International Journal of Scientific Research and Engineering Development-– Volume 6 Issue 4, July- Aug 2023

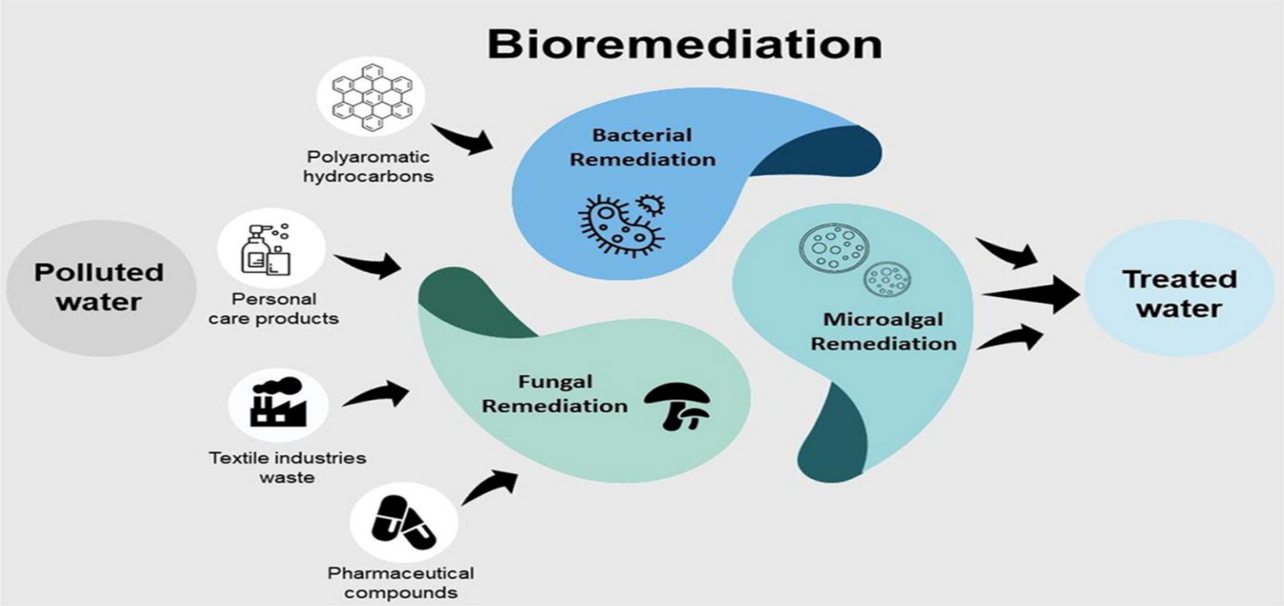
Available at ***www.ijsred.com***

RESEARCH ARTICLE OPEN ACCESS

Innovative Inorganic Pollutant Bioremediation Approaches for Industrial Wastewater Treatment: A Review

Muhammad Zaib*,Muhammad Aryan**, Haseeb Ullah***
*Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Punjab. Pakistan
Email: zaibch767@gail.com
**Department of environmental sciences Kohat University of Science and Technology Kohat, Khyber Pakhtunkhwa, Pakistan
Email: ktkaryan098@gmail.com
***Department of Medical Laboratory Technology Kohat University of Science and Technology, Kohat, Khyber Pakhtunkhwa, Pakistan
Email: haseebullah1717@gmail.com

Corresponding Author:
Muhammad Zaib
Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Punjab. Pakistan
zaibch767@gmail.com



Graphical Abstract

Abstract:

Industrial activities contribute significantly to the release of inorganic pollutants into wastewater, posing environmental and human health risks.Inorganic pollutants, also known as inorganic contaminants, refer to chemical substances that do not contain carbon-hydrogen (C-H) bonds in their molecular structure. These substances are typically derived from minerals and elements found in nature, and they can have various adverse effects on the environment and human health when present in excessive amounts. Inorganic pollutants are often released into the environment as a result of industrial activities, mining, agriculture, and other human-related processes. Bioremediation, a sustainable and cost-effective approach, holds promise for addressing these challenges. This comprehensive review explores cutting-edge bioremediation strategies tailored for the removal of inorganic pollutants from industrial wastewater. The review highlights innovative techniques, reactor designs, and successful case studies from various industries. By delving into the mechanisms, benefits, challenges, and potential synergies of combining bioremediation with industrial processes, this review offers insights into advancing sustainable wastewater treatment in industrial settings.

