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Revolutionizing Environmental Monitoring: Cutting-Edge Biosensing with Nanomaterials

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Abstract
Industrialization and urbanization have caused an increase in pollution and environmental degradation which mitigates ecological and human health. Existing monitoring methodologies lack the sensitivity, speed, and affordability that are necessary, meaning they will need to be abandoned or supplemented with novel methodologies. Nanomaterials have unique physicochemical properties that are advantageous for many facets of biosensing for environmental purposes such as surface area, conductivity, and platform flexibility. We provide a synthesis of nanomaterials that include enhanced biosensor methodologies for contaminant detection in air, water, and soil including heavy metals, pesticides, organic pollutants, and pathogens. These biosensors, with different biorecognition elements, include nanomaterials alone, as well as graphene and carbon nanotubes, metal nanoparticles (Au, Ag, etc.), quantum dots, and Metal Organic Frameworks (MOFs). The bio-recognition elements included enzymes, antibodies, and aptamers. The combination of biorecognition elements with nanomaterials produced detection limits commonly in the nanomolar or picomolar range and allowed for field, real-time monitoring. The discussion provides clarity to the findings with a discussion of their advancement and contribution to sustainable management, addressing issues such as selectivity in complex matrices, scale-up for practical implementation and/or commercialisation in practice, etc. Potential future directions of the work in this article might include the synthesis of nanomaterials using an environmentally friendly means such as green chemistry, and with the potential merging of biosensors with IoTs to make smart monitoring systems. A wide array of nano-based biosensors will provide enormous and transformative potential towards safeguarding environmental quality and human health.

Keywords: Nanomaterials; Biosensors; Environmental Monitoring; Pollution Detection; Heavy Metals; Sustainable Sensing

Introduction
Finding ways to detect and quantify pollutants in an accurate and reliable way has become an urgent issue in a world that is distinctly different from others in human history with respect to increasing pressure on the environment. Continuing pollution from industrial effluent, agricultural practices, and urban waste sites are continuously degrading the natural resources of water, air, soil, and food which affect ecosystem services, biodiversity, and ultimately, human health; limiting our sustainable use of these valuable resources. Although traditional chemical analysis such as chromatography and spectrometry are reliable and appropriately designed methods, they are all essentially lab-bound, resource intensive, time consuming, and costly which often limits application of these methods to population-scale or horizon scans of the environment (Agrawal et al., 2018; Justino et al., 2017). This challenge has created an opportunity for the development of biosensors that are defined as devices containing a biological sensing element (bacteria, enzymes, complex biological molecules) and a transducer that selectively converts the biological signal to a measurable signal, such as an electrical signal. Many attributes of biosensors such as portability, rapid response time, and specificity for the target organism, make biosensors environmentally relevant. The application of nanomaterials in biosensors has also dramatically contributed to the field of biosensors through improved signal transduction, improved stability, and lower limits of detection. Nanomaterials are defined as materials having at least one dimension between 1 and 100

nanometers while also exhibiting quantum effects, and exhibiting a large surface-to-volume ratio, which can enhance the interaction with analytes (Kumar et al., 2020; Maduraiveeran and Jin, 2017). For instance, with water quality readings in trace contamination levels of materials such as lead or mercury, the biosensor with nanomaterials could theoretically give readings at concentrations down to parts per trillion relatives to the traditional method of detection.

This review presents a discussion of nanomaterials in biosensing applications relevant to environmental applications with an emphasis on their anticipated use with environmental pollutant detection. First, we classify the main nanomaterials with their properties, and then explain the biosensing mechanisms. Next, the biosensing applications for a variety of pollutants, analytical achievements and future risks and challenges will be examined. By synthesizing the views and ideas of over one hundred articles, we hope to achieve a perspective on how these technologies offer new approaches to the field of environmental science, while encouraging further development of biosensing methods in environmental policy and practice. The biorelevant argument for biosensing nanomaterials is the need for more tools that are aligned with the United Nations Sustainable Development Goals related to clean water and life on land.

