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MICROBIAL BIOREMEDIATION OF INDUSTRIAL WASTEWATER CONTAMINATED WITH TOXIC HEAVY METALS

Venkanna Jeedi
Research Scholar, Jayoti Vidyapeeth Women's University, Jaipur, Rajasthan

Dr. Nidhi Goyal
Research Supervisor, Jayoti Vidyapeeth Women's University, Jaipur, Rajasthan

ABSTRACT

Industrial wastewater contaminated with toxic heavy metals represents a serious environmental challenge because metals such as lead, cadmium, chromium, mercury, nickel, and copper are persistent, non-biodegradable, and capable of accumulating in living organisms. Conventional physicochemical treatment methods can be costly and may generate secondary pollutants. Microbial bioremediation provides an eco-friendly and sustainable alternative by utilizing microorganisms such as bacteria, fungi, algae, and yeast to remove or transform heavy metals from contaminated wastewater. Microbial mechanisms include biosorption, bioaccumulation, bioprecipitation, oxidation-reduction reactions, and enzymatic transformation. These processes can reduce metal toxicity and improve wastewater quality under suitable environmental conditions. The present study focuses on the potential of microorganisms for the remediation of toxic heavy metals in industrial wastewater and examines their major mechanisms, influencing factors, and practical applications. Microbial bioremediation offers significant advantages in terms of environmental compatibility, cost effectiveness, and sustainability, making it a promising approach for the treatment of heavy-metal-contaminated industrial wastewater.

KEYWORDS-Microbial bioremediation, Industrial wastewater, Heavy metals, Toxic metals, Biosorption, Bioaccumulation, Bio precipitation.

INTRODUCTION

The production of wastewater containing harmful heavy metals has grown due to industrialisation, which has greatly aided economic growth. Metals including lead, cadmium, chromium, mercury, nickel, and copper are released into aquatic ecosystems by industries like mining, electroplating, metal processing, textiles, batteries, and chemical production. Because they are long-lasting and resistant to biological degradation, these metals pose a significant threat to ecosystems and human health when they build up in water, sediments, and living things. Heavy metal removal using conventional techniques may be costly to operate, chemically intensive, and lead to secondary waste. Thus, a sustainable and eco-friendly option known as microbial bioremediation has arisen. Biosorption, bioaccumulation, bioprecipitation, and enzymatic reduction or oxidation is some of the ways that bacteria, fungus, algae, and yeasts may eliminate or change heavy metals. While lowering environmental concerns, this technique may effectively remove metals. Therefore, there is great hope for the long-term treatment of industrial wastewater polluted with heavy metals by microbial bioremediation.

REVIEW OF LITRETURE

Jyothirmayee, Kola Pratap & Krishnan, Kannabiran (2024) The contamination of soil, water, and the environment with heavy metals is a major threat to human health. Because they do not break down naturally, they end up in the environment and food chain, where they may harm plants, animals, and water systems. Traditional physiochemical techniques have a number of drawbacks and are harmful to the environment. As an alternative, bioremediation is a natural, effective, fast, and safe way to remove harmful heavy metals from the environment. A wide variety of microbial bioremediation (MBR) processes exist, including oxidation/reduction, biosorption, biomineralisation, biotransformation, bioaccumulation, bioprecipitation, biocrystallization, bioleaching or biomining, bioaugmentation, biofilm formation, biosurfactant production, and nanoparticle immobilisation, all of which show great promise for the efficient removal of harmful heavy metal pollution. This review focuses on the latest developments in heavy metal biodegradation technologies, microbial bionano remediation (MBNR), and bioremediation (BR) as well as the metagenomics approach to screening bacteria for new genes implicated in these processes. Heavy metal contamination in soil and water is addressed, along with potential developments in BR and MNBR techniques for efficient removal, degradation, and control of this problem.

Reddy, Kondakindi et al., (2024) Air pollution from heavy metals (HM) is a major problem for ecosystems. Physical and chemical treatments, which have long been used to remove HM-contaminated locations, have their drawbacks when it comes to efficiency, cost, and environmental effect. Consequently, bioremediation and other sustainable alternatives are gaining attention. Bioremediation is an exciting new field that harnesses microbes' natural power to break down or change contaminants into safer versions. Their capacity to interact with heavy metals and their distinct physicochemical characteristics have made microbial exopolysaccharides attractive candidates for use in bioremediation techniques. An overview of the function of microbial extracellular polymeric substances (EPS) in bioremediation of locations polluted with HM is the goal of this study. One of the first things that will be covered is how EPS helps with heavy metal sequestration. To lessen the bioavailability and toxicity of heavy metals, EPS may create metal-complexing agents such chelators and ion-binding sites. These agents improve the immobilisation and precipitation of heavy metals. EPS has the potential to form a barrier that prevents microbes from being stressed by heavy metals, allowing them to survive and even thrive. Bioremediation methods may be more effective if EPS synthesis is initiated or augmented in response to heavy metal exposure.

Abo-Alkasem, Mohamed et al., (2023) As a consequence of the industrial revolution, there is a growing need to develop new technologies that can prioritise the elimination of heavy metals entirely. Researchers discovered that bioremediation significantly reduced the amount of both organic and inorganic contaminants in the environment. Bioremediation, in its main body, is an interdisciplinary field that has shown to be a cost-effective, efficient, and safe technique. The in-situ treatment, which decreases the likelihood of spreading the toxins to another location, is another key element of bioremediation technique. Among the most exciting new developments in bioremediation is the use of genetic engineering to create transgenic plants or microorganisms with the capacity to remove several heavy