Research & Reviews in Biotechnology & Biosciences
Website: www.biotechjournal.in
Volume: 12, Issue: 2, Year: 2025
DOI: https://doi.org/10.5281/zenodo.17995287

ISSN: 2321-8681
Research Paper
PP: 123-132
Peer Reviewed Refereed Journal

NANOPARTICLE-BASED SENSORS FOR REAL-TIME MONITORING OF ENVIRONMENTAL POLLUTANTS

Deep Narayan Maurya[1*], Nitin Kumar Agrawal[2], Animesh Agarwal[2], Manish Saxena[2], Shama Parveen[3]

[1*]*Department of Chemistry, DN (P.G.) College Meerut, Uttar Pradesh, India*

[2]*Department of Applied Sciences and Humanities, Moradabad Institute of Technology, Moradabad, Uttar Pradesh, India*

[3]*Department of Chemistry, Ethics University, Pauri Garhwal, Uttarakhand, India*

Article History

Received: 23/11/2025

Accepted: 19/12/2025

Article ID: RRBB/10_2025

Corresponding Author:

E-Mail: mauryadeep343@gmail.com

ABSTRACT

Environmental pollution has become a critical global challenge, requiring rapid, accurate, and continuous monitoring systems. Nanoparticle-based sensors have emerged as powerful tools for real-time detection of pollutants due to their unique physicochemical properties, including high surface area, tunable optical behavior, and enhanced catalytic activity. In this study, the role of various nanoparticles—such as gold nanoparticles, iron oxide nanoparticles, carbon dots, quantum dots, and graphene-based nanomaterials—in environmental sensing is reviewed. These nanomaterials interact with pollutants through adsorption, reduction, or surface binding, causing detectable changes in color, fluorescence, conductivity, or magnetic response. Such signal variations enable highly sensitive and selective detection of heavy metals, industrial dyes, pesticides, pharmaceutical residues, toxic gases, and micro-pollutants even at trace concentrations. The integration of nanomaterials with optical, electrochemical, and fluorescence-based sensing platforms further enhances detection speed and reliability. Overall, nanoparticle-based sensors represent a promising advancement for environmental monitoring by providing real-time, low-cost, portable, and eco-friendly solutions for pollution assessment and environmental protection.

Keywords; nanoparticle-based sensors**,** environmental pollutants**,** real-time monitoring**,** heavy metal detection**,** fluorescence and electrochemical sensing.

INTRODUCTION

Environmental pollution has intensified over the past decade due to rapid industrial expansion, urbanization, and the excessive discharge of chemical wastes into natural ecosystems. During the last five years (2020–2024), global reports have repeatedly highlighted rising concentrations of heavy metals, dyes, pesticides, pharmaceutical residues, microplastics, and gaseous pollutants in air, water, and soil. These contaminants not only threaten human health but also disturb ecological balance, reduce soil fertility, and contaminate freshwater resources. Although advanced analytical instruments—such as ICP-MS, GC-MS, and AAS—are widely used to monitor pollutants, they often require well-equipped laboratories, high operational cost, and long analysis times, which limits their application for rapid or on-site detection.

Recent research from 2020 onward has increasingly focused on nanotechnology as a promising alternative for environmental monitoring. Nanoparticles possess remarkable properties, including high surface-to-volume ratio, tunable optical and electronic behavior, and strong surface reactivity. These characteristics allow nanoparticles to interact efficiently with toxic substances, resulting in measurable changes that can be detected through optical, fluorescence, magnetic, or electrochemical methods. Because of these advantages, nanosensors can identify pollutants at trace levels, respond quickly, and operate with minimal sample preparation.

Over the last five years, materials such as gold nanoparticles, silver nanoparticles, graphene nanostructures, carbon dots, metal oxide nanoparticles, and iron oxide–based magnetic nanoparticles have gained significant attention. Researchers have reported their ability to detect heavy metals like Pb^{2+}, Cd^{2+}, Cr^{6+}, As^{3+}; dyes such as methylene blue and Congo red; pesticides; pharmaceutical residues; and harmful gases including ammonia and nitrogen oxides. Many studies published between 2021 and 2024 have also explored portable and field-ready nanosensor devices that combine smartphones, optical readers, or miniaturized electrochemical interfaces. These innovations make it possible to monitor contaminated sites in real time without relying on laboratory facilities.

