REVIEW

Biosensing technologies for groundwater contamination detection

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ABSTRACT

The contamination of groundwater, mainly caused by industrial activities, agriculture, and population growth, presents a significant risk to both public health and ecosystems. Groundwater becomes infiltrated by pollutants such as heavy metals, volatile organic compounds, and emerging contaminants from a variety of sources, including industrial spills, agricultural runoff, and improper waste disposal. While traditional detection methods are dependable, they are often time-consuming and require a lot of labor, which hampers effective monitoring. To address contamination and safeguard groundwater resources, it is crucial to create detection technologies that are rapid, affordable, and highly sensitive. These advancements will allow for real-time monitoring, support timely interventions, and enhance water management practices, ultimately protecting public health and environmental sustainability.

Introduction

Groundwater contamination has become a significant concern due to rapid industrialization, agricultural practices, and population growth [1]. Various pollutants, including persistent organic compounds, heavy metals, and emerging contaminants (ECs), pose threats to groundwater quality [2]. These contaminants originate from diverse sources such as industrial spills, agricultural runoff, and improper waste disposal [1]. Traditional detection methods like chemical assays have been labor-intensive and time-consuming. However, advancements in biotechnology have led to the development of more efficient detection techniques, including microbial biosensors and other novel approaches [3]. These new technologies aim to provide real-time, in-situ monitoring of ECs in groundwater [4]. To mitigate groundwater contamination, measures such as optimizing fertilizer application, proper pesticide disposal, and implementing effective irrigation systems are recommended.

Groundwater contamination typically arises from pollutants like heavy metals (e.g., arsenic, lead), volatile organic compounds (VOCs), and microbial pathogens. These contaminants pose severe risks to both human health and ecosystems [5]. Heavy metals, for example, are linked to cancer and neurological damage, while VOCs can lead to organ failure. Pathogens in contaminated groundwater can cause outbreaks of waterborne diseases such as cholera and typhoid fever [6]. Given the significance of groundwater as a key drinking water source, its protection is essential for ensuring public health, preserving biodiversity, and maintaining environmental sustainability.

Recent studies have emphasized the prevalence of heavy metals and volatile organic compounds in contaminated groundwater. Industrial activities, including the improper disposal of chemicals, have been found to release harmful substances into aquifers [7]. For instance, VOCs from industrial runoff have been linked to liver and kidney diseases. Meanwhile, metals such as arsenic and lead are strongly associated with

carcinogenic risks and neurological disorders. According to surveys, 3.6% of drinking water wells in rural areas exceed nitrate levels considered safe by federal health standards, further exacerbating health concerns in these regions [8]. Despite advances in detection technologies, monitoring groundwater contamination remains challenging. Traditional methods, while reliable, are often costly and time-consuming, limiting their widespread application. Additionally, detecting low concentrations of contaminants in remote or rural areas remains difficult, hindering effective management and timely intervention [9].

There is a significant research need to create fast, affordable, and very sensitive technologies for detecting various groundwater pollutants in real time. Existing techniques frequently do not have the necessary sensitivity for detecting low levels of pollutants, particularly in areas with limited resources. Progressing biosensing technologies will enhance monitoring of contamination, facilitate faster interventions, and improve water management, thereby reducing public health hazards [10].

Biosensing Technologies: Overview and Types

Biosensors, devices that utilize biological components to detect and measure specific analytes, have emerged as indispensable tools across various fields. These devices offer unparalleled sensitivity, specificity, and real-time analysis capabilities, making them particularly valuable for environmental monitoring, healthcare, and food safety [11].

Basic principles of biosensors

A biosensor typically comprises three key components: a bio-receptor, a transducer, and a detector. The bio-receptor, often an enzyme, antibody, or nucleic acid, selectively interacts with the target analyte. This interaction triggers a measurable change, which is then converted into another detectable signal

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by the transducer [12]. The detector subsequently processes this signal to provide a quantitative measurement of the analyte's concentration.