Keywords: **Industrial wastewater, inorganic pollutants, bioremediation, innovative approaches, hybrid systems, sustainability**

1. Introduction

Industrial wastewater is a consequential byproduct of various industrial processes, encompassing various sectors such as manufacturing, mining, chemical production, and power generation. This type of wastewater is characterized by its complexity and often contains a diverse array of pollutants, including both organic and inorganic compounds. Inorganic pollutants, in particular, play a significant role in industrial wastewater's composition and potential environmental impact. Unlike organic compounds, inorganic pollutants refer to chemical substances that do not contain carbon-hydrogen (C-H) bonds. These pollutants are derived from various sources within industrial processes, such as raw materials, chemical reactions, and equipment used in manufacturing. They can take various forms, including metals, metalloids, acids, bases, salts, and other mineral-based compounds. Common examples of inorganic pollutants include heavy metals like lead, mercury, cadmium, chromium and non-metallic substances like arsenic and cyanide. Inorganic pollutants in industrial wastewater can have profound environmental and health implications. These pollutants are often persistent and can accumulate in ecosystems over time. When released into natural water bodies like rivers, lakes, and oceans, they can disrupt aquatic ecosystems, impair water quality, and harm aquatic organisms [1]. Industrial processes involve the use of various chemicals, solvents, and raw materials, leading to the production of wastewater with complex compositions. This wastewater can contain contaminants such as heavy metals, metalloids, salts, acids, alkalis, and other inorganic compounds. The type and concentration of pollutants depend on the industry, the processes involved, and the specific materials used [2]. Inorganic pollutants encompass a wide range of chemical substances that originate from industrial activities. These pollutants include heavy metals such as cadmium, lead, mercury, and chromium, as well as metalloids like arsenic. Additionally, inorganic acids, bases, and salts are often present in wastewater, originating from various chemical processes [3]. Inorganic pollutants pose significant environmental and human health risks due to their persistence, bioaccumulation, and potential toxicity. These pollutants can contaminate water bodies, soil, and groundwater, impacting ecosystems and entering the food chain. Moreover, they can have detrimental effects on aquatic life, disrupt natural habitats, and compromise the quality of water resources [4].

Inorganic pollutants, originating from various industrial and anthropogenic sources, have become a pressing concern due to their detrimental effects on the environment and human health. These pollutants include heavy metals, metalloids, and other non-organic substances that can accumulate in ecosystems, contaminating soil and water. The effective treatment of inorganic pollutants is paramount to mitigate their adverse environmental impacts and ensure the well-being of ecosystems and human populations. Inorganic pollutants, such as heavy metals (e.g., lead, mercury, cadmium) and metalloids (e.g., arsenic), are persistent and can accumulate in the environment over time. Inorganic pollutants can leach into water bodies, contaminating drinking water sources and aquatic ecosystems. This can disrupt aquatic life; affect biodiversity, and compromise water quality [5]. The deposition of inorganic pollutants in soil can lead to soil degradation, reduced agricultural productivity, and potential crop contamination, impacting food safety. Accumulating inorganic pollutants can disrupt natural ecosystems, affecting plant growth, nutrient cycling, and overall ecosystem health. Inorganic pollutants can enter the food chain through plants and animals, posing health risks to humans who consume contaminated food and water. These risks include developmental issues, organ damage, and even carcinogenic effects [6]. Effective treatment strategies for inorganic pollutants are critical to minimize their environmental impacts and associated risks. Such treatment methods aim to remove, immobilize, or transform these pollutants into less harmful forms. Common approaches include chemical precipitation, ion exchange, adsorption, and advanced oxidation processes. However, bioremediation holds significant promise among these methods due to its sustainability, cost-effectiveness, and potential for long-term pollutant removal. Bioremediation, which employs microorganisms to degrade or immobilize pollutants, has gained attention as a sustainable approach for inorganic pollutant remediation. Microbes can metabolize or bind with pollutants, transforming them into less toxic forms. This approach can be especially practical for heavy metals and metalloids. Bioremediation reduces environmental impacts and promotes ecosystem restoration by leveraging natural biological processes [7].

The objective of employing various bioremediation techniques for inorganic pollutants from wastewater is to mitigate the environmental and human health risks associated with the release of these pollutants. Bioremediation offers a sustainable and cost-effective approach to remove or transform inorganic contaminants, such as heavy metals and metalloids, from wastewater, thereby reducing their impact on ecosystems and water resources.

2. Industrial Wastewater Composition and Challenges

Industrial wastewater refers to the contaminated water generated as a byproduct of various industrial processes. It is distinct from domestic wastewater due to its complexity, higher pollutant concentrations, and diverse composition. This type of wastewater originates from sectors such as manufacturing, mining, chemical production, power generation, and food processing, among others. The nature of industrial wastewater varies significantly depending on the industry, the processes involved, and the types of materials used.