Nanotechnology-based sensing systems are increasingly recognized as tools aligned with global sustainability goals. Their ability to offer rapid, low-cost, and highly selective detection makes them essential for early pollution warning systems and long-term environmental protection strategies. With the continuous advancement of material synthesis and sensor engineering, nanoparticle-based sensors are expected to become central to modern environmental surveillance in the coming years.

Research has also expanded into bio-fabricated nanoparticles synthesized from plant extracts, fungi, and bacteria. Green-synthesized nanoparticles—such as those produced using *Ajuga macrosperma*, *Azadirachta indica*, *Ocimum sanctum*, and *Moringa oleifera*—show improved biocompatibility and eco-friendliness. Recent publications from 2021–2024 have demonstrated that plant-derived nanoparticles possess additional functional groups (phenolics, flavonoids, terpenoids) that enhance pollutant binding ability and improve sensing performance. This trend aligns with sustainable sensor development and eliminates the use of hazardous chemicals commonly involved in nanoparticle synthesis.

The integration of nanoparticles with advanced detection technologies (fluorescence spectroscopy, electrochemical readouts, smartphone-based imaging, and microfluidic chips) has led to portable, low-cost, and highly accurate sensing devices. According to literature from 2023–2024, smart nanosensors are increasingly being used for rapid field testing of contaminated water bodies, industrial discharge, agricultural runoff, and air pollutants. These innovations support global environmental goals by enabling early detection, improved regulatory compliance, and timely pollution control measures.

Collectively, recent research demonstrates that nanoparticle-based sensors have transformed the field of environmental monitoring, offering faster detection, minimal sample preparation, and superior sensitivity compared to conventional techniques. As nanotechnology continues to evolve, it is expected to play an essential role in developing next-generation sensing systems for cleaner ecosystems and long-term environmental sustainability.

NANOPARTICLE-BASED SENSORS

Nanoparticle-based sensors have gained significant attention in analytical science due to their unique structural, optical, electrical, and catalytic properties, which outperform conventional sensing materials. Nanoparticles possess a high surface-area-to-volume ratio, tunable surface chemistry, and remarkable electronic behavior that allow for highly sensitive, selective, and rapid detection of chemical and biological targets. Over the past decade, a variety of nanoparticles—including gold (AuNPs), silver (AgNPs), metal oxides (ZnO, TiO_2, Fe_3O_4), carbon-based nanomaterials (graphene, carbon nanotubes), and semiconductor quantum dots—have been integrated into sensor platforms to enhance performance across environmental, biomedical, and industrial applications.

Gold nanoparticles (AuNPs) are among the most extensively explored materials due to their strong localized surface plasmon resonance (LSPR). According to Gupta et al. (2019), the plasmonic properties of AuNPs significantly amplify the optical response of sensors, enabling the detection of biomolecules at extremely low concentrations. Similarly, silver nanoparticles (AgNPs) exhibit sharp plasmonic peaks and high electrical conductivity, making them suitable for colorimetric and electrochemical sensing systems. Metal-oxide nanoparticles, such as ZnO and TiO_2, are known for their excellent electron mobility and catalytic efficiency, which enhance gas-sensing and biosensing performance.

Optical nanoparticle-based sensors have shown remarkable potential in complex mixture analysis. Bigdeli et al. (2017) demonstrated that optical sensor arrays constructed using nanoparticles can distinguish subtle chemical differences using pattern-recognition algorithms, similar to an “artificial nose.” These sensors are increasingly used in environmental monitoring, such as detecting pollutants, heavy metals, and hazardous gases. Their rapid response empowers real-time monitoring, which is essential for industrial and public health applications.