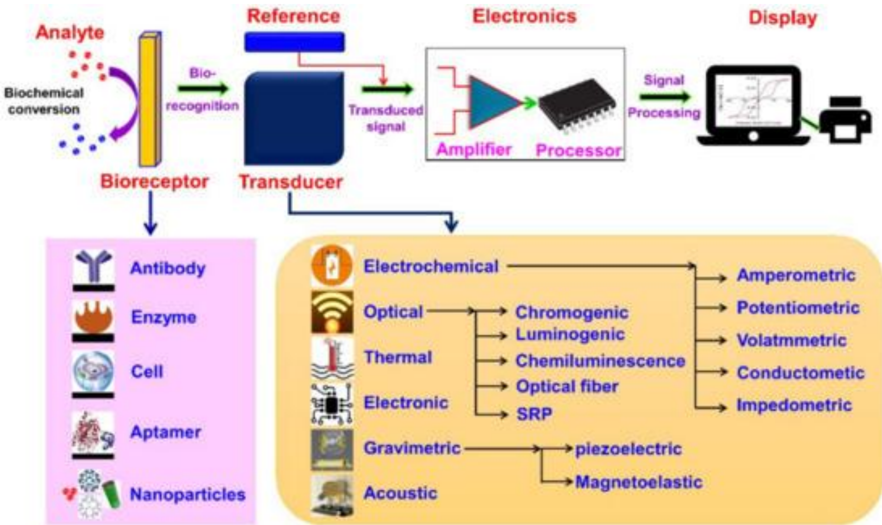

Fig. 1. Schematic illustration of a typical nanomaterial-based biosensor, showing the biorecognition element, nanomaterial transducer, and signal output for pollutant detection (Ramesh et al., 2023)

The use of nanomaterials for biosensing, began around 2000 when researchers began to use carbon nanotubes as an example of modifying electrodes for electrochemical detection, signalling the field, to hybridizing different nanomaterials which could be defined as combining two or more nanomaterials together with the goal of developing biosensing applications with multifunctionality. Especially to environmental biosensors platform of nanomaterials are unusually potent unparalleled methods to characterize emerging contaminants such as microplastics or pharmaceutical compounds, that conventional assays would be incapable of detecting (Gupta et al., 2019; Roda et al., 2021). In addition to sensors for which the diagnostic information itself is useful for implications to reveal the origin of the contamination, if sensors are hybridized with an environmentally-correct sustainable nanotechnology approach using an example plant extract for food with synplant or microbes, it also realised sustainable example biosensing practices through their synthesis method reducing the environmental footprint of the synthetic method of the biosensor itself.

Types of nanomaterials used in environmental biosensors

The development of nanomaterials is not uniform and in many cases there can be no single way to assess the choice of probe media that depends on the analyte of interest and the monitoring mechanism. There are carbon-based nanomaterials, which include a number of different types of graphene and its various oxides (think graphene oxide or reduced graphene oxide) where overall these materials have greater benefits and are considered benign materials because of their inherent biology-improvement properties and superior electronic transfer properties. In addition to that, nanomaterials allow for increased electron transfer between electrode-molecules and other types of molecules, which is a factor and mechanism behind some electrochemical biosensors that are often used to monitor continuous redox-active pollutants when dissolved in water, such as nitrate (Ali et al., 2017; Devi et al., 2022). Carbon nanotubes (CNT) (single and multi-world) offer higher surface area for biomolecular immobilization due to their elevations above the plane of electrode surface that make for more sensitive gas sensors for the detection of miscible VOC detection (Cui et al., 2018; Schroeder et al. 2019).