Inorganic pollutants are chemical compounds that lack carbon-hydrogen (C-H) bonds and are often associated with industrial processes. These pollutants can contaminate wastewater discharged from industries, posing significant environmental and health risks. Some common inorganic pollutants found in industrial wastewater include heavy metals, such as lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr), as well as ions like nitrates (NO_3^-), phosphates (PO_4^{3-}), and sulfates (SO_4^{2-}) [8]. These pollutants can originate from various industrial activities, including mining, metal processing, chemical manufacturing, and agriculture. Improper disposal and inadequate treatment of wastewater can lead to the release of these pollutants into water bodies, contaminating water supplies and negatively impacting aquatic ecosystems and human health.

The complex nature of industrial effluents refers to the diverse and often intricate composition of wastewater produced by industrial processes. This composition can vary widely depending on the industry, leading to challenges for conventional treatment methods. Different industries generate effluents with distinct combinations of contaminants, including organic matter, heavy metals, suspended solids, chemicals, and even potentially hazardous substances. For instance, effluents from food processing, textile manufacturing, and chemical production may contain different types and concentrations of pollutants. This variability makes it challenging to design a one-size-fits-all treatment approach. Conventional wastewater treatment methods, which typically include physical, chemical, and biological processes, may need to be improved when dealing with complex industrial effluents. Some conventional treatment methods might not effectively remove specific contaminants present in certain industrial effluents. For instance, traditional biological treatment might struggle to effectively degrade complex organic compounds or remove certain heavy metals. Industrial effluents can contain toxic or recalcitrant compounds that resist degradation through standard treatment processes, potentially harming the environment even after treatment. Treating complex effluents often requires customizing treatment processes, which can be cost-intensive. Moreover, achieving the desired level of purification might require additional steps and resources. Some industrial effluents might cause clogging or fouling of treatment equipment due to the presence of high concentrations of suspended solids, oils, or other substances. Complex effluents might contain valuable resources, such as metals or organic compounds, which could be recovered but are often challenging to extract through conventional methods[9].The concept of "Demand for tailored approaches to manage specific pollutants" underscores the necessity to customize environmental pollution management solutions based on the unique attributes of each pollutant. This constitutes a vital stride towards curbing environmental contamination. Pollutants emanate from diverse sources, display varied behaviors, and wield a range of impacts on ecosystems and human well-being. Consequently, employing a one-size-fits-all pollution management strategy may not yield success universally. Instead, specialized methodologies become imperative to effectively mitigate the adverse consequences posed by distinct contaminants. To illustrate, mitigating airborne pollutants like particulate matter (PM), volatile organic compounds (VOCs), and sulphur dioxide (SO_2) might require diverse techniques due to the disparate origins and distinct chemical properties of these pollutants. Similarly, addressing waterborne contaminants such as heavy metals, fertilizers, and pharmaceuticals mandates bespoke approaches that carefully consider the sources of these pollutants and their persistence within aquatic systems [10].

3. Emerging Bioremediation Techniques

Bioaugmentation is a bioremediation strategy that enhances microbial communities to effectively degrade pollutants in various environments, such as soil, water, and sediments. It is a process where specific microorganisms that can degrade pollutants are introduced or added to the existing microbial community to enhance the degradation of targeted contaminants. The goal is to accelerate the natural biodegradation process and reduce the concentration of pollutants to non-hazardous levels. The first step is identifying the pollutants in the contaminated site. This helps in selecting the appropriate microbial strains that can effectively degrade the identified pollutants. Microbial strains capable of degrading the identified pollutants are isolated from similar contaminated environments. These strains are then screened for their effectiveness in pollutant degradation and their compatibility with the target environment. The selected microbial strains are cultured and multiplied in the laboratory under controlled conditions to ensure their viability and activity. The cultured microbial strains are introduced to the contaminated site through various methods, such as direct injection, spraying, or mixing with the soil/water/sediments. This introduces a higher concentration of pollutant-degrading microorganisms to the environment. The progress of pollutant degradation is monitored over time. The bioaugmentation approach may be adjusted based on monitoring results to optimize degradation efficiency. Ideally, the introduced microbial strains establish themselves within the existing microbial community, creating a synergistic effect that enhances pollutant degradation. Over time, the introduced microorganisms may become part of the natural microbial community, contributing to the ongoing degradation of pollutants even after the initial introduction [11].Microbial Fuel Cells (MFCs) are innovative bioelectrochemical devices that utilize the metabolic activity of microorganisms to generate electrical energy from organic matter and other pollutants present in wastewater or other organic-rich substrates. These devices simultaneously address two critical environmental challenges:

pollutant removal from water and energy generation. The concept behind MFCs is rooted in the ability of certain microorganisms to undergo metabolic processes that involve the transfer of electrons between different components, such as during the breakdown of organic compounds [12]. In MFCs, microorganisms, usually bacteria, participate in biodegradation processes, oxidizing organic matter in the wastewater. During this metabolic activity, electrons are released as byproducts. These electrons can then be transferred to an anode electrode through the metabolic pathways of the microorganisms. The MFC setup consists of two main compartments: an anode and a cathode, separated by a membrane. The anode compartment contains the microorganisms that break down organic matter, releasing electrons [13]. The cathode compartment serves as the site where oxygen or other terminal electron acceptors are reduced. The electrons generated by the microbial oxidation of organic matter at the anode flow through an external circuit towards the cathode. This flow of electrons constitutes an electrical current, which can be harnessed to do practical work. The flow of electrons through the external circuit creates an electric current that can be captured and utilized to power various devices or systems. As microorganisms consume organic matter, pollutants in the wastewater are naturally broken down and converted into harmless byproducts, thus contributing to water purification. MFCs have promising applications in wastewater treatment, bioremediation of contaminated environments, and even renewable energy generation. They can be used in settings with a continuous influx of organic-rich wastewater, such as municipal wastewater treatment plants or industries generating organic waste [14].

Bioremediation involves using biological processes to remove or degrade pollutants from contaminated environments. On the other hand, nanotechnology deals with manipulating matter at the nanoscale (typically 1 to 100 nanometers) to create novel materials and devices with unique properties [13]. The phrase suggests that nanostructured materials, which are materials with features or components at the nanoscale, can improve bioremediation processes' efficiency and effectiveness. These materials can enhance the performance of bioremediation techniques by offering advantages such as increased surface area, improved reactivity, and targeted delivery of active agents. Nanotechnology involves working with materials at the nanoscale to create new properties, behaviors, and applications. Nanotechnology can design materials with specific properties that aid in pollutant removal in bioremediation. This process utilizes living organisms (such as bacteria, fungi, or plants) to degrade or remove environmental pollutants. It is a sustainable and eco-friendly approach to remediate contaminated sites. These materials have been intentionally engineered or manipulated at the nanoscale to exhibit unique properties due to their small size and high surface area. Nanostructured materials can be used to enhance various processes, including bioremediation. By incorporating nanostructured materials into bioremediation processes, the goal is to improve pollutant removal's overall performance and efficiency. This can involve faster degradation rates, higher pollutant adsorption capacity, and more targeted delivery of active agents to contaminated areas [14].Phytoremediation and constructed wetlands are innovative and sustainable approaches to mitigate environmental pollution, particularly in industrial settings. These methods harness the natural abilities of plants and wetland ecosystems to remove, degrade, or immobilize contaminants from soil, water, and air. They offer cost-effective and environmentally friendly alternatives to traditional remediation techniques. Phytoremediation is the use of plants to remediate contaminated environments. Plants can absorb, accumulate, and transform pollutants through phytoextraction, phytostabilization, biodegradation, and rhizofiltration. Different types of plants have specific mechanisms for dealing with various pollutants, making them valuable tools for cleaning up contaminated sites [15].

4. Hybrid Approaches: Integrating Bioremediation with Industrial Operations

Combining bioremediation with traditional treatment methods involves using biological processes alongside conventional techniques to enhance the cleanup of contaminated environments. Bioremediation utilizes living organisms, such as bacteria, fungi, and plants, to degrade or neutralize pollutants, while traditional methods encompass physical, chemical, or mechanical treatments. This combined approach capitalizes on the strengths of both methods to achieve more effective and sustainable remediation outcomes. Complementary Processes: Bioremediation and traditional treatment methods often target contaminants through different mechanisms. Bioremediation relies on the metabolic capabilities of microorganisms to break down or transform pollutants into less harmful substances. Traditional methods, on the other hand, might involve techniques like soil excavation, physical separation, chemical oxidation, or stabilization. By using both approaches together, you can effectively address a broader spectrum of contaminants and tailor the treatment to the specific site conditions [16].