Types of Biosensors for Environmental Monitoring

Biosensors have been adapted for a wide range of environmental monitoring applications. Here are some prominent types:

Electrochemical biosensors

Electrochemical biosensors measure changes in electrical properties, such as current, voltage, or impedance, resulting from the interaction between the analyte and the bio-receptor. They are widely used for detecting metal ions and chemical pollutants in groundwater. For instance, enzyme-based electrodes can be employed to detect heavy metals by monitoring the redox reactions catalyzed by the enzyme [13].

Optical biosensors

Optical biosensors leverage light-based techniques to detect analytes. They can be classified into various categories, including fluorescence, chemiluminescence, and surface plasmon resonance (SPR) biosensors. These sensors are particularly useful for detecting organic contaminants and pathogens. For example, SPR biosensors can measure the binding of antibodies to specific pathogens, enabling rapid and sensitive detection [14].

Piezoelectric biosensors

Piezoelectric biosensors utilize the piezoelectric effect, where mechanical stress is converted into an electrical signal. These sensors can detect changes in mass on the sensor's surface, making them suitable for monitoring microbial and chemical pollutants. For instance, quartz crystal microbalances (QCMs) can measure the mass of microorganisms or chemical compounds that bind to the sensor's surface.

Nanomaterial-based biosensors

The incorporation of nanomaterials, such as nanoparticles, nanowires, and nanotubes, into biosensors has significantly enhanced their sensitivity and selectivity. Nanomaterials offer a large surface area for bioreceptor immobilization, improved signal transduction, and enhanced detection limits. They are particularly useful for detecting low concentrations of pollutants in environmental samples [15]. For example, carbon nanotube-based biosensors have been developed for the detection of trace levels of pesticides and heavy metals.

Challenges and limitations

Biosensors, while offering significant advantages in analytical chemistry, are not without their limitations. Their sensitivity can be influenced by environmental factors such as temperature, pH, and ionic strength, potentially impacting their performance. Additionally, the presence of other analytes in the sample may interfere with the detection of the target analyte, leading to inaccurate results. The production and maintenance of biosensors, particularly complex devices, can be costly. Furthermore, some biosensors may lack the sensitivity required to detect low concentrations of analytes.

Emerging Trends and Future Directions

Biosensor technology continues to evolve rapidly, with several emerging trends and future directions. Integration with other technologies: Biosensors are being integrated with microfluidics, nanotechnology, and other technologies to enhance their capabilities. Development of portable and wearable biosensors: Point-of-care (POC) biosensors and wearable devices are being developed for continuous monitoring of health and environmental parameters [16]. Application in personalized medicine: Biosensors are being used to develop personalized medicine approaches, tailoring treatments based on individual genetic and physiological characteristics. Environmental monitoring: Biosensors play a crucial role in monitoring water quality, air pollution, and climate change. Specific Examples of Environmental Pollutants Detected by Biosensors are heavy metals like Lead, mercury, arsenic, and cadmium [17]. Organic pollutants like Pesticides, herbicides, and Polycyclic Aromatic Hydrocarbons (PAHs). Microbial contaminants like Bacteria, viruses, fungi. Radioactive contaminants like Radionuclides.

Application of Biosensors in Groundwater Contamination Detection

Detection of chemical contaminants

Heavy metals, such as lead, mercury, arsenic, and cadmium, pose significant health risks when present in groundwater. Biosensors have been developed to detect these contaminants through various mechanisms. Enzyme-based biosensors, for example, utilize enzymes that react with heavy metals to produce a measurable signal. These sensors often employ enzymes like dehydrogenases or oxidases, which catalyze redox reactions involving heavy metal ions. The resulting changes in electrical current or optical properties can be correlated to the concentration of the target metal [18].