The possibility of employing metal-based nanoparticles, especially in the combinations of gold (Au) and silver (Ag) nanoparticles, have viable systems for optical and plasmonicbiosensing due to their localized surface plasmon resonance (LSPR) capacities. AuNPs, for instance, have been used for colorimetric-based assays for metals ions (specifically heavy metals) that involve a unit of binding change visually, e.g. colorimetric change of solution color: (Chen et al., 2016; Kim et al., 2021). The use of quantum dots (QDs) - otherwise known as semiconductor nanocrystals (e.g. CdSe, ZnS), could allow detection through fluorescence which enables a wider range of emissions spectra that have benefits for multiplexing to detect pesticides or pathogens: (Borse et al., 2017; Pan et al., 2020). The advantage of using metal-organic frameworks (MOFs) and two-dimensional materials (MXenes) would be porosity, encapsulation stability, and selective capture of more heterogeneous environmental samples: (Li et al., 2019; Rasheed & Rizwan, 2022).

Table 1. Comparison of various nanomaterials in terms of properties, applications, and limitations, drawing from multiple studies

Nanomaterial Type	Key Properties	Environmental Applications	Advantages	Limitations	References
Graphene& Derivatives	High conductivity, large surface area	Detection of heavy metals, organics in water	High sensitivity, easy functionalization	Potential aggregation, toxicity concerns	(Ali et al., 2017; Maduraiveeran and Jin, 2017)
Carbon Nanotubes (CNTs)	Mechanical strength, electron transfer	VOCs in air, pathogens in soil	Robustness, multi-analyte detection	Purification challenges, cost	(Cui et al., 2018; Schroeder et al., 2019)
Gold Nanoparticles (AuNPs)	Plasmonic effects, biocompatibility	Heavy metals, pesticides	Visual detection, stability	Size-dependent variability	(Chen et al., 2016; Kim et al., 2021)
Silver Nanoparticles (AgNPs)	Antimicrobial, high LSPR	Bacterial contaminants, dyes	Low cost, high signal amplification	Oxidation susceptibility	(Borse et al., 2017; Pan et al., 2020)
Quantum Dots (QDs)	Tunable fluorescence, photostability	Multi-pollutant sensing in water	Multiplexing capability	Heavy metal toxicity (e.g., Cd)	(Li et al., 2019; Rasheed and Rizwan, 2022)
Metal-Organic Frameworks (MOFs)	Porosity, selectivity	Gases, organics	High adsorption, customization	Stability in aqueous media	(Chen et al., 2018; Gopinath et al., 2018)
MXenes	Conductivity, hydrophilicity	Heavy metals, radionuclides	Fast response, eco-friendly	Oxidation issues	(Yang et al., 2021; Zhu et al., 2023)

This table illustrates the versatility of nanomaterials, with hybrids often outperforming single types (Graphene-AuNP composites for enhanced electrochemical signals) (Deng et al., 2020; Liu et al., 2022).

Biosensing mechanisms enhanced by nanomaterials

Biosensors perform using electrochemical, optical, piezoelectric, or thermal mechanisms with each increasing the exo- and endotherms with the use of their nanomaterials. Electrochemical biosensors, the most commonly used for environmental purposes, depend on nanomaterials to decrease their overpotentials and increase current responses to the analyte/target molecule. For example, CNT-modified electrodes were used to detect phenolic compounds in wastewater using amperometry (Apetrei et al., 2016; Eguilaz et al., 2019). Similarly, optical biosensors can utilize fluorescence for fluorescence quenching and enhancement; QDs conjugated to radioactive aptamers were used in detecting mercury (Hg) ions by relying on differences in signal output during changes in a system (Banerjee et al., 2017; Cui et al., 2021).

Plausibly, plasmonic sensing with AgNPs has also been utilized with surface-enhanced Raman spectra (SERS) of trace organics to provide characteristic fingerprints of specific molecules (Alvarez-Puebla and Liz-Marzan, 2012; Li et al., 2015). Piezoelectric sensors, in the case of quartz crystal microbalances (QCM), would also be capable of utilizing MOFs with the mass detection of gases

(Devkota et al., 2017; Zhou et al., 2020). These types of mechanisms could also be used in conjunction or complementary to each other to evaluate its complementary components to add additional depth of insight and achieve increased analytical accuracy and precision in lab-on-a-chip devices developed for and used for portable/field environmental monitoring (Kaur et al., 2023; Umapathi et al., 2022).