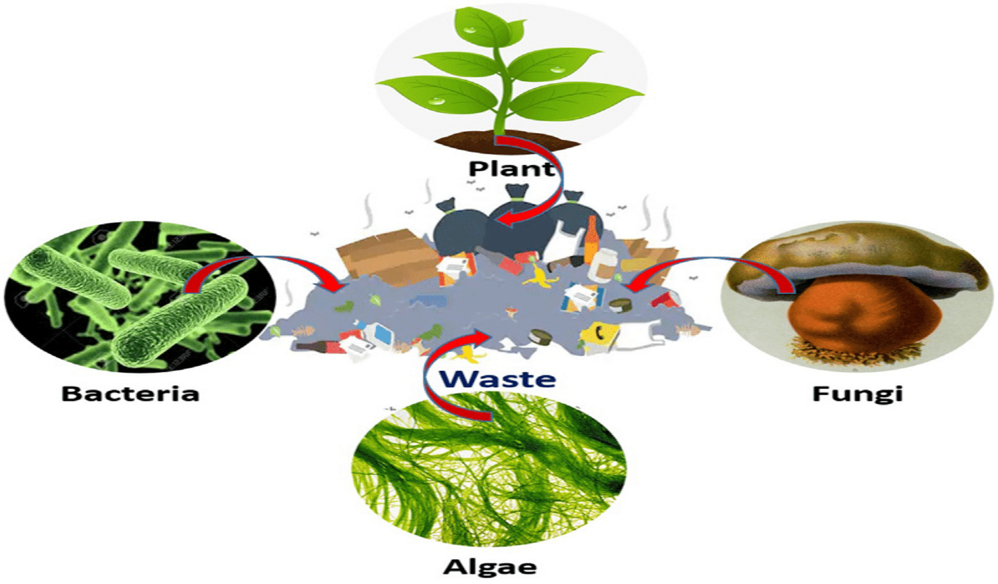
Hybrid systems refer to a combination of different technologies, processes, or approaches that work together to achieve improved performance, efficiency, and optimization. In various fields, including engineering, energy, and business, hybrid systems have shown significant advantages. Three key benefits of hybrid systems are increased efficiency, reduced costs, and process optimization. Hybrid systems often leverage the strengths of different components to enhance overall efficiency. By integrating complementary technologies or processes, these systems can achieve better results than their individual components alone. For instance, in the context of renewable energy, hybrid systems combining solar and wind power generation can provide a more consistent energy output by capitalizing on the variable nature of both sources [17]. This improved efficiency is due to the synergy of the combined system. Cost reduction is a major advantage of hybrid systems. By optimizing the utilization of resources and minimizing waste, hybrid approaches can lead to substantial cost savings. A study in the field of transportation suggests that hybrid electric vehicles (HEVs) offer lower operating costs compared to traditional internal combustion engine vehicles due to improved fuel efficiency and regenerative braking [18]. The integration of renewable energy sources like solar and wind with traditional power sources can also lead to cost savings in the energy sector by reducing reliance on fossil fuels [19]. Hybrid systems allow for the optimization of processes by combining different methodologies to achieve optimal results. In industrial settings, combining physical processes with advanced data analytics and automation technologies can lead to better production outcomes. For example, the integration of Industry 4.0 principles, which involve the digitalization and interconnectivity of manufacturing processes, can lead to optimized production processes, reduced downtime, and improved product quality [20].

5. Bioremediation Technique for Wastewater Treatment
6. In bioremediation, living organisms, such as microorganisms (bacteria, fungi, and
7. algae) or plants, are used to degrade and detoxify the hazardous pollutants present
8. in the environment and convert them into CO
9. 2
1 0 . , H
11. 2
12. O, microbial biomass, and
13. metabolites (by-products which are less toxic than the parent compound), as
14. shown in Fig. 1.1. These microorganisms can be indigenous to that contaminated
15. site or may be isolated and brought from outside to that contaminated site for bio-

16. remediation. Microorganisms degrade and transform these pollutants through their
17. metabolic reactions and utilize them for their growth. Complete degradation of a

In bioremediation, living organisms, such as microorganisms (bacteria, fungi, and algae) or plants, are used to degrade and detoxify the hazardous pollutants present in the environment and convert them into CO2, H2O, microbial biomass and metabolites (by-products which are less toxic than the parent compound), as shown in Fig. 1.1. These microorganisms can be indigenous to that contaminated site or may be isolated and brought from outside to that contaminated site for bioremediation. Microorganisms degrade and transform these pollutants through their metabolic reactions and utilize them for growth. Complete degradation of a pollutant requires the action of several microbes; therefore, potential microbes can sometimes be added to the contaminated site for the effective degradation process, which is called bioaugmentation.

The biodegradation process depends on favorable environmental conditions, the pollutant type and solubility, and the bioavailability of the pollutant to the microbes; the environmental conditions are controlled or manipulated to allow sufficient microbial growth and, thus, fast and effective biodegradation.



