring new nanomaterials with improved stability and biocompatibility, and integrating sensors with other technologies, such as artificial intelligence and the Internet of Things, to develop smart, networked sensing platforms (Darwish et al., 2024).

6. New Developments and Technological Innovations

This review provides insights into integrating hybrid nanomaterials with the Internet of Things to develop wearable sensors for advanced environmental monitoring (Kaur et al., 2024). Such developments hold promise for a new generation of sensitive, personal wearable environmental monitoring sensors, particularly through the use of screen-printed sensors with nanocomposites exhibiting enhanced electrochemical properties (Godja & Munteanu, 2024). This process not only enables cost-efficient fabrication but also offers customizable designs, particularly through the incorporation of carbon-based nanomaterials and functionalized Mxenes to improve sensor performance (Godja & Munteanu, 2024).

Moreover, by incorporating these advanced nanomaterials, wearable devices can provide real-time physiological and environmental monitoring, capitalising on the large surface area and superior properties of these nanomaterials and delivering enhanced sensitivity and fast response (Jayathilaka et al., 2018; Mamun & Yuce, 2020; Yao et al., 2017). This enables detection of a broad spectrum of analytes, ranging from toxic gases in air to specific biomarkers in biological fluids, which are important for public safety and health care (Anwer et al., 2024; Peng et al., 2020). The unmatched sensing performance of these next-generation chemical sensors (often containing graphene-based materials, MXenes, carbon nanotubes and metal-organic frameworks) enables detection limits down to parts-per-billion or even parts-per-trillion levels (Machín & Márquez, 2025a, 2025b). The judicious integration of different nanomaterials into hybrid nanocomposites allows fine-tuning of the physicochemical and morphological properties, such as tunable interlayer spacing, porosity and surface area, which are essential for designing next-generation chemiresistors (Chaudhary et al., 2022).

7. Future Perspectives

The growing use of nanomaterials in various applications requires well-developed regulatory measures and standardised protocols for their safe

DOI: https://doi.org/10.65477/ijrems.v2.i5.03

and effective use in various environmental monitoring programs (Corsi et al., 2018; Jebril et al., 2024). This encompasses the development of standardized protocols for evaluating the environmental fate of nanomaterials and the establishment of norms to help guide the synthesis, characterization, and use of nanomaterials in sensor technologies (Fadel et al., 2016). Importantly, this includes the development of robust evaluation systems for evaluating the toxicity of engineered nanomaterials and toxicity biomarkers (Ahamed et al., 2020).

Moreover, global harmonization of nanotechnology regulations is crucial to enable international collaboration and avoid regulatory barriers that may obstruct innovation or open the door to unsafe practices (Chávez-Hernández et al., 2024). This involves working together between academia, industry and regulatory authorities to fill knowledge gaps related to the long-term environmental and health effects of nanomaterials (Gidiagba et al., 2023; Ulucan-Karnak et al., 2024). This collaboration is especially critical for the development of advanced sensor platforms featuring nanomaterials integrated with multi-modal sensors, to ensure their efficacy and regulatory compliance (Godja & Munteanu, 2024). These practices should also include sustainable and environmentally friendly synthesis of nanomaterials, and next-generation ecotoxicological testing methods, to minimise adverse effects and optimise the benefits of nano-enabled remediation (Ganie et al., 2021).

8. Conclusion

In this section, we will first briefly recap the key lessons from the above discussions, and then look ahead to the potential future of nanomaterial-based sensor technologies. In particular, we will reiterate the crucial role of nanomaterial-based sensors in enhancing environmental monitoring and then explore the possibilities for their adoption and future development. This could involve the discovery of new nanomaterials with improved performance, the integration of these sensors with other technologies such as artificial intelligence and the Internet of Things (IoT), and the sustainable and economical production of the sensors (Darwish et al., 2024). The future of research should focus on enhancing the selectivity, stability and durability of nanomaterial composites, as well as developing new types of nanomaterials and sophisticated characterization techniques to further optimise detection (Asghar et al., 2024). Additionally, the use of multiplexed biosensors to simultaneously detect several contaminants will provide a more holistic approach to environmental safety (“Nanobiosensors: Application in Healthcare, Environmental Monitoring and Food Safety,” 2023).

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