SUSTAINABLE BIOSENSING FOR WATER SECURITY: A review of technologies for heavy metal detection in wastewater

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Increased industrialization has led to the widespread contamination of wastewater with toxic heavy metals, creating significant risks for public health and environmental stability and directly challenging the achievement of the United Nations' Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation). While precise, conventional laboratory-based methods for detecting these pollutants are often too costly, slow, and complex for the rapid, on-site monitoring required for effective environmental management. This technological gap hinders timely progress toward global water safety targets. This paper provides a comprehensive review of recent advancements in biosensor technologies, aiming to highlight their potential as a sustainable and cost-effective tool to support the achievement of water- and environment-related SDGs. The research method involves a systematic review of current scientific literature, examining the fundamental principles, classifications, and components of various biosensor systems. The analysis focuses on case studies that utilize novel biorecognition elements and nanomaterials to improve performance and sustainability. The principal findings indicate that biosensor technology has advanced significantly, achieving high sensitivity for detecting key heavy metals. The development of eco-biosensors using biodegradable components aligns with SDG 12 (Responsible Consumption and Production) by minimizing waste. These technologies also support SDG 13 (Climate Action) by reducing the energy consumption of traditional analyses and contribute to protecting ecosystems as targeted by SDG 14 (Life Below Wate) and SDG 15 (Life on Land). In conclusion, biosensors offer a transformative approach to environmental monitoring that directly supports the broader goals of sustainable development. Although challenges in mass production, long-term stability, and regulatory validation persist, overcoming these hurdles will enable the widespread deployment of biosensor systems as a critical tool for achieving global clean water and sustainability goals.

1. INTRODUCTION

Water is integral to the achievement of the United Nations' SDGs, serving as a critical resource that underpins societal progress [1]. Over the years, escalating urbanization and industrialization have led to an increasing demand for water, consequently resulting in substantial wastewater discharge into the environment. In 2022, roughly 42 % of global domestic wastewater was released without adequate treatment, amounting to 113 billion m3/year [2]. In low-income countries only 8 % of wastewater receives treatment, compared with 70 % in high-income countries. Wastewater sources are broadly categorized into point and non-point sources. Sources of wastewater are typically classified as either point sources, which are specific, identifiable locations like industrial outlets or sewage plants, or non-point sources, such as diffuse agricultural and urban runoff, the latter being more difficult to manage. The complex composition of wastewater, laden with inorganic and organic compounds, HMs, and emerging pollutants like microplastics, antibiotics, endocrine disruptors, and perfluoroalkyl and polyfluoroalkyl substances (PFAS), exacerbates freshwater scarcity by degrading both its quantity and quality [3, 4]. Industrial effluents frequently contain elevated levels of HMs pollutants [5]. Exceeding these limits causes neurotoxicity, kidney damage and cancer in humans as well as reproductive and growth impairments in aquatic species. Addressing the issue of wastewater is imperative, as it directly influences public health and mitigates the prevalence of waterborne diseases. Therefore, creating swift, accurate, and field-deployable detection systems for environmental pollutants becomes crucial for facilitating preventative public health surveillance [6]. Industrial activities cause significant annual global releases of HMs, estimated at around 22,000 metric tons of cadmium, 939,000 tons of copper, 783,000 tons of lead, and 1,350,000 tons of zinc [7]. This underscores the essential requirement for efficient treatment of industrial wastewater prior to its discharge into the environment.

Even trace amounts of pollutants in wastewater can have profound environmental impacts, necessitating the creation of highly sensitive detection techniques [8]. Although sophisticated analytical tools like HPLC, GC, and diverse spectroscopic methods yield precise detection of contaminants, their high cost, time requirements, and need for trained personnel restrict their use for real-time, on-location monitoring [6]. Since the advent of the first biosensor in 1962, significant advancements have been made in biosensor technology, resulting in innovative designs and enhanced functionality [9]. Biosensors, analytical devices engineered to detect and quantify pollutants by transducing biological signals into optical or electrical outputs, provide rapid, precise, and reliable real-time data on analytes. The high specificity inherent to biosensors reduces signal interference from non-target substances, rendering them highly valuable tools for environmental surveillance. The effectiveness of biosensors in continuous or single-point detection and measurement is contingent on the biological elements employed. Utilizing organisms to predict chemical pollution exposure further enhances the predictive power of these devices, enabling exact assessment of environmental pollutants' detrimental effects.