Bioremediation is a technique that utilizes living organisms, such as bacteria, fungi, or plants, to degrade or remove pollutants from contaminated environments, including wastewater. In the context of treating inorganic pollutants from wastewater, bioremediation offers a sustainable and environmentally friendly approach. It can be achieved through different mechanisms, such as bioaccumulation, biosorption, and microbial transformation.

17.1. Bioaccumulation and Bioconcentration

Bioaccumulation and bioconcentration are techniques that involve the uptake and accumulation of pollutants, including inorganic pollutants, by living organisms, often in the context of wastewater treatment. These techniques leverage the natural ability of certain organisms to concentrate pollutants from their environment, thereby providing a potential method for removing pollutants from wastewater. Bioaccumulation refers to the process by which pollutants accumulate in the tissues of living organisms over time. This can occur through direct uptake from the surrounding environment, such as water, or through the organisms' diet. In the context of wastewater treatment, certain microorganisms, plants, and even some aquatic animals have the ability to accumulate and store inorganic pollutants like heavy metals (e.g., lead, cadmium, mercury) from wastewater. Bioconcentration is a similar process but specifically refers to the increase in pollutant concentration in an organism's tissues compared to the concentration in the surrounding environment. Bioconcentration factors (BCFs) are used to quantify the extent of this process [21].

In the context of wastewater treatment, these techniques can be utilized in constructed wetlands, bioremediation systems, and even in aquaculture setups to remove inorganic pollutants from wastewater. Microorganisms and plants with metal-accumulating capabilities can be employed to actively uptake and store pollutants. The harvested plants or organisms can then be removed from the treatment system, effectively removing the pollutants along with them.

17.2. Biosorption

"Biosorption" is a technique used for removing inorganic pollutants from wastewater using biological materials, such as various types of biomass (e.g., algae, bacteria, fungi) or waste byproducts from agricultural or industrial processes. This method takes advantage of the natural affinity that certain biological materials have for binding to specific pollutants, effectively pulling these pollutants out of the wastewater and onto the surface of the biomass. Biomass is collected and prepared for use. This may involve washing, drying, and grinding the biomass to increase its surface area and expose binding sites. The prepared biomass is then brought into contact with the wastewater containing the inorganic pollutants. Through various mechanisms, such as ion exchange, complexation, and electrostatic interactions, the pollutants bind to the surface of the biomass. Once the pollutants are adsorbed onto the biomass, the next step is to separate the loaded biomass from the treated wastewater. Depending on the type of biomass and pollutants, different separation techniques can be used, including filtration, sedimentation, and centrifugation. The biomass can be regenerated and reused in subsequent treatment cycles. After the separation, the biomass that is loaded with pollutants can either be disposed of safely or, in some cases, further processed to recover the valuable metals or materials present in the pollutants. This can potentially turn the pollutant removal process into a resource recovery opportunity. The advantages of biosorption include its cost-effectiveness, simplicity, and potential for using waste materials as sorbents. However, there are limitations to consider, such as biomass availability, the need for regular regeneration of the sorbent, and potential competition between different ions for binding sites on the biomass [21].

17.3. Microbial Transformation

Microbial transformation is a technique that utilizes microorganisms such as bacteria, fungi, or algae to transform or remove pollutants from various environments, including wastewater. In the context of inorganic pollutant extraction from wastewater, microbial transformation involves the metabolic activities of these microorganisms to either convert the pollutants into less harmful forms or accumulate them within their biomass. This environmentally friendly technique can be a sustainable approach to treating wastewater contaminated with heavy metals and other inorganic pollutants. Microorganisms possess a property called biosorption, where they can accumulate heavy metals and other pollutants onto their cell surfaces. This occurs due to functional groups on the microbial cell surfaces like carboxyl, amino, and phosphate groups. These groups can bind to metal ions, effectively removing them from the water. The accumulated pollutants can then be harvested along with the biomass of the microorganisms. Some microorganisms can facilitate bioreduction, which enzymatically converts highly toxic metal ions into less toxic or insoluble forms. For instance, some bacteria can reduce toxic hexavalent chromium (Cr(VI)) to less toxic trivalent chromium (Cr(III)). Microorganisms can also induce the precipitation of metal ions in the form of metal sulfides or other insoluble compounds, which can be easily separated from the water. This process is called biomineralization and is particularly effective for removing heavy metals. Certain microorganisms can accumulate high concentrations of metals within their cells without being adversely affected. This phenomenon is used to extract and recover valuable metals from wastewater [22].