In the domain of food safety and quality assurance, nanoparticle-based sensors play a transformative role. Bülbül et al. (2015) reported that portable nanoparticle-enabled sensing devices allow for fast detection of toxins, adulterants, and pathogens. These sensors reduce the need for expensive laboratory infrastructure and enable field-based detection with high accuracy. In food packaging, metal-based nanoparticles are being developed as both sensing and antimicrobial agents. Kumar et al. (2021) highlighted their ability to enhance freshness monitoring, detect spoilage indicators, and extend shelf life.

Biomedical sensing has also significantly benefited from nanoparticle integration. Quantum dots, because of their narrow emission spectra and high photostability, are ideal for fluorescence-based biosensing. Additionally, magnetic nanoparticles facilitate label-free detection through magnetic relaxation switching, offering advantages in disease diagnostics. Biogenic nanoparticles, synthesized using plant extracts or microorganisms, have gained attention due to their eco-friendly production and biocompatibility (Singh et al., 2016).

Overall, recent literature emphasizes the versatility and high performance of nanoparticle-based sensors. Their ability to detect analytes with ultrahigh sensitivity, combined with low-cost fabrication and potential for miniaturization, positions them as key components in next-generation sensing technologies. While challenges such as stability, reproducibility, and environmental safety remain, ongoing research continues to strengthen their reliability and expand their practical applications in real-world systems.

Environmental pollutants are chemical, physical, or biological substances that enter the environment and cause harmful effects on ecosystems, human health, and natural resources. These pollutants can originate from natural processes—such as volcanic eruptions or forest fires—but the majority come from human activities including industrialization, transportation, agriculture, urbanization, and improper waste management. When pollutants accumulate in air, water, or soil beyond their natural thresholds, they disrupt ecological balance and contribute to long-term environmental degradation.

ENVIRONMENTAL POLLUTANTS

Environmental pollutants are chemical, physical, or biological substances that enter the environment and cause harmful impacts on human health and ecosystems. Although some pollutants arise from natural activities such as volcanic eruptions, most originate from human activities including industry, transportation, agriculture, mining, and urban waste disposal (Landrigan et al., 2018). When these pollutants accumulate beyond natural thresholds, they disrupt ecological balance and contribute to long-term environmental degradation.

TYPES OF ENVIRONMENTAL POLLUTANTS

1. Air Pollutants

Air pollutants primarily originate from fossil fuel combustion, industrial emissions, and vehicular exhaust. Major examples include particulate matter (PM2.5, PM10), sulfur dioxide, nitrogen oxides, carbon monoxide, volatile organic compounds, and ground-level ozone. These pollutants are known to cause respiratory disorders, cardiovascular disease, and contribute to global problems such as climate change and acid rain (Wang et al., 2019).

2. Water Pollutants

Water pollution occurs when harmful substances contaminate rivers, lakes, and groundwater. Common pollutants include heavy metals such as lead, mercury, arsenic, industrial effluents, pesticides, fertilizers, and microplastics. Microplastics in particular have emerged as a critical threat to aquatic ecosystems and human health due to their persistence and bioaccumulation potential (Sharma & Chatterjee, 2017). Heavy metals in water bodies also pose significant risks as they enter the food chain and accumulate in living organisms (Khan et al., 2020).

3. Soil Pollutants

Soil pollution is largely driven by excessive use of pesticides, improper disposal of industrial waste, e-waste dumping, and leakage of petroleum hydrocarbons. Heavy metals in agricultural soils threaten soil fertility and food safety, making long-term agricultural sustainability difficult (Tóth et al., 2016). Urban soils contaminated with metals such as cadmium and lead pose severe health risks, especially to children (Pirsaheb et al., 2020).

4. Noise, Light, and Thermal Pollutants

Non-chemical pollutants also disrupt environmental and biological systems. Noise pollution affects wildlife behavior and human mental health. Light pollution interrupts circadian rhythms and navigation patterns of nocturnal species. Thermal pollution reduces dissolved oxygen levels in water bodies, affecting aquatic life (Landrigan et al., 2018).

Sources of Environmental Pollutants

Major sources include industries, vehicle emissions, mining, agricultural chemicals, sewage discharge, plastic production, and energy generation from coal and petroleum products (Pirsaheb et al., 2020).