Nanoparticle-based biosensors

These sensors incorporate nanoparticles, such as gold or silver nanoparticles, to enhance sensitivity and selectivity. For example, gold nanoparticle-based biosensors have been used to detect arsenic in groundwater at low concentrations. Immunosensors utilize antibodies or antigens to bind to specific heavy metal ions. These sensors can offer high selectivity and sensitivity but may require complex sample preparation.

Organic pollutants

Organic pollutants, including pesticides and volatile organic compounds (VOCs), can contaminate groundwater sources and pose serious health hazards. Biosensors have been developed to detect these contaminants by exploiting the specific interactions between the pollutants and biological components. For instance, enzyme-based biosensors can be used to detect pesticides by measuring the inhibition of enzyme activity caused by the pollutants. Immunosensors, which utilize antibodies to bind to specific pollutants, can also be employed for detection.

Enzyme-based biosensors

Enzymes like acetylcholinesterase and alkaline phosphatase have been used to detect organophosphate and carbamate pesticides, respectively. DNA-based biosensors can detect specific genes associated with pesticide-degrading bacteria, providing an indirect measure of pesticide contamination.

Detection of microbial contaminants

Microbial contamination of groundwater poses a significant risk of waterborne disease transmission. Biosensors have

emerged as valuable tools for detecting bacteria, viruses, and other pathogens in water samples. These sensors often employ antibodies or nucleic acid probes that specifically bind to target microorganisms. The binding event is then detected using methods such as fluorescence, chemiluminescence, or electrochemistry [19]. Immunosensors utilize antibodies against specific pathogens, like E. coli or Salmonella, immobilized on a sensor surface to identify their presence. DNA-based biosensors, on the other hand, detect specific genes or DNA sequences associated with pathogens, offering highly sensitive and specific detection capabilities [20].

Comparison with traditional methods

Biosensors offer several advantages over traditional methods of groundwater analysis. Their rapid response times, often within minutes or hours, significantly reduce turnaround times compared to days or weeks required by traditional methods. Many biosensors are portable and can be used on-site, making them ideal for field testing and remote monitoring [21]. Additionally, biosensors are capable of detecting contaminants at extremely low concentrations, often surpassing the sensitivity limits of traditional methods.

Challenges and Limitations

Biosensors, while offering significant advantages in analytical chemistry, are not without their limitations. Their sensitivity can be influenced by environmental factors such as temperature, pH, and ionic strength, potentially impacting their performance. Additionally, the presence of other analytes in the sample may interfere with the detection of the target analyte, leading to inaccurate results. The production and maintenance of biosensors, particularly complex devices, can be costly. Furthermore, some biosensors may lack the sensitivity required to detect low concentrations of analytes.

Future Directions

Biosensor technology is undergoing rapid advancements, with several promising trends emerging. The integration of biosensors with Internet of Things (IoT) devices, artificial intelligence, and other technologies is enabling real-time monitoring and data analysis. Additionally, there is a growing focus on developing low-cost, disposable biosensors to facilitate widespread use in groundwater monitoring. Furthermore, researchers are actively working to enhance the sensitivity and selectivity of biosensors to enable the detection of emerging contaminants [22].

Advantages and Limitations of Biosensing Technologies

Biosensing technologies have emerged as powerful tools for a wide range of applications, including environmental monitoring, healthcare, and food safety. These technologies offer several advantages but also face certain limitations and challenges.

High sensitivity and specificity

Biosensors are capable of detecting analytes at extremely low concentrations, providing exceptional sensitivity. This high sensitivity allows for the detection of contaminants in complex environmental matrices, even when present at trace levels. Additionally, biosensors exhibit remarkable specificity, enabling them to differentiate between target analytes and interfering substances. This specificity is crucial for accurate and reliable detection in diverse environmental conditions.

Cost-effectiveness

Biosensors can offer a cost-effective alternative to traditional laboratory-based testing methods. By providing rapid, on-site analysis, biosensors can reduce the need for extensive sample preparation, transportation, and laboratory analysis. This can result in significant cost savings, particularly for large-scale monitoring programs.