18. Future Prospects and Emerging Trends

The "Role of artificial intelligence (AI) and machine learning (ML) in optimizing bioremediation" involves the application of advanced computational techniques to enhance the efficiency and effectiveness of bioremediation processes, particularly in treating inorganic pollutants from wastewater. Bioremediation is a sustainable technique that uses microorganisms to break down or transform pollutants into less harmful substances. AI and ML can play a significant role in the context of inorganic pollutant treatment from wastewater. AI and ML algorithms can analyze complex datasets to predict the behavior of microorganisms and their interaction with pollutants. This information helps in optimizing the conditions required for efficient pollutant removal. AI can assist in determining the optimal environmental conditions (such as pH, temperature, and nutrient levels) for the growth and activity of specific microorganisms involved in pollutant degradation. ML algorithms can continuously analyze real-time sensor data and adjust the real-time conditions to ensure optimal performance. AI and ML can perform sensitivity analyses to identify which parameters significantly impact the bioremediation process. This information guides researchers and operators in focusing on the most critical factors. ML algorithms can identify patterns in microbial activity and pollutant concentrations over time, helping to understand the dynamics of the bioremediation process and detect any anomalies or deviations from expected behavior. AI-powered decision support systems can provide real-time recommendations for adjusting operational parameters, such as aeration rates or nutrient supplementation, based on the current state of the bioremediation system. AI and ML can assist in selecting the most suitable microorganisms for a specific type of pollutant removal based on their genetic and metabolic characteristics. These technologies can assess the potential risks associated with bioremediation, such as releasing harmful byproducts, and provide strategies to mitigate those risks. AI can integrate data from various sources, such as genetic information, pollutant concentration measurements, and environmental conditions, to provide a comprehensive view of the bioremediation process. ML algorithms can learn from historical data and adapt over time to improve pollutant removal efficiency based on changing conditions. AI and ML techniques accelerate optimization, reducing the need for extensive trial and error experiments and making the overall bioremediation process more cost-effective.

Decentralized treatment systems refer to wastewater treatment approaches that are smaller in scale and located closer to the source of pollution, such as industrial facilities, rather than relying on a centralized municipal treatment plant. These systems offer several advantages, including reduced transportation costs, flexibility in treating specific pollutants, and the ability to address local environmental concerns.

In treating inorganic pollutants from industrial wastewater, decentralized treatment systems can effectively mitigate the negative impact of pollutants such as heavy metals (e.g., lead, mercury, cadmium), metalloids (e.g., arsenic), and other inorganic compounds. AOPs involve the generation of highly reactive hydroxyl radicals (·OH) to oxidize and break down complex and persistent pollutants into more straightforward, less harmful compounds. Techniques like ozone (O_3) treatment, ultraviolet (UV) photocatalysis, and Fenton reaction can be employed in decentralized systems to treat inorganic pollutants. EC involves passing an electric current through wastewater to destabilize and aggregate pollutants, forming larger particles that can be more easily removed. This technique effectively removes heavy metals and suspended solids from wastewater. Ion exchange involves replacing undesirable ions in wastewater with other ions of similar charge in an exchange resin. This process is useful for removing specific ions like heavy metals from industrial wastewater. Various adsorbents, such as activated carbon or other specialized materials, can be used to adsorb inorganic pollutants onto their surfaces. This method is effective for removing heavy metals and metalloids from wastewater. These decentralized systems use natural processes involving plants, microorganisms, and soil to remove pollutants. They can be designed to effectively treat inorganic pollutants through processes like sedimentation, adsorption, and microbial degradation. Techniques like reverse osmosis (RO) and nanofiltration (NF) use semi-permeable membranes to remove ions and compounds from wastewater selectively. These membranes can be tailored to target specific inorganic pollutants. Microorganisms can sometimes be harnessed to convert or immobilize inorganic pollutants through biological processes. For instance, sulfate-reducing bacteria can treat sulfate-rich wastewater containing heavy metals.

Conclusion

Through an in-depth analysis of various bioremediation strategies, the article highlights the significant advancements in efficiently removing inorganic pollutants from wastewater, contributing to environmental sustainability and human well-being. In conclusion, the reviewed approaches underscore the remarkable potential of harnessing microbial processes and innovative technologies for tackling complex pollutants in industrial wastewater. From bioaugmentation to nanomaterial-based interventions, each method presents a unique set of advantages and challenges, paving the way for a diversified toolkit of solutions. However, the article also emphasizes the importance of considering site-specific conditions and regulatory frameworks when implementing these approaches, recognizing that a more than one-size-fits-all solution may not be viable. As industries continue to expand and diversify, the demand for effective wastewater treatment strategies grows in tandem. The insights provided in this review shed light on the dynamic landscape of inorganic pollutant bioremediation, inspiring further research, collaboration, and the integration of interdisciplinary expertise. By embracing these innovative approaches, stakeholders in environmental management can work towards a cleaner and more sustainable industrial future.