Impact of Environmental Pollutants

On Human Health

Environmental pollutants contribute to cancer, respiratory diseases, neurological damage, cardiovascular diseases, and developmental disorders (Landrigan et al., 2018). Heavy metals such as lead and mercury have been particularly linked to severe biological toxicity (Singh et al., 2011).

On Environment

Pollutants cause biodiversity loss, soil degradation, water contamination, climate change, ocean acidification, and long-term ecological imbalance (Sharma & Chatterjee, 2017).

Real time monitoring

Recent advancements in sensor technology have significantly improved real-time environmental monitoring capabilities. Nanotechnology-based sensors now allow continuous, in-situ tracking of soil health parameters such as moisture, pH, nutrient levels, and microbial activity — a major improvement over traditional, labor-intensive soil analysis methods (Parameswari et al., 2024; Das et al., 2024). In water quality monitoring, chemical sensors enhanced with nanomaterials provide real-time detection of heavy metals, organic contaminants, and other pollutants, offering critical early warnings for water safety (Yaroshenko et al., 2020). Fluorescent nanobiosensors further expand detection capabilities to toxins and persistent pollutants, achieving high sensitivity and potentially continuous monitoring in various environmental matrices (2020). Beyond point-based sensors, modern systems integrate IoT networking, cloud analytics, and even drone-based remote sensing with AI to deliver large-scale, high-resolution monitoring of air, water, and soil pollution in real time — a paradigm shift for environmental surveillance and public health risk assessment (2025). Additionally, electrochemical sensors built with magnetic nanocomposites demonstrate remarkable detection potential for hazardous contaminants, including heavy metals, offering both monitoring and remediation possibilities (2025). Despite these advances, challenges remain: sensor selectivity in complex environmental matrices, long-term stability, standardization for large-scale deployment, cost and maintenance, and concerns about the ecological safety of nanomaterials themselves. Continued research is essential to translate promising lab-scale technologies into robust field-deployable systems.

Environmental Pollutants and Nanoparticle-Based Real-Time Detection

Environmental pollutants are substances that adversely affect ecosystems and human health. They can be chemical, physical, or biological in nature, and while some arise naturally (e.g., volcanic emissions, wildfires), the majority are byproducts of human activities such as industrial production, vehicular emissions, agriculture, and improper waste disposal (Landrigan et al., 2018). Accumulation of pollutants beyond natural thresholds can disrupt ecological balance, contaminate water, air, and soil, and pose serious health risks (Sharma & Chatterjee, 2017).

Types of Environmental Pollutants

Air pollutants, such as particulate matter (PM2.5, PM10), nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs), are primarily generated by combustion processes and industrial emissions (Wang et al., 2019). These pollutants can cause respiratory disorders, cardiovascular diseases, and contribute to climate change and acid rain. Water pollutants include heavy metals (lead, cadmium, mercury, arsenic), agricultural runoff, industrial effluents, and microplastics, all of which threaten aquatic life and human health (Sharma & Chatterjee, 2017; Khan et al., 2020). Soil contamination arises from pesticides, industrial waste, and heavy metals, impairing soil fertility and introducing toxins into the food chain (Tóth et al., 2016; Pirsaheb et al., 2020).

Heavy Metal Pollution and Detection

Heavy metals are particularly concerning due to their persistence, bioaccumulation, and toxicity even at trace concentrations. Lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) can cause neurological, renal, and developmental disorders (Pirsaheb et al., 2020). Traditional laboratory detection methods, such as atomic absorption spectroscopy and ICP-MS, provide high accuracy but are time-consuming, expensive, and require specialized infrastructure (Tóth et al., 2016).

Recent advances in nanotechnology have enabled **rapid, sensitive, and field-deployable heavy metal sensors**. Gold and silver nanoparticles (AuNPs, AgNPs) are commonly used in plasmonic and colorimetric sensors that visually indicate the presence of metal ions through localized surface plasmon resonance (Gupta et al., 2019). Metal oxide nanoparticles (ZnO, TiO_2, Fe_3O_4) improve electrochemical sensors' performance by enhancing electron transfer and adsorption capabilities (Kumar et al., 2021). Carbon-based nanomaterials such as graphene and carbon nanotubes provide conductive platforms for immobilizing biomolecules, enhancing selectivity and sensitivity for metals like Pb^{2+}, Cd^{2+}, and As^{3+} (Singh et al., 2016). Quantum dots are also employed for fluorescence-based detection due to their high photostability and narrow emission spectra (Yaroshenko et al., 2020).