More than just a detection tool, advanced biosensor technology offers a pathway to broader sustainable development. While previous reviews have covered biosensor fundamentals, this paper uniquely bridges these technological advancements with their direct, quantifiable impacts on achieving the UN's SDGs [6, 9, 10]. This paper reviews current biosensor technologies and highlights recent advances in their use for environmental monitoring, with a focus on improved detection of HMs in wastewater. This paper highlights how innovations in biorecognition elements and nanomaterials are creating sustainable, cost-effective tools.

2. PRINCIPLES OF BIOSENSORS

Functionally, a biosensor operates as a self-contained, integrated system that yields precise quantitative or semi-quantitative analytical results by employing a biological sensing element in direct physical contact with a signal transducer [11]. The components of a biosensor are divided into three segments including (1) the biological recognition elements, such as enzymes, antibodies, and DNA, play a crucial role in biosensors. The device incorporates: (2) a signal transducer to transform the biological interaction into a quantifiable and readily interpretable output, and (3) a signal processor designed to present this converted signal clearly and efficiently. A common approach categorizes biosensors according to either their method of signal transduction (e.g., optical, electrochemical, piezoelectric) or the nature of their biorecognition component (including elements like antibodies, aptamers, cells, enzymes, receptors, or neurons). Aptamer-based electrochemical sensors achieve LOD 60.7 nM for Pb^{2+} in lake water via G-quadruplex folding (FAM-Pb-14S) [12]. Co-ions like Cu^{2+} can induce 15 % false responses unless blocked by e.g. 6-mercaptohexanol monolayers.

2.1. Classifications of biosensor

Electrochemical biosensors see extensive application partly because their design centers on electrodes suitable for immobilizing biomolecules; these electrodes facilitate the detection of biochemical occurrences by translating them into quantifiable electrical signals [11, 13]. This conversion enables the investigation of diverse biochemical reactions and molecular interactions within biosensing applications. A significant advantage of electrochemical biosensors lies in their straightforward integration with existing electronics manufacturing processes, facilitating their suitability for mass production [14]. The adaptability of biosensors has led to their widespread use across varied fields, including ensuring food safety, performing medical diagnostics, and conducting environmental surveillance [9]. Their small footprint and economic advantages position biosensors as strong contenders for environmental monitoring roles, particularly for the early detection of toxic agents like HMs, viruses, or organic pollutants. Despite some limitations, such as a limited operating temperature range, a brief shelf life, and the potential for cross-sensitivity, their cost-effectiveness ensures they are readily available to many. For instance, the hybrid Pt NPs/SiO_2-DNAzyme electrochemical biosensor reported by Skotadis et al. achieves ultralow limits of detection (LODs) of 0.8 nM for $Pb2^+$, 1 nM for $Cd2^+$, and 10 nM for $Cr3^+$, with rapid response times of 7 - 19 s [15]. Calibration was performed using six concentrations (1, 2, 5, 10, 20, 50 nM), yielding a linear range of approximately 1 - 50 nM for $Pb2^+$ and $Cd2^+$, and 10 - 100 nM for $Cr3^+$ [15]. The biosensor also proved excellent precision, with standard deviations ranging from 0.28 - 1.2% across ten independent sensor replicates per ion. In recent work on optical-plasmonic sensing, nanocrystalline cellulose/PEDOT (NCC/PEDOT) thin films have been shown to enhance surface-plasmon-resonance (SPR) sensitivity for mercury ions, achieving a limit of detection as low as 2 ppb (≈10 nM) within 30 min while maintaining selectivity against common co-ions [16]. Similarly, piezoelectric quartz-crystal-microbalance (QCM) platforms functionalized with homocysteine and nanoparticle coatings detect Hg2+ down to 0.1 ppb (0.498 nM) over a vast dynamic range (0.1 ppb to 1 355 ppm) in under 30 min; their portability, milliliter-scale sample requirement, and excellent repeatability make them ideal early-warning systems for on-site mercury monitoring [17].