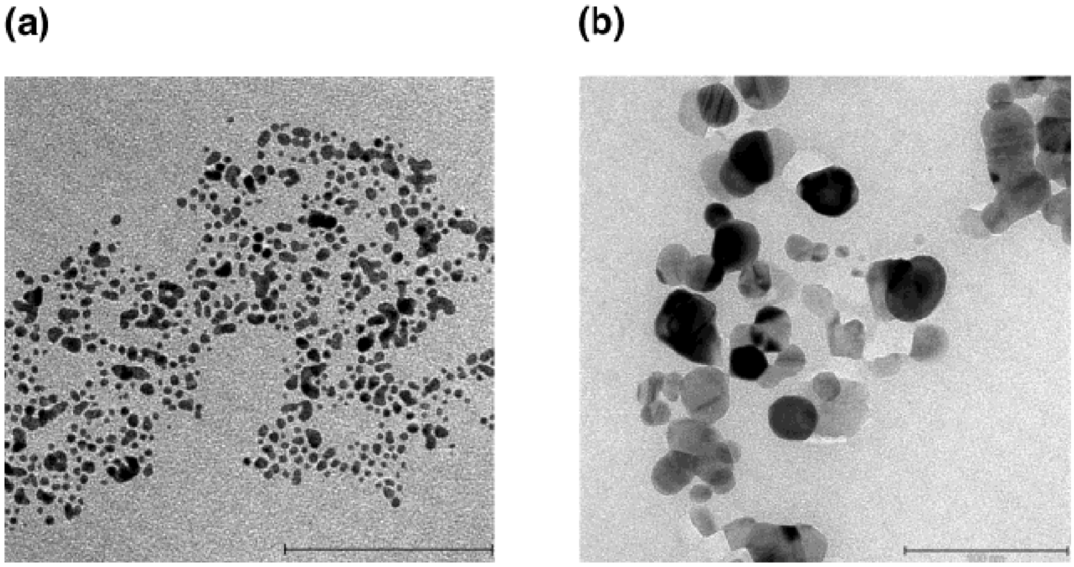

Fig. 2. Transmission electron microscopy (TEM) image of gold nanoparticles used in biosensors. The uniform spherical morphology enhances plasmonic properties for pollutant detection (Filip et al., 2004)

