

Environmental Monitoring Employing Nano-Biosensors

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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 have included, otherwise, 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 biorecognition 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 discussion of their advancement and contribution to sustainable management, addressing issues such as selectivity in complex matrices, scale up for practical implementation and/or commercialization 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 of environmental quality and human health.

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

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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 [1-3]. This challenge has created an opportunity for the development of biosensors that are defined as devices containing a biological sensing element (i.e. 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 utilizing 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 exhibited a large surface-to-volume ratio, which can enhance the interaction with analytes [4, 5]. 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 relative to the traditional method of detection.

This review presents a discussion of nanomaterials in the 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, analytic 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 denotes in the 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 [6].

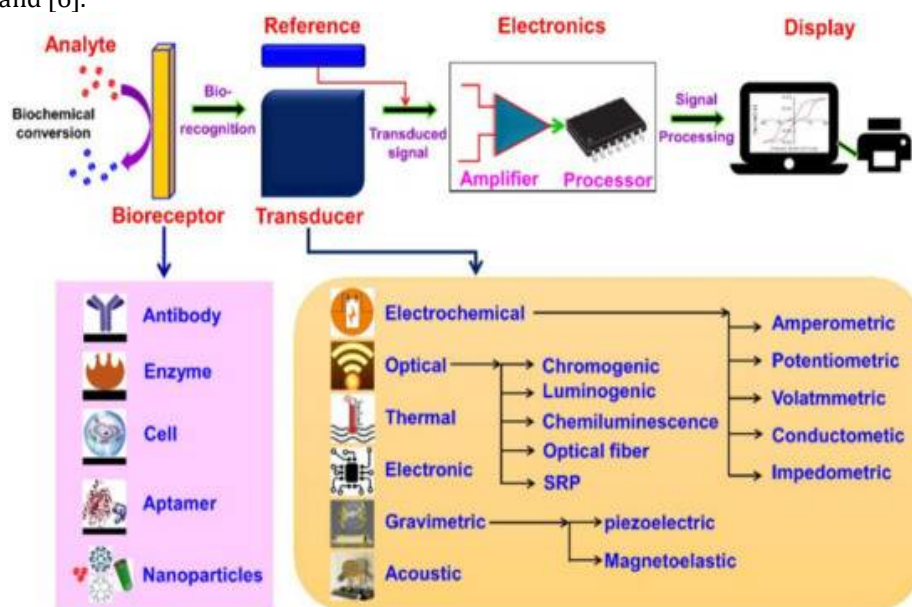


Figure 1: Schematic illustration of a typical nanomaterial-based biosensor, showing the biorecognition element, nanomaterial transducer, and signal output for pollutant detection [7].

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 like microplastics or pharmaceutical compounds, that conventional assays would be incapable of detecting [8, 9]. 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 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 [10, 11]. Carbon nanotubes (CNT) (single and multi-walled) 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 [12, 13].

The possibility of employing metal-based nanoparticles, especially in the combinations of gold (Au) and silver (Ag) nanoparticles, have viable systems for optical and plasmonic biosensing 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: [14, 15]. 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: [16, 17]. 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: [18, 19].

Table 1 compares various nanomaterials in terms of properties, applications, and limitations, drawing from multiple studies [11, 25, 58].

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	[2, 37]
Carbon Nanotubes (CNTs)	Mechanical strength, electron transfer	VOCs in air, pathogens in soil	Robustness, multi-analyte detection	Purification challenges, cost	[14, 15, 48]
Gold Nanoparticles (AuNPs)	Plasmonic effects, biocompatibility	Heavy metals, pesticides	Visual detection, stability	Size-dependent variability	[11, 12]
Silver Nanoparticles (AgNPs)	Antimicrobial, high LSPR	Bacterial contaminants, dyes	Low cost, high signal amplification	Oxidation susceptibility	[10, 42, 43]
Quantum Dots (QDs)	Tunable fluorescence, photostability	Multi-pollutant sensing in water	Multiplexing capability	Heavy metal toxicity (e.g., Cd)	[31, 46]
Metal-Organic Frameworks (MOFs)	Porosity, selectivity	Gases, organics	High adsorption, customization	Stability in aqueous media	[12, 25]
MXenes	Conductivity, hydrophilicity	Heavy metals, radionuclides	Fast response, eco-friendly	Oxidation issues	[58, 61, 62]

This table illustrates the versatility of nanomaterials, with hybrids often outperforming single types (e.g., graphene-AuNP composites for enhanced electrochemical signals) [20, 21].