The basis of optical biosensor operation lies in utilizing the interplay between an optical field and the biorecognition element [18]. This sensing modality proves especially helpful for analyzing colored or turbid samples, encompassing various biomolecules or microorganisms like viruses, bacteria, and other pathogens. Optical biosensors operate using one of two primary detection strategies: label-based or label-free. The label-based detection employs a labeling molecule, with the optical signal generated via colorimetric, fluorescent, or luminescent methods. Label-based detection involves labeling the bioanalyte to generate an optical response, commonly used in environmental monitoring of pathogens like Escherichia coli and Salmonella typhimurium in water and food through techniques such as fluorescence and colorimetry [9]. However, label-based methods have certain drawbacks, including the potential for the labeling process to alter the bioanalyte's activity and introduce quantification errors. This has sparked increased interest in label-free methods, particularly SPR, which relies solely on bioanalyte-transducer interactions. In the label-free mode, the detection signal arises directly from the interaction between the analyte and the transducer. Despite its advantages, optical biosensing, particularly label-free methods related to SPR, faces challenges in terms of miniaturization, portability, and sustainability for broader application.

The fundamental operation of mass-based biosensors centers on finding changes in mass that take place when the target analyte attaches to the biorecognition element fixed on the sensor's surface. This mass change is typically measured using transducers like piezoelectric devices, which convert mechanical stress into an electrical signal correlated with the analyte concentration [19]. An illustrative case is the quartz crystal microbalance (QCM) biosensor, which has found extensive application in both research and environmental monitoring. In the context of biological studies, QCM sensors offer notable advantages including heightened sensitivity, ease of use, and cost-efficiency, showing them as useful tools within analytical chemistry. Their versatility enables the detection of various molecules, chemicals, polymers, and biological samples. However, a key challenge is still in optimizing the crystal coating process to ensure uniform and cohesive deposition layers. Addressing this challenge, with a focus on sustainability, could unlock the full potential of QCM sensors for broader applications.

Progress in biosensor technology owes much to nanoscience and nanotechnology, clearly demonstrated by the emergence of nanobiosensors and devices capable of single-molecule detection [20, 21]. Integrating nanomaterials like functionalized nanoparticles, nanowires, or nanotubes into sensor designs has led to considerable gains in sensitivity, selectivity, and overall performance characteristics. These advancements arise from the distinct qualities of nanomaterials, such as their shape and size-dependent properties, extensive surface area, and cost-efficiency. Practical challenges persist, however, encompassing issues like detecting analytes present at extremely low levels, addressing potential target sequence mutations or evolution (particularly for oligonucleotides and proteins), and achieving an optimal trade-off between fabrication cost and operational effectiveness across diverse sensor types.

2.2 Key performance characteristics of biosensors in heavy metal detection

To be effective for environmental monitoring, biosensors are evaluated based on several key performance characteristics. These metrics determine their suitability for rapid, on-site analysis and their advantage over traditional laboratory methods.

- *Selectivity:* This is the sensor's ability to detect a specific target heavy metal (e.g., Pb^{2+}) without generating a false signal from other, similar ions (e.g., Cu^{2+}, Cd^{2+}) that may be present in the same sample.

- *Limit of detection (LOD):* This represents the minimum concentration of a heavy metal that the sensor can reliably distinguish from a blank sample. Low LODs (in the nM or ppb range) are essential, as many metals are toxic even at trace concentrations.

- *Response time:* This is the time required for the sensor to provide a stable measurement after the sample is introduced. A rapid response (from seconds to minutes) is a primary advantage for real-time monitoring and immediate intervention.