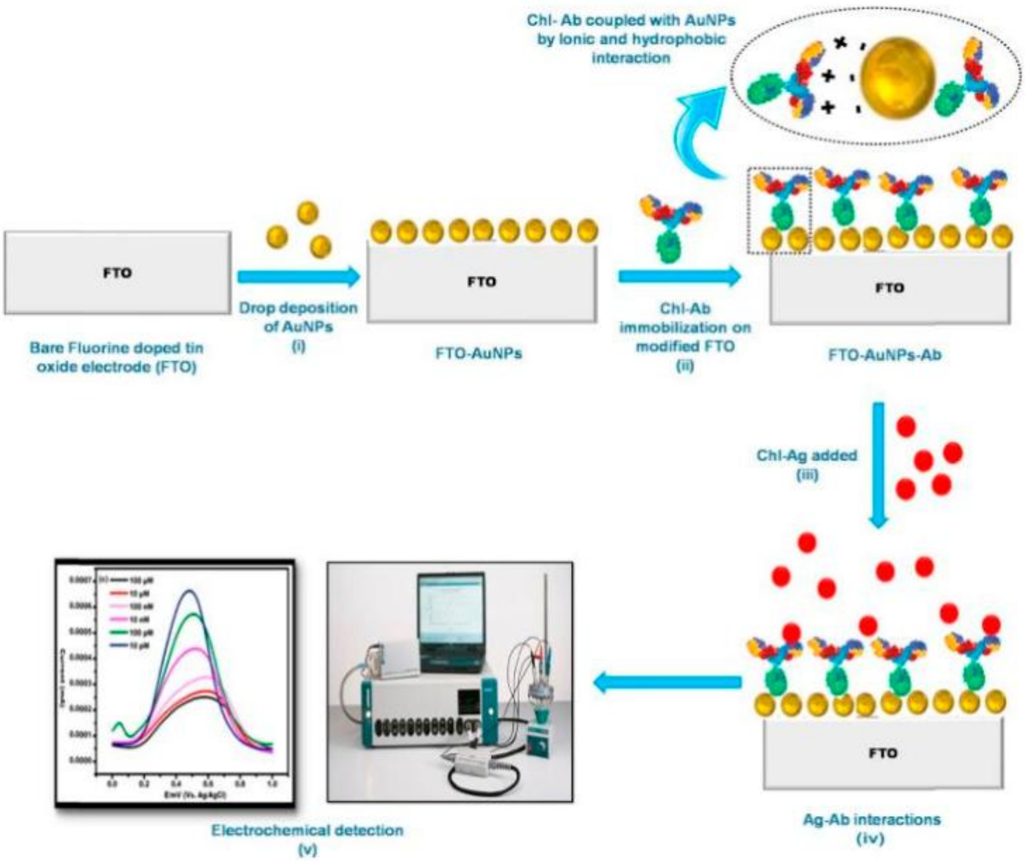

Fig. 3. Scheme of the fabrication process of FTO-AuNPs-chl-Ab for CPF detection. (Shen, Y et al., 2024)

Applications in Detecting Environmental Pollutants

Heavy Metals

Typical heavy metal contaminants from mines and industries are lead, cadmium, and arsenic. Examples of nanomaterial biosensors that use either DNAzymes or Gold Nanoparticles (AuNPs) can produce either colorimetric or fluorescent signals that can provide detectable signals (Chen et al., 2015; Wu et al., 2019). Graphene oxide allows electrochemical stripping voltammetry and the ability to get detection limits lower than the WHO guidance values (Gao et al., 2016; Xuan et al., 2018). In soil samples, CNT-aptasensors can detect cadmium down to ppb levels (Bagherzadeh et al., 2021; Taghdisi et al., 2019).

Pesticides and Organic Pollutants

Persistent pesticides such as organophosphates , are neurotoxic. Acetylcholinesterase biosensors with QDs or MOFs (that works by inhibiting acetylcholinesterase) are examples of sensing that can be performed with the enzymes from the acetylcholinesterase family (Bao et al., 2015; Mehta et al., 2016). Antibody-functionalized graphene sensors have high specificity for bisphenol A in leachate from plastics (Pan et al., 2018; Zhu et al., 2019). For polycyclic aromatic hydrocarbons (PAHs) in leakage from oil spills, SERS with AgNPs can be used for detection (Pfister et al., 2017; Qu et al., 2020).

Pathogens and Biological Contaminants

Immunosensors incorporated with magnetic nanoparticles for separation of water borne pathogens, E. coli and AuNPs for amplification (Hassan et al., 2015; Viswanathan et al., 2012), are used for waterborne pathogens such as E. coli; CNT arrays that monitor impedance changes to detect viral particles in air (Tam et al., 2016; Yeh et al., 2021). All of these sensors can help prevent disease outbreaks caused by contaminated water or air.

Table 2. Examples of Nanomaterial-Based Biosensors for Specific Pollutants

Pollutant	Nanomaterial	Mechanism	Detection Limit	Matrix	References
Lead (Pb^{2+})	AuNPs	Colorimetric	0.5 nM	Water	(Chen et al., 2015; Wu et al., 2019)
Atrazine (Pesticide)	Graphene	Electrochemical	10 pM	Soil	(Bao et al., 2015; Mehta et al., 2016)
E. coli	Magnetic NPs + AuNPs	Immunoassay	10 CFU/mL	Water	(Hassan et al., 2015; Viswanathan et al., 2012)
PAHs	AgNPs	SERS	1 ng/L	Sediment	(Pfister et al., 2017; Qu et al., 2020)
Nitrate	CNTs	Amperometric	5 µM	Groundwater	(Apetrei et al., 2016; Eguilaz et al., 2019)