References

[1] Mishra, V. K., &Balomajumder, C. (2011). Review: Bioremediation: An eco-sustainable green technology—its applications and limitations. World Journal of Microbiology and Biotechnology, 27(6), 1209-1219.

[2] Kumar, A., Biswas, K., Bhowmick, S., &Maiti, S. (2021). Heavy metals removal from industrial wastewater: Current technologies and potential biotechnological approaches. Environmental Technology & Innovation, 23, 101735.

[3] Matilainen, A., Vepsäläinen, M., Sillanpää, M. (2010). Natural organic matter removal by coagulation during drinking water treatment: A review. Advances in Colloid and Interface Science, 159(2), 189-197.

[4] Shukla, P., &Dubey, S. (2019). Heavy metals contamination in water and its impact on human health: A critical review. Journal of Water Chemistry and Technology, 41(6), 363-372.

[5] Chen, H., Teng, Y., & Lu, S. (2015). Environmental Geochemistry of Heavy Metals in Soils of Foshan City, Pearl River Delta: Concentration, Source, and Health Risk. Environmental Monitoring and Assessment, 187(6), 349.

[6] Miretzky, P., &Cirelli, A. F. (2010). Hg(II) Removal from Water by Floating Macrobiofilms of Bacillariophyceae Diatom. Chemical Engineering Journal, 165(2), 585-594.

[7] Das, S. K., Das, A. R., &Guha, A. K. (2017). Heavy Metals and Their Impact on Environment: A Review. International Journal of Current Research in Biosciences and Plant Biology, 4(7), 46-54.

[8] World Health Organization (WHO). (2011). Guidelines for Drinking-Water Quality (4th ed.). Retrieved from https://www.who.int/publications/i/item/9789241548151

[9] Kennes, C., &Veiga, M. C. (2001). Waste gases and waste waters: assessment and treatment. In Biotechnology for the Environment (pp. 3-27).Springer.

[10] United Nations Environment Programme (UNEP). (2016). Marine and Coastal Ecosystems and Human Well-being: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment.

[11] Van Hamme, J. D., Singh, A., & Ward, O. P. (2003). Recent advances in petroleum microbiology. Microbiology and Molecular Biology Reviews, 67(4), 503-549.

[12] Rabaey, K., &Rozendal, R. A. (2010). Microbial electrosynthesis — revisiting the electrical route for microbial production. Nature Reviews Microbiology, 8(10), 706-716.

[13] Santoro, C., & Li, B. (2015). Bioelectrochemical systems for energy production from organic wastes: a review. Waste Management, 35, 41-58.

[14] Logan, B. E., &Rabaey, K. (2012). Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. Science, 337(6095), 686-690.

[15] Meagher, R. B. (2000). Phytoremediation of toxic elemental and organic pollutants. Current Opinion in Plant Biology, 3(2), 153-162.

[16] Sarkar, D., Ferguson, M., Datta, R., & Birnbaum, S. (2019). Bioremediation of petroleum hydrocarbons in cold regions.In Polar and Alpine Microbiology (pp. 437-450).Springer, Cham.doi: 10.1007/978-3-030-05759-8_20

[17] S. Islam et al., "A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications," Renewable and Sustainable Energy Reviews, 16(1), 2012. [DOI: 10.1016/j.rser.2011.07.143]

[18] K. A. Kromer, J. B. Heywood, "Electric and Plug-In Hybrid Vehicle Greenhouse Gas Emissions: A Life-Cycle Study," Transportation Research Part D: Transport and Environment, 14(1), 2009. [DOI: 10.1016/j.trd.2008.10.003]

[19] J. N. Sahu, P. K. Sahu, "A review on hybrid renewable energy sources for sustainable energy generation in smart cities," IOP Conference Series: Earth and Environmental Science, 293(1), 2019. [DOI: 10.1088/1755-1315/293/1/012031]

[20] L. Wang et al., "Towards smart manufacturing: A new business model for Industry 4.0," Journal of Manufacturing Science and Engineering, 141(5), 2019. [DOI: 10.1115/1.4043590]

[21] Pinto, A. P., &Louvado, A. (2019). Bioaccumulation and bioremediation potential of heavy metals in aquatic plants.In Aquatic Plants (pp. 211-236).IntechOpen.

[22] Gomes, H. I., Dias-Ferreira, C., &Ribeiro, A. B. (2019). Removal of inorganic pollutants from water using microorganisms: A review. Science of the Total Environment, 671, 906-926. doi:10.1016/j.scitotenv.2019.03.396