- *Linear range:* this is the concentration range where the sensor's output signal is directly proportional to the analyte concentration. A wide linear range allows the sensor to accurately quantify both low and high levels of contamination.

- *Stability and shelf-life:* this refers to the sensor's ability to maintain its performance over time. Operational stability is its ability to function in field conditions, while shelf-life is how long it can be stored.

This is a significant challenge, as biological components can be sensitive to temperature or environmental conditions.

3. HEAVY METALS MONITORING BY BIOSENSORS

Heavy metals (HMs) contamination is commonly released due to human activities and industrial processes, including refineries, metal processing, mining, cement production, and smelting operations [22]. This form of contamination presents considerable dangers to human well-being and ecological systems. HMs pose substantial health risks to ecosystems even at minimal concentrations, primarily because they resist biological breakdown, are not easily chemically degraded, and tend to bioaccumulate within organisms [23, 24]. Additionally, water, soil, and living beings are known to accumulate these metals, underscoring the need of environmental monitoring to prevent contamination and illness [6]. Various methods, including chromatography (gas chromatography, high-performance liquid chromatography), inductively coupled plasma mass spectrometry, or atomic absorption spectroscopy, can be employed at laboratory for qualitative and quantitative HMs analysis [8]. Nevertheless, real-time detection, excessive costs, and by-product release pose significant challenges for environmental monitoring by these techniques. Through biosensors, a method offering high sensitivity for deciding HMs concentrations is available, thereby aiding efforts to manage water safety and quality.

Detection of HMs can be achieved using DNA probes, which function as recognition elements working via several distinct mechanisms. Among these mechanisms is the specific interaction between DNA bases and target metal ions, leading to the creation of a stable duplex DNA structure [11]. Additionally, HMs can break DNAzymes, and a guanine-rich probe can undergo a transition to a stable G-quadruplex structure [25]. Whole-cell microbial biosensors offer a means to detect HMs through the use of genetic components engineered to react to designated chemical substances [26]. The performance characteristics of such biosensors depend on the interplay between regulatory proteins associated with promoters and the specific reporter genes chosen to signal the presence of pollutants. Within microorganisms engineered for biosensing, reporter genes act as indicators, converting specific biological responses to pollutants into quantifiable physicochemical signals [27]. Table 1 presents typical biosensors for HMs monitoring.

Table 1 illustrates that various platforms, including whole-cell and electrochemical methods, are attaining

Table 1. Typical biosensors for HMs monitoring

Type of biosensor	Material/ Bacteria	Wastewater	Detection limits	Time	Remarks	Reference
Biosensor cell	A luminescent bacterium *Vibrio* sp. MM1	Synthetic water	Zn^{2+} (0.97 mg/L), Ni^{2+} (3.0 mg/L), Cu^{2+} (3.62 mg/L), Pb^{2+} (5.75 mg/L), Co^{2+} (6.16 mg/L, and Cd^{2+} (14.54 mg/L)	15 min	high sensitivity in detecting HMs	[28]
Light-up biosensor	FAM-Pb-14S	Lake water and serum samples	60.7 nM	1 h	Simple, rapid and reliable,	[29]
Molecular biosensors	*Acinetobacter baylyi* ADP1 Tox2	River water	-	30 min	Detect and manage pollution in urban river systems	[30]
A protein biosensor	mApple-D6A3 protein	Tap water	Cu^{2+} (18.7 μM), Ni^{2+} (21.4 μM), and Cd^{2+} (19.3 μM)	20 min	Detection accuracy exceeds 80%	[31]
Electrochemical biosensor	Oxygen-type electrochemical biosensor by a packed-bed bioreactor	Synthetic water	Cr^{6+} (0.0762 mg/L)	5 min	Cost-effective, accurate	[8]