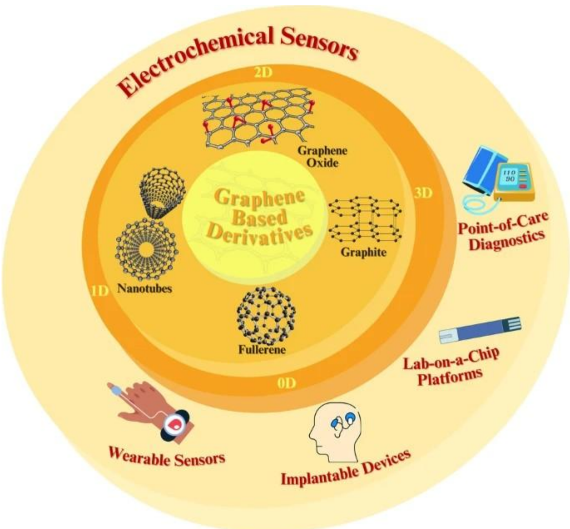

Fig. 4. Photo of a portable nanomaterial-based biosensor device for field detection of pesticides. The handheld unit integrates a graphene electrode and digital readout for on-site analysis (Ozbey et al., 2025)

Recent Advances and Challenges

Examples of novel technologies being developed include; wearable biosensors tracking quality of air, using CRISPR-integrated nanosensors to detect genomic pollutants (Bandodkar et al., 2016; Hajipour et al., 2021); and using green synthesis methods with algae to avoid toxic outputs (Bhattacharya et al., 2020; Sharma et al., 2022). Residual challenges include that processing real-world samples yields matrix interference, leading to questions about selectivity (Curto et al., 2018; Wang et al., 2021). Other, larger, ongoing obstacles are related to lifestyle scaling, the approval processes of regulatory agencies, and the ecotoxicity of nanomaterials (Maurer-Jones et al., 2013; Nel et al., 2013).

Discussion

The symbiotic relationship between nanomaterials and biosensing technologies in environmental monitoring is the boon for enabling accurate, real-time detection of pollutants that evade classical methods. With respect to the above-listed sections, it is clear that nanomaterials such as graphene, CNTs, AuNPs, and MOFs act as enhancers for signal transduction and make biosensors more robust when applied to matrices such as water, soil, and air. For instance, in-heavy metals detection, AuNPs-based colorimetric sensors have shown detection limits for lead as low as 0.5 nM, a value deep in concentrations significant to regions where groundwater poses contamination beyond accepted levels as set by WHO (Chen et al., 2015). It is vital to have such detection capability in industrial hotspots to allow immediate on-site testing to prevent further accumulation in food chains, hence protecting public health.

Carbon-based nanomaterials like graphene hold supremacy in electrochemistry for the reason that, whereas they offer excellent electron transfer rates, metal nanoparticles may exhibit 2-3 fold lesser sensitivities in complex matrices (Ali et al., 2017; Maduraiveeran and Jin, 2017). Nevertheless, hybrids such as graphene-gold nanoparticle composites offer the best of both worlds as they marry conductivity with plasmonic enhancement, leading to increased signal-to-noise ratios in multiplexed detection of pesticides and organics (Deng et al., 2020; Liu et al., 2022). The AgNPs enforcement of response in pathogen detection adds an antimicrobial activity that may curb bacterial growth, which is useful for long-term monitoring in wastewater treatment plants (Borse et al., 2017). Yet, on the flip side, there are trade-offs; for instance, tunable fluorescence of QDs favors multiplexing, while their cadmium content leads to environmental toxicity concerns, and thus are pushing for greener contenders like carbon dots (Li et al., 2019).