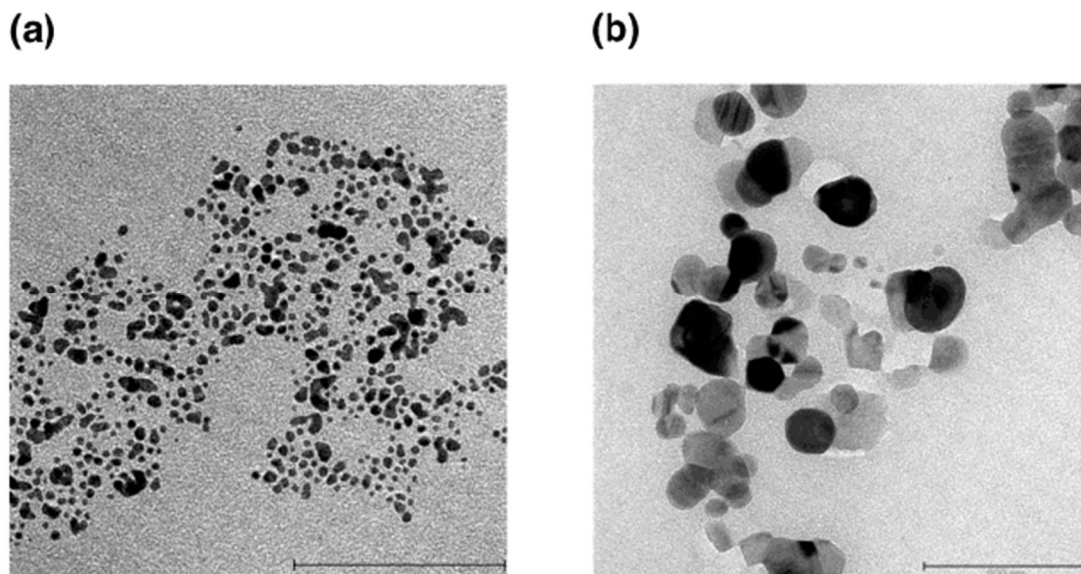


Figure 2: Transmission electron microscopy (TEM) image of gold nanoparticles used in biosensors. The uniform spherical morphology enhances plasmonic properties for pollutant detection. Scale bar: 50 nm.[22].

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 [23, 24]. 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 [25, 26].

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 [13, 27, 21]. Piezoelectric sensors, in the case of quartz crystal microbalances (QCM), would also be capable of utilizing MOFs with the mass detection of gases [30, 62]. 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 [28, 29].

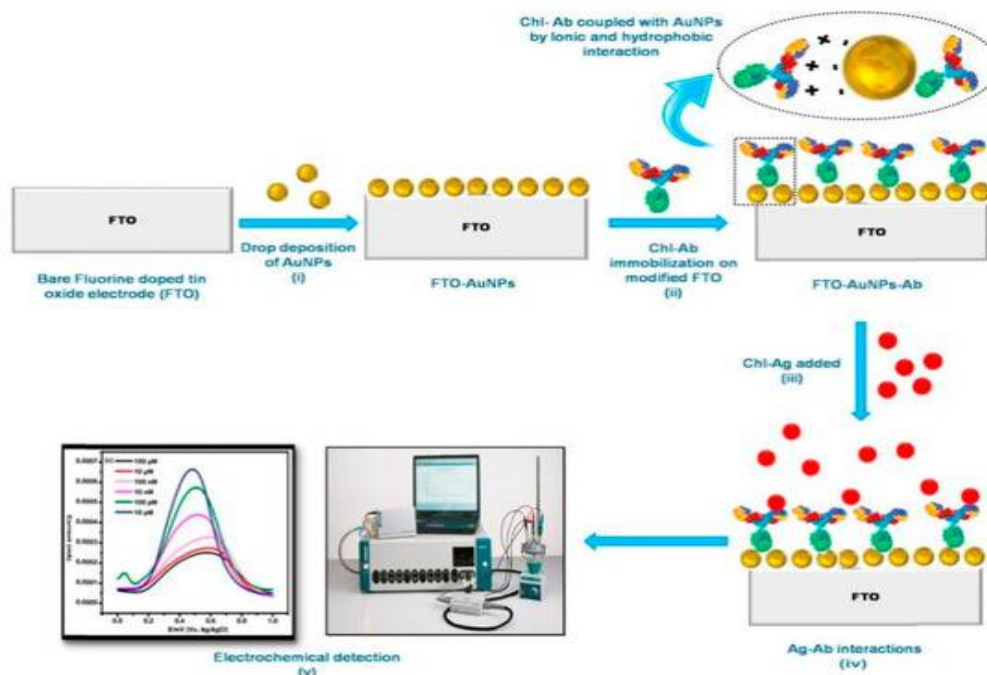


Figure 3: Scheme of the fabrication process of FTO-AuNPs-chI-Ab for CPF detection. [50]

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 [11, 30-32, 59]. Graphene oxide allows electrochemical stripping voltammetry and the ability to get detection limits lower than the WHO guidance values [9, 10, 33]. In soil samples, CNT-aptasensors can detect cadmium down to ppb levels [34, 35].