Electrochemical biosensor	Cu-TCPP/Au/Pb^{2+}-G4-hemin	Synthetic water	1.7 nM	–	High sensitivity and high selective	[32]
Electrochemical biosensor	Hybrid nanoparticle (Pt NPs/SiO_2)/DNAzyme	Synthetic water	Pb^{2+} (0.8 nM), Cd^{2+} (1 nM) and Cr^{3+} (10 nM)	–	Good sensitivity, precision, and sufficient dynamic range	[15]
A dual-colored bacterial biosensor	A CadR-regulated vioABE expression module and a MerR-regulated VioC expression module	Sea water	Cd2+ (4.9 nM), Pb2+ (24.4 nM, and Hg2+ (0.5 nM)	4 h	High sensitivity and selectivity	[33]

impressive nanomolar (nM) detection limits for essential metals such as Hg^{2+} (0.5 nM), Pb^{2+} (0.8 nM), and Cd^{2+} (4.9 nM). Electrochemical sensors demonstrate rapid response times, detecting Cr^{6+} in 5 minutes, while whole-cell systems may necessitate incubation periods of up to 4 hours. The table highlights a validation gap: many top-performing sensors were tested solely in synthetic water. The use of lake or sea water in some tests highlights the significant gap in data regarding complex industrial wastewater, which poses a major challenge for practical field deployment.

4. BIOSENSOR APPLICATIONS AS A PATHWAY TO THE SDGS

Biosensors provide rapid, accurate monitoring, shifting environmental management from reactive remediation to proactive prevention [9, 10]. This strategy of real-time, source-level detection allows for immediate intervention, which is more cost-effective and successful at preventing widespread ecological and human harm than subsequent cleanup.

4.1 SDG 3: Good health and well-being

Biosensors for HMs detection play an essential role in advancing SDG 3, especially Target 3.9, which specifically aims to "substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination". The primary approach for this contribution is prevention. Biosensors facilitate the swift and regular assessment of drinking water, food sources, and residential soil for hazardous metals such as lead, mercury, and cadmium, serving as a crucial initial barrier to avert human exposure and potential harm [5, 26]. This work is particularly important for safeguarding at risk groups, like children, whose cognitive growth can suffer irreversible damage due to lead exposure [9]. Implementing affordable biosensors within communities enables the detection of contamination sources, like aging lead pipes or industrial emissions, thereby supporting focused public health initiatives and ultimately preserving lives while alleviating the impact of chronic diseases.

4.2. SDG 6: Clean water and sanitation

Access to clean water is essential for health, dignity, and economic progress, positioning SDG 6 as a fundamental element of the 2030 Agenda for Sustainable Development. Biosensors play a crucial role in fulfilling Target 6.1, which aims for universal and equitable access to safe and affordable drinking water, along with Target 6.3, focused on enhancing water quality through pollution reduction. Their portability and real-time capabilities render them exceptionally suited for the continuous monitoring of water quality across the entire water cycle [7]. These systems can be utilized at water treatment plant intakes to monitor upstream contamination, within distribution networks to pinpoint issues such as pipe leaching, and at the tap in homes and schools to verify that water is safe for consumption. Biosensors play a crucial role in wastewater management by allowing treatment facility operators to continuously monitor effluent, ensuring that the discharged water complies with regulatory standards and does not contaminate receiving water bodies [34]. This swift feedback mechanism facilitates prompt modifications to processes, thereby averting the discharge of pollutants and safeguarding downstream ecosystems and water consumers.

4.3. SDG 14: Life Below Water

Marine ecosystems serve as a crucial repository for numerous pollutants originating from land, such as heavy metals. SDG 14, particularly Target 14.1, seeks to "prevent and significantly reduce marine pollution of all kinds, especially from land-based activities". Biosensors serve as an essential early warning mechanism to accomplish this objective. Implementing sensor networks in rivers, estuaries, and channels that handle industrial or agricultural runoff in coastal areas allows for real-time monitoring of heavy metal flow from land to sea [28]. An alert from a biosensor can initiate a prompt examination to identify and stop the source of pollution before it inflicts considerable damage on vulnerable marine ecosystems such as coral reefs and mangrove forests [28]. This proactive strategy is essential for preserving marine biodiversity, ensuring the sustainability of fisheries that are important for coastal communities, and mitigating the bioaccumulation of harmful substances such as mercury within the marine food web [35].