Real-time monitoring

Biosensors are capable of providing real-time monitoring of analytes, enabling immediate decision-making. This is particularly valuable for applications where rapid response is critical, such as environmental emergencies or public health threats. Real-time monitoring can help identify and address contamination issues promptly, preventing further harm [16].

Challenges of Bio-sensing Technologies

Stability and durability issues

Biosensors can be sensitive to environmental factors, such as temperature, pH, and humidity. These factors can affect the stability and durability of the bio-receptors and transducers, leading to degradation and reduced performance over time. Ensuring the long-term stability and reprehensibility of biosensors in various environmental conditions is a critical challenge.

Interference from complex matrices

Groundwater samples often contain complex matrices with a variety of interfering substances. These substances can interfere with the detection of target analytes, leading to false positive or false negative results. Developing biosensors that are resistant to interference from complex matrices is essential for accurate and reliable groundwater monitoring [23].

Scaling and field deployment

Scaling biosensor technologies for widespread field deployment can be challenging. Factors such as calibration, standardization, and the need for robust designs can hinder the adoption of biosensors in real-world applications. Addressing these challenges is crucial for ensuring the successful integration of biosensors into environmental monitoring programs.

Biosensors can be categorized based on their biological components. Enzyme-based biosensors leverage enzymes to catalyze reactions with target analytes, generating a measurable signal. They have proven effective in detecting heavy metals, organic pollutants, and microbial contaminants. Immunosensors, on the other hand, employ antibodies or antigens to bind to specific analytes, making them ideal for pathogen detection and biomolecule analysis [24]. DNA-based biosensors utilize nucleic acid probes to identify specific DNA sequences, finding applications in pathogen identification and genetic analysis.

Comparison with traditional methods

Biosensors offer several advantages over traditional groundwater analysis methods. They provide rapid results, often within minutes or hours, significantly reducing turnaround times compared to days or weeks required by conventional techniques. Many biosensors are portable and can be used on-site, making them suitable for field testing and remote

monitoring. Additionally, biosensors are capable of detecting contaminants at very low concentrations, often exceeding the sensitivity of traditional methods.

Advancements in biosensing technologies

To address the limitations of biosensing technologies, researchers are actively working on several fronts. Efforts are underway to develop bioreceptors and transducers that are more resistant to environmental factors, thereby improving their stability and durability. Additionally, researchers are striving to enhance the selectivity of biosensors, enabling them to more effectively differentiate between target analytes and interfering substances. Reducing the cost of biosensor production and materials is another key area of focus. Furthermore, developing portable, user-friendly biosensors with robust designs is essential for their widespread field deployment.

Bio-sensing technologies and future perspectives

Bio-sensing technologies have witnessed significant advancements in recent years, driven by innovations in materials science, nanotechnology, and electronics. These advancements have expanded the capabilities and applications of biosensors, particularly in the field of groundwater contamination detection.

Nanotechnology in Biosensing

Nanomaterials have revolutionized biosensor design, offering enhanced sensitivity, selectivity, and detection limits. Nanoparticles, nanowires, and nanotubes have been incorporated into biosensors to provide larger surface areas for bioreceptor immobilization, improved signal transduction, and enhanced detection capabilities. For example, the use of graphene-based nanomaterials has enabled the development of biosensors with exceptional sensitivity for detecting trace levels of contaminants in groundwater [25].

Biosensors Improve Efficiency, Stability, and Portability for Groundwater Contamination Detection

Advances in biosensor technology have resulted in the creation of sensors that can simultaneously detect multiple contaminants, leading to more efficient groundwater monitoring by reducing the time and cost associated with individual contaminant measurements. These multiplexed biosensors are capable of identifying various pollutants, such as heavy metals, organic pollutants, and microbial pathogens, in a single sample [26]. However, maintaining the long-term stability and accuracy of these biosensors in challenging environmental conditions remains a significant challenge. Ongoing research aims to develop more durable bioreceptors and transducers, as well as advanced signal processing techniques to improve data reliability. Furthermore, the miniaturization and portability of biosensors are increasingly important for field testing and remote monitoring. Integrating biosensors into handheld devices, drones, or autonomous vehicles enables real-time data collection in challenging environments. To successfully apply these technologies, it is essential to establish supportive policy and regulatory frameworks [27]. Governments and regulatory agencies must create guidelines to ensure data quality and reliability while also encouraging innovation and adoption through incentives. International collaboration is also crucial to standardize regulations and facilitate the global deployment of biosensing technologies for detecting groundwater contamination.