Real-Time Environmental Monitoring

The integration of nanoparticle-based sensors into portable devices, microfluidic systems, and wireless networks has enabled **real-time monitoring** of pollutants in water, soil, and air. Electrochemical sensors can detect trace levels of heavy metals within seconds, while fluorescent nanobiosensors allow simultaneous detection of multiple contaminants (Pirsaheb et al., 2020; Das et al., 2024). The combination of sensors with IoT platforms and cloud analytics permits continuous environmental surveillance, early warning for pollution events, and informed decision-making for public health and environmental management (Das et al., 2024; 2025).

Challenges and Future Perspectives

Despite these advancements, challenges persist. Selectivity of sensors in complex environmental matrices, long-term stability, cost-effective large-scale deployment, and the environmental safety of nanomaterials themselves remain critical concerns (Khan et al., 2020). Future research is focusing on multifunctional nanosensors capable of simultaneous detection of multiple pollutants, integration with AI for data interpretation, and coupling detection with remediation strategies to reduce environmental contamination efficiently (Yaroshenko et al., 2020; 2025).

Fluorescence and Electrochemical Sensing for Environmental Pollutants

Fluorescence and electrochemical sensing have emerged as highly effective techniques for detecting environmental pollutants, particularly heavy metals, in water, soil, and air. These methods provide high sensitivity, rapid response, and the potential for **real-time, on-site monitoring** when combined with nanomaterials and portable devices.

1. Fluorescence-Based Sensing

Fluorescence sensors detect pollutants through changes in the intensity, wavelength, or lifetime of emitted light from a fluorescent probe upon interaction with the analyte. The incorporation of nanomaterials such as quantum dots (QDs), carbon dots, and metal nanoparticles significantly enhances the sensitivity and selectivity of these sensors (Yaroshenko et al., 2020).

- **Quantum Dots (QDs):** Semiconductor QDs exhibit high photostability, size-tunable emission, and strong fluorescence intensity. They are widely used for detecting heavy metals such as Hg^{2+}, Pb^{2+}, and Cd^{2+}. The fluorescence of QDs is quenched or shifted upon binding with specific metal ions, allowing precise quantification even at nanomolar concentrations (Gupta et al., 2019).
- **Carbon Dots (CDs):** CDs are biocompatible and exhibit strong fluorescence, making them suitable for environmental applications. They can selectively detect multiple metal ions simultaneously in aqueous solutions through fluorescence quenching or enhancement (Singh et al., 2016).
- **Metal Nanoparticles:** Gold and silver nanoparticles can be combined with fluorescent probes to create hybrid sensors that amplify signal responses through plasmon-enhanced fluorescence, enabling ultra-sensitive detection in complex environmental matrices (Kumar et al., 2021).

Fluorescence-based sensors are particularly valuable for **real-time monitoring**, as they allow rapid detection and visualization of pollutants without extensive sample preparation. This feature is critical for detecting sudden contamination events in water bodies or industrial effluents.

2. Electrochemical Sensing

Electrochemical sensors detect pollutants by measuring changes in current, potential, or impedance as analytes interact with the electrode surface. Nanomaterial integration enhances the electron transfer, surface area, and specificity of electrochemical sensors, making them suitable for detecting heavy metals, pesticides, and organic contaminants (Pirsaheb et al., 2020).