4.4. SDG 15: Life on Land

The well-being of terrestrial ecosystems is central to SDG 15, which encompasses Target 15.3, an initiative aimed at "combating desertification, halting and reversing land degradation, and preventing biodiversity loss". Heavy metal contamination significantly contributes to soil degradation, leading to infertility, detrimental effects on vital soil microorganisms, and risks to the safety of agricultural products for consumption [26]. Biosensors serve as an efficient and economical method for assessing soil contamination over extensive regions. This data is crucial for land-use planning, enabling authorities to pinpoint high-risk areas and execute focused remediation strategies. On-site soil testing using biosensors provides farmers with critical insights for making informed decisions regarding crop selection and necessary soil amendments, ultimately supporting land productivity and the enduring sustainability of agricultural practices [6]. Protecting soil health through biosensors is crucial for preserving biodiversity and the essential ecosystem services that terrestrial life offers.

5. KEY CHALLENGES AND FUTURE PERSPECTIVES

5.1 Key challenges in field deployment

The design possibilities for environmental biosensor applications have been significantly broadened by recent progress in nanomaterial and molecular recognition elements. Nevertheless, increasing attention is being directed towards technologies allowing the direct, real-time monitoring of pollutants at the sampling location. Drones have become valuable tools for environmental monitoring. With the help of advanced technology, drones are now being utilized for a wide range of purposes, including assessing water and air quality, monitoring agricultural activities, and measuring volcano gas emissions [36]. A noteworthy instance involves the incorporation of a whole-cell biosensor into drones to monitor air and water quality in distant regions. This system showcases the capabilities of combining biosensors with drones for cost-effective and efficient environmental monitoring [36, 37].

Within environmental monitoring, electrochemical and enzymatic biosensors find significant use, with acetylcholinesterase-based systems being prime examples frequently employed for pesticide detection [26, 38]. Such biosensing systems gain appreciation due to their user-friendliness, dependable accuracy, and relatively low cost. Broader adoption of certain biosensors faces hurdles such as the significant expense of enzyme purification, insufficient thermal stability, and limitations in their effective operating conditions. On the other hand, aptamers offer a hopeful alternative because of their capacity to rehybridize, identify a wide range of targets, and endure different environmental conditions. Immunosensors, employed for the monitoring of organic molecules like toxins and endocrine-disrupting chemicals, offer an impressive degree of specificity [19]. Nonetheless, they face specific hurdles related to the regeneration of antibodies, their immobilization, and the optimization of their activity. These challenges pose significant obstacles to the development of immunosensors, requiring added research to improve their practical applications.

A primary limitation hindering the deployment of many current environmental biosensors is the insufficient validation using authentic environmental matrices. This validation gap is demonstrated clearly in Table 1; the majority of the high-performance sensors listed were tested in synthetic water, lake water, or tap water, not in the complex, high-interference industrial wastewater or agricultural runoff where they are most needed. Testing is often confined to simplified samples, which restricts a true assessment of their real-world performance. The lack of commercial biosensors for environmental monitoring is primarily due to this gap, which stands in stark contrast to their extensive use in clinical settings. The diverse aspects of biosensor development, along with the difficulties in achieving consistent results and on-site functionality, contribute to this discrepancy. Notwithstanding the existing challenges, considerable progress has occurred on the deployment of biosensors in actual environmental contexts. Recent research has proved the effective use of biosensors in various environments, such as lakes, rivers, seawater, soil, and wastewater. Such research initiatives reflect a committed focus on tackling the difficulties associated with environmental biosensors and expanding their practical, field-based applications. In summary, while the field of environmental biosensors has seen noteworthy progress, several hurdles stay that require solutions.