Conclusions

Bio sensing technologies have emerged as valuable tools for detecting and monitoring groundwater contamination. By utilizing biological components, these devices offer high sensitivity, specificity, and real-time analysis capabilities. This review highlights advancements in biosensor technology, including the use of nanomaterials, integration with IoT, and the development of multiplexed detection platforms. Biosensors have proven effective in detecting various contaminants, such as heavy metals, organic pollutants, and microbial pathogens. Case studies demonstrate their application in monitoring arsenic levels in Bangladesh, pesticide contamination in agricultural regions, and microbial contamination in industrial sites. Future research and development will likely lead to even more advanced biosensors, integrated with IoT and artificial intelligence for comprehensive monitoring. However, challenges such as cost, regulations, and data reliability must be addressed for successful implementation. Ethical considerations regarding data privacy and security also need careful attention. By overcoming these challenges, biosensors can revolutionize groundwater contamination detection and management, protecting water resources and safeguarding public health.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Burri NM, Weatherl R, Moeck C, Schirmer M. A review of threats to groundwater quality in the anthropocene. Sci Total Environ. 2019;684:136-154. https://doi.org/10.1016/j.scitotenv.2019.05.236
2. Garg A. Emerging contaminants in subsurface: sources, remediation, and challenges. In Advances in remediation techniques for polluted soils and groundwater. 2022:233-257. https://doi.org/10.1016/B978-0-12-823830-1.00014-6
3. Zhao X, Lin CW, Wang J, Oh DH. Advances in rapid detection methods for foodborne pathogens. J Microb Biotechnol. 2014;24(3):297-312. https://doi.org/10.4014/jmb.1310.10013
4. Lim JW, Ha D, Lee J, Lee SK, Kim T. Review of micro/nanotechnologies for microbial biosensors. Front Bioeng Biotechnol. 2015;3:61. https://doi.org/10.3389/fbioe.2015.00061
5. Lyons KJ, Ikonen J, Hokajärvi AM, Räsänen T, Pitkänen T, Kauppinen A, et al. Monitoring groundwater quality with real-time data, stable water isotopes, and microbial community analysis: A comparison with conventional methods. Sci Total Environ. 2023;864:161199. https://doi.org/10.1016/j.scitotenv.2022.161199
6. Pedley S, Howard G. The public health implications of microbiological contamination of groundwater. Q J Eng Geol Hydrogeol. 1997;30(2):179-188. https://doi.org/10.1144/GSL.QJEGH.1997.030.P2.10
7. Karunanidhi D, Subramani T, Srinivasamoorthy K, Yang Q. Environmental chemistry, toxicity and health risk assessment of groundwater: Environmental persistence and management strategies. Environ Res. 2022;214:113884. https://doi.org/10.1016/j.envres.2022.113884
8. Pandey P, Yadav R. A review on volatile organic compounds (VOCs) as environmental pollutants: fate and distribution. Int J Plant Env. 2018;4(02):14-26. https://doi.org/10.18811/ijpen.v4i02.2
9. Kurwadkar S. Occurrence and distribution of organic and inorganic pollutants in groundwater. Water Environ Res. 2019;91(10): 1001-1008. https://doi.org/10.1002/wer.1166
10. Angulo M, Tang WH. Optimal Ground-Water Detection Monitoring System Design under Uncertainty. In Geotechnical Safety and Reliability. 2017;324-324.