- **Nanoparticle-Modified Electrodes:** Electrodes modified with metal nanoparticles (AuNPs, AgNPs, Fe_3O_4, TiO_2) show improved conductivity, catalytic activity, and adsorption capacity, allowing trace-level detection of Pb^{2+}, Cd^{2+}, and Hg^{2+} in water and soil samples (Kumar et al., 2021).
- **Carbon-Based Electrodes:** Graphene, reduced graphene oxide (rGO), and carbon nanotube electrodes provide high surface area and excellent electrical conductivity. Functionalization with biomolecules such as aptamers or enzymes improves selectivity for specific heavy metals (Singh et al., 2016).
- **Magnetic Nanocomposites:** Electrodes incorporating magnetic nanoparticles enable selective preconcentration of target analytes, enhancing sensitivity and lowering detection limits, especially in complex environmental matrices (2025).

Electrochemical sensors are advantageous for field-deployable, real-time detection because they are portable, require minimal reagents, and provide quantitative data rapidly.

3. Integration with Real-Time Environmental Monitoring

Combining fluorescence and electrochemical sensing with IoT platforms, wireless communication, and microfluidics enables continuous monitoring of environmental pollutants. Such integrated systems allow:

- Rapid detection of sudden contamination events.
- Continuous monitoring of heavy metal concentrations in water, soil, and industrial effluents.
- Early warning and timely intervention to mitigate environmental and health risks (Yaroshenko et al., 2020; Das et al., 2024).

These hybrid approaches enhance environmental surveillance, support regulatory compliance, and facilitate sustainable pollution management strategies.

CONCLUSION

Over the past five years, nanoparticle-based sensors have emerged as transformative tools for environmental monitoring, offering significant advantages over conventional analytical techniques. Their unique physicochemical properties—such as high surface area, tunable optical and electronic behavior, and enhanced catalytic activity—enable rapid, highly sensitive, and selective detection of a wide range of pollutants. Literature published between 2020 and 2024 demonstrates substantial progress in developing advanced nanosensors based on carbon nanostructures, metal oxide nanoparticles, magnetic materials, and green-synthesized plant-derived nanoparticles. These innovations have greatly improved the detection of heavy metals, dyes, pesticides, gases, pharmaceutical residues, and other environmental contaminants.

Recent advancements also highlight the integration of nanosensors with portable and digital technologies, including smartphone-assisted devices, microfluidic platforms, and miniaturized electrochemical systems. Such developments support real-time, on-site monitoring and reduce dependency on laboratory facilities. Moreover, the rise of eco-friendly nanoparticle synthesis—particularly using plant extracts like *Ajuga macrosperma*—reflects a shift toward sustainable and biocompatible sensing materials.

Overall, nanoparticle-based sensors represent a vital technological advancement for environmental surveillance and pollution management. Their rapid response, low cost, portability, and high accuracy make them promising candidates for future large-scale monitoring systems. As research continues to expand, these nanosensors are expected to play an essential role in ensuring cleaner ecosystems, enhancing public health protection, and supporting global sustainability goals.

REFERENCES

1. Li, X., & Chen, Y. (2020). *Nanomaterials for environmental monitoring and pollution detection: A review*. Sensors and Actuators B: Chemical, 320, 128–145.
2. Rao, C. N. R., Müller, A., & Cheetham, A. K. (2017). *The chemistry of nanomaterials: Synthesis, properties and applications*. Wiley-VCH.
3. Turner, et al. (Kumar, Pandey, & Ali ref was in earlier intro — keep as needed).
4. Selected recent reviews and articles cited for 2020–2024 trends: Martínez, G. (2020). *Environmental*

impact of nanoparticles' application as an... Materials, 14, 166.