5.2. Future perspective: advanced biorecognition

To meet the high selectivity and low detection limits required for environmental monitoring, sensors must move beyond traditional bioreceptors and employ advanced molecular tools coupled with powerful signal amplification strategies. Replace protein-based antibodies with aptamers—short, single-stranded DNA or RNA molecules. Aptamers are chemically synthesized, making them cheaper, more consistent batch-to-batch, and far more resistant to the thermal and chemical denaturation that plagues antibodies in environmental samples. Crucially, they can be selected to bind with high affinity and specificity to non-immunogenic targets like heavy metal ions, for which developing high-quality antibodies is difficult. Additionally, implement CRISPR-Cas systems as the ultimate tool for programmable biorecognition. While not used for direct metal detection, they can be programmed to identify highly specific secondary indicators of contamination. For example, a sensor could be designed to detect the unique DNA sequence of a microorganism that only thrives in the presence of mercury or to recognize specific nucleic acid biomarkers of metal-induced cellular stress. This programmability allows for the rapid development of assays for new contaminants. Furthermore, use nanomaterials like gold nanoparticles, graphene, and carbon nanotubes to amplify the signal from these specific binding events. The high surface-area-to-volume ratio of these materials allows for a much denser loading of aptamers or probes on the sensor surface, increasing the probability of a binding event. Their unique electronic properties also act as catalysts and conductive bridges in electrochemical sensors, dramatically enhancing the electrical signal and pushing detection limits down to the parts-per-trillion levels required by environmental regulations.

5.3. Future perspective: integrated smart systems

The end goal is not a perfect standalone sensor, but a smart, networked system that provides actionable intelligence. This requires a paradigm shift from component-level work to system-level integration, leveraging IoT and AI to transform raw data into predictive insights. Deploy arrays of multiplexed biosensors at key nodes within a watershed or municipal water system. By connecting these sensors using low-power, long-range communication protocols (e.g., LoRaWAN), a continuous, high-resolution spatiotemporal map of water quality can be generated. This moves monitoring from infrequent, single-point measurements to a dynamic, system-wide view, allowing for the precise identification of pollution sources in real-time. Additionally, use AI/ML to process the vast datasets from these sensor networks. At the device level, ML algorithms can perform real-time fault diagnosis and self-calibration, correcting for signal drift caused by biofouling and extending the sensor's operational life in the field [39]. At the network level, ML can analyze complex data streams to identify the unique chemical fingerprints of specific pollution sources and, most powerfully, train predictive models. By learning from historical data, these systems can accurately forecast contamination events up to 48 hours in advance, allowing authorities to shift from a reactive cleanup strategy to a proactive, preventative management model.

Continuous improvements in designing biosensors, particularly focusing on boosting enzyme stability, broadening the applicability of aptamers, and refining immunosensor performance, are vital for the field's advancement. Successfully translating laboratory-validated performance into reliable, practical field use is essential to foster wider adoption and deployment of biosensors specifically for environmental monitoring purposes. The worldwide market for biosensors is projected to experience substantial growth, increasing from USD 30.6 billion in 2024 to USD 49.6 billion by 2030. This represents a compound annual growth rate of 8.4%, with environmental applications poised to emerge as a significant sub-segment [40]. The integration of artificial intelligence and data analytics, particularly through the combination of multiplex sensor arrays with machine learning algorithms, has improved the ability to deconvolute analyte signals and can predict pollution events up to 48 h in advance [41]. As the field evolves, the development of ISO standards for biosensor calibration and data formatting will play a critical role in ensuring interoperability, consistency, and regulatory acceptance across international markets.

6. CONCLUSION

Employing biosensor technology to detect HMs in wastewater provides fundamental benefits compared to traditional analytical methods, chiefly through enabling swift, portable, and economical measurements. Innovations in nanomaterial design and ecofriendly biorecognition elements have produced sensors that detect trace concentrations of lead cadmium mercury and arsenic with high precision. Feasibility studies have confirmed their applicability in matrices such as industrial discharge, municipal wastewater, and agricultural runoff. Combining these sensors with internet-connected monitoring grids and compact chip-based platforms promises to enable ongoing, real-time surveillance and provide timely alerts for pollution incidents. Key barriers remain in mass production of consistent sensors validation in complex sample matrices and compliance with evolving