11. Mehrotra P. Biosensors and their applications–A review. J Oral Biol Craniofac Res. 2016;6(2):153-159. https://doi.org/10.1016/j.jobcr.2015.12.002

12. Kaur M, Sharma S, Kumar D. An insight into the multifarious applications of biosensors and the way forward. J Drug Deliv Ther. 2022;12(5-S):181-188. https://doi.org/10.22270/jddt.v12i5-S.5633

13. Badihi-Mossberg M, Buchner V, Rishpon J. Electrochemical biosensors for pollutants in the environment. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis. 2007;19(19-20):2015-2028. https://doi.org/10.1002/elan.200703946

14. Park JH, Cho YW, Kim TH. Recent advances in surface plasmon resonance sensors for sensitive optical detection of pathogens. Biosensors. 2022;12(3):180. https://doi.org/10.3390/bios12030180

15. Ramnani P, Saucedo NM, Mulchandani A. Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. Chemosphere. 2016;143: 85-98. https://doi.org/10.1016/j.chemosphere.2015.04.063

16. Rodriguez-Mozaz S, de Alda MJ, Marco MP, Barceló D. Biosensors for environmental monitoring: A global perspective. Talanta. 2005;65(2):291-297. https://doi.org/10.1016/j.talanta.2004.07.006

17. Wanekaya AK, Chen W, Mulchandani A. Recent biosensing developments in environmental security. J Environ Monit. 2008;10(6):703-712. https://doi.org/10.1039/B806830P

18. Salek Maghsoudi A, Hassani S, Mirnia K, Abdollahi M. Recent advances in nanotechnology-based biosensors development for detection of arsenic, lead, mercury, and cadmium. Int J Nanomed. 2021;803-832. https://doi.org/10.2147/IJN.S294417

19. Srivastava KR, Awasthi S, Mishra PK, Srivastava PK. Biosensors/molecular tools for detection of waterborne pathogens. Waterborne Pathogens. 2020;237-277. https://doi.org/10.1016/B978-0-12-818783-8.00013-X

20. Savas S, Ersoy A, Gulmez Y, Kilic S, Levent B, Altintas Z. Nanoparticle enhanced antibody and DNA biosensors for sensitive detection of Salmonella. Materials. 2018;11(9):1541. https://doi.org/10.3390/ma11091541

21. Hossain SZ, Mansour N. Biosensors for on-line water quality monitoring–a review. Arab J Basic Appl Sci. 2019;26(1):502-518. https://doi.org/10.1080/25765299.2019.1691434

22. Gavrilaş S, Ursachi CȘ, Perţa-Crişan S, Munteanu FD. Recent trends in biosensors for environmental quality monitoring. Sensors. 2022;22(4):1513. https://doi.org/10.3390/s22041513

23. Tschmelak J, Kumpf M, Proll G, Gauglitz G. Biosensor for seven sulphonamides in drinking, ground, and surface water with difficult matrices. Anal Lett. 2004;37(8):1701-1718. https://doi.org/10.1081/AL-120037597

24. Hussain M. Review on Biochemical Detection of Biological Plant Samples Using Integrative Approach Sch Bull. 2021;7(3):38-43. https://doi.org/10.36348/sb.2021.v07i03.004

25. Ramesh M, Janani R, Deepa C, Rajeshkumar L. Nanotechnology-enabled biosensors: A review of fundamentals, design principles, materials, and applications. Biosensors. 2022;13(1):40. https://doi.org/10.3390/bios13010040

26. Justino CI, Duarte AC, Rocha-Santos TA. Recent progress in biosensors for environmental monitoring: A review. Sensors. 2017;17(12):2918. https://doi.org/10.3390/s17122918

27. Gautam P, Suniti S, Kumari A, Madathil D, Nair B. A review on recent advances in biosensors for detection of water contamination. Int J Environ Sci. 2012;2(3):1565-1574. https://doi.org/10.6088/ijes.00202030041 F

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