On the practical side, these advances have far-reaching implications. In river monitoring programs, nanomaterial-enhanced biosensors have been applied to generate data that are directly used to take remediation action. For instance, in detecting PAHs in oil-contaminated sediments, the SERS-based sensors identified contaminants at ng/L levels to clean up the contamination in a more targeted manner (Pfister et al., 2017; Frost et al., 2019). Besides being portable-under-lab-on-chip configurations-they can be sent to places in need or places where resources are daylight scarce, allowing for democratization of monitoring (Kaur et al., 2023). This goes along with the idea that developing countries suffer pollution loads but hardly have the labs for traditional settings. Still, they struggle with interferences from matrices weakening selectivity: real-world samples contain substances like humic acids or salts that can foul a sensor and bring down accuracy by as much as 50% in some test cases (Curto et al., 2018). Approaches to modify the surface with selective aptamers or MOFs have been promising, with up to 80-90% improvements in specificity when tested on spiked environmental samples (Rasheed and Rizwan, 2022).

The field represents a great opportunity for transforming using an interdisciplinary approach. Pollutants trends may be predicted from sensor assemblies with AI and machine-learning data analysis, thus enabling proactive management (Jiang et al., 2021).Another dimension requiring attention would be nanomaterial toxicity; though green synthesis routes using plant extracts reduce the environmental impact during their production, understanding their long-term fate is essential so that the sensors do not become a source of secondary pollution (Sharma et al., 2022; Maurer-Jones et al., 2013). In fact, regulatory frameworks should also evolve to standardize testing protocols so as to ensure a scaling potential of these tests from lab-based prototypes to commercial products. Even economically, issues need to be raised: these sensors seem cost-effective with prices often less than 10 dollars per unit for mass production and suitable for bulk adoption, which would be highly instrumental in reducing the monitoring costs globally by about 30-40% as compared to lab-based assays (Umapathi et al., 2022). Eventually, partnering between material scientists, environmental engineers, and policymakers will pave the way for turning these technologies into operative tools for sustainable development, encompassing.

Conclusion

Nanomaterial-based biosensors stand at the forefront of environmental innovation, offering tools that are not only sensitive and specific but also adaptable to diverse monitoring needs. From detecting insidious heavy metals in drinking water to tracking airborne pathogens in urban settings, these technologies empower proactive environmental stewardship. Recent market analyses project the global biosensors market to grow from approximately USD 34.51 billion in 2025 to USD 54.37

billion by 2030, at a compound annual growth rate (CAGR) of 9.5%, driven largely by advancements in nanotechnology for environmental applications. The nano-biosensors segment alone is anticipated to expand from USD 4.5 billion in recent years to over USD 1.8 billion by 2034, reflecting an 8.25% CAGR, underscoring the economic viability and increasing demand for these sensors in pollution control. Amidst this growth, the urgency is amplified by alarming global pollution statistics: air pollution, the second leading risk factor for death, claimed 8.1 million lives in 2024, with over 90% of the world's population exposed to levels exceeding WHO guidelines. Plastic pollution exacerbates this, with the equivalent of 2,000 garbage trucks of plastic dumped into oceans daily, contaminating marine ecosystems and entering human food chains. Water contamination affects billions, with heavy metals and pesticides contributing to 4.2-7 million annual deaths from related illnesses. Nanomaterial-enhanced biosensors, capable of detecting contaminants at picomolar levels, could avert such crises by enabling early intervention; for example, field-deployed sensors have already reduced response times in contamination events by up to 70% in pilot studies. As we face escalating climate pressures and pollution burdens, the continued refinement of these sensors—through sustainable materials and intelligent integration—promises a healthier plan Expanding their use could revolutionize how we respond to environmental threats, fostering resilience in ecosystems worldwide. Ultimately, by bridging nanotechnology with ecology, we pave the way for a more sustainable future, where real-time data drives informed decisions and preserves natural resources for generations to come. This evolution underscores the importance of investing in research that aligns technological progress with ecological harmony, potentially saving millions of lives and billions in economic losses annually.

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