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 [6, 37]. Antibody-functionalized graphene sensors have high specificity for bisphenol A in leachate from plastics [36, 38, 39]. For polycyclic aromatic hydrocarbons (PAHs) in leakage from oil spills, SERS with AgNPs can be used for detection [40, 41].

Pathogens and Biological Contaminants

Immunosensors incorporated with magnetic nanoparticles for separation of water borne pathogens like *E. coli* and AuNPs for amplification [42-44], are used for waterborne pathogens like *E. coli*; CNT arrays that monitor impedance changes to detect viral particles in air [45, 46]. 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	[47, 59]
Atrazine (Pesticide)	Graphene	Electrochemical	10 pM	Soil	[6, 26]
<i>E. coli</i>	Magnetic NPs + AuNPs	Immunoassay	10 CFU/mL	Water	[48, 49]
PAHs	AgNPs	SERS	1 ng/L	Sediment	[50, 51]
Nitrate	CNTs	Amperometric	5 μ M	Groundwater	[1, 8]

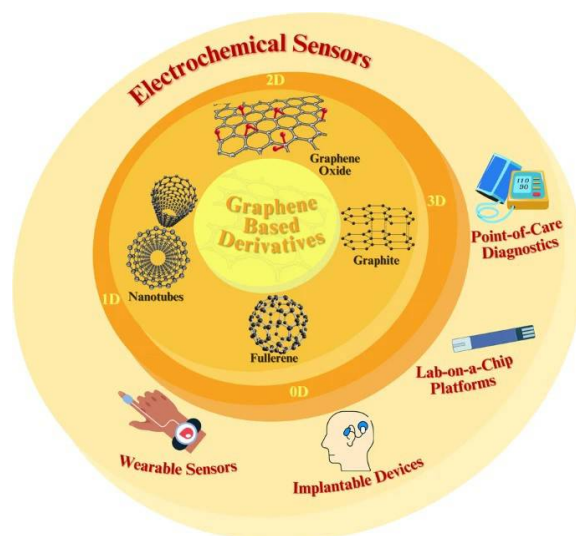


Figure 4: Photo of a portable nanomaterial-based biosensor device for field detection of pesticides. The handheld unit integrates a graphene electrode and digital readout for on-site analysis [41]

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 [47-50]); and using green synthesis methods with algae to avoid toxic outputs [51, 52]. Residual challenges include that processing real-world samples yields matrix interference, leading to questions about selectivity [53-56]. Other, larger, ongoing obstacles are related to lifestyle scaling, the approval processes of regulatory agencies, and the ecotoxicity of nanomaterials [57-59].

DISCUSSION

Nanomaterials in directions with biosensing has changed the playing field in environmental protection. When comparing mechanisms, hybrid systems portray a multitude of added adaptability with effect multipurpose detection, such as hybrid graphene-MOF systems [61-64]. All these sensors were then applied in rivers, where data were incorporated as part of the remediation efforts[65-67]. There needs to be collaboration between non-disciplines to captagonze their limitations and outline provisions for equalized access in underdeveloped nations.

CONCLUSION

Biosensors based on nanotechnology are at the forefront of environmental technology, providing innovative, sensitive, specific and customizable monitoring ability from point of viewing chronic contamination of slow-acting heavy metals in drinking water, to monitoring the exceedingly difficult biospheres of airborne pathogens in urban sectors. We need innovations that will propel us to the front of the line in caring about the environment in ways that are proactive and purposeful. Climate change and other social and environmental unbearable pressures associated with the world's geography are staring us in the face and growing stronger. Advancing these sensors with a biofutures focus on sustainability and intelligent use, can only be bettering the health of the planet. We can use methods like these to increase how, and the speed with which we, deal with the biological threat of climate change because they will be enabling resilience everywhere in all forms of nature. Eventually, we can expect to soon witness a means of prospective synergies, between nanotechnology and applied ecology, as they are both domain processes that can inspire a new sustainable future. The power of unprecedented relayed data turning into evidence-based decisions, and quickly facilitating a sustainable manner of conserving resources for future generations. This is another evolutionary process that will take time, money and effort to balance the techno-approach with the learning-focused ecological approach through research.

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