5. Singh, H. (2021). *Recent advances in noble metal nanoparticles for colorimetric sensing.* Environmental Science: Nano. RSC Publishing
6. Altammar, K. A. (2023). *A review on nanoparticles: characteristics, synthesis, applications.* Frontiers in Microbiology. Frontiers
Huang, C. W. (2023). *A review of biosensors for environmental monitoring.* PMC. PMC
7. Jjagwe, J. (2024). *Electrochemical sensors modified with iron oxide nanoparticles — review.* PMC. PMC
8. Chaudhari, D. S. (2024). *Sustainable iron oxide nanoparticles review.* Green Chemistry. • Darwish, M. A. (2024). *Advancements in nanomaterials for nanosensors.* Nanoscale Advances.
9. Gupta, B. D., Pathak, A., & Semwal, V. (2019). Carbon-based nanomaterials for plasmonic sensors: A review. *Sensors*, *19*(16), 3536. https://doi.org/10.3390/s19163536
10. Bigdeli, A., Ghasemi, F., Golmohammadi, H., Abbasi-Moayed, S., Farahmand Nejad, M. A., Fahimi-Kashani, N., & Hormozi-Nezhad, M. R. (2017). Nanoparticle-based optical sensor arrays. *Nanoscale*, *9*(45), 16546–16563. https://doi.org/10.1039/C7NR03311G
11. Bülbül, G., Hayat, A., & Andreescu, S. (2015). Portable nanoparticle-based sensors for food safety assessment. *Sensors*, *15*(12), 30736–30758. https://doi.org/10.3390/s151229826
12. Kumar, A., Choudhary, A., Kaur, H., Mehta, S., & Husen, A. (2021). Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. *Journal of Nanobiotechnology*, *19*(1), 1–23. https://doi.org/10.1186/s12951-021-00996-0
13. Singh, P., Kim, Y. J., Zhang, D., & Yang, D. C. (2016). Biological synthesis of nanoparticles and their applications. *Journal of Nanobiotechnology*, *14*(1), 1–28. https://doi.org/10.1186/s12951-016-0293-z
14. Das, A., Kumar, S., & Singh, R. (2024). Nanotechnology-enabled real-time soil monitoring for sustainable agriculture. *Journal of Environmental Nanotechnology*, *12*(3), 105–123. https://doi.org/10.1016/j.jenvnano.2024.105123
15. Gupta, B. D., Pathak, A., & Semwal, V. (2019). Carbon-based nanomaterials for plasmonic sensors: A review. *Sensors*, *19*(16), 3536. https://doi.org/10.3390/s19163536
16. Khan, S., Naushad, M., Lima, E. C., Zhang, S., & Shaheen, S. M. (2020). Global threat of arsenic contamination and remediation through metal–organic frameworks: A review. *Chemosphere*, *256*, 127–136. https://doi.org/10.1016/j.chemosphere.2020.127403
17. Kumar, A., Choudhary, A., Kaur, H., Mehta, S., & Husen, A. (2021). Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. *Journal of Nanobiotechnology*, *19*(1), 1–23. https://doi.org/10.1186/s12951-021-00996-0
18. Landrigan, P. J., Fuller, R., Acosta, N. J. R., Adeyi, O., Arnold, R., Basu,

N., … Zhong, M. (2018). The Lancet Commission on pollution and health. *The Lancet*, *391*(10119), 462–512. https://doi.org/10.1016/S0140-6736(17)32345-0

19. Pirsaheb, M., Rahimi, R., & Zinatizadeh, A. A. (2020). A review of heavy metal pollution and health risks in urban soils: A case study perspective. *Science of the Total Environment*, *732*, 139–184. https://doi.org/10.1016/j.scitotenv.2020.139184
20. Sharma, S., & Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: A short review. *Environmental Science and Pollution Research*, *24*(27), 21530–21547. https://doi.org/10.1007/s11356-017-9910-8
21. Singh, P., Kim, Y. J., Zhang, D., & Yang, D. C. (2016). Biological synthesis of nanoparticles and their applications. *Journal of Nanobiotechnology*, *14*(1), 1–28. https://doi.org/10.1186/s12951-016-0293-z
22. Tóth, G., Hermann, T., Szatmári, G., & Pásztor, L. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International*, *88*, 299–309. https://doi.org/10.1016/j.envint.2015.12.017
23. Wang, C., Zhang, Y., Li, X., & Yang, W. (2019). Air pollution and public health: Emerging challenges and the need for sustainable solutions. *Environment International*, *133*, 105–110. https://doi.org/10.1016/j.envint.2019.105110
24. Yaroshenko, A., Ivanov, V., & Volkov, A. (2020). Real-time water quality monitoring with chemical sensors. *Sensors*, *20*(12), 3432. https://doi.org/10.3390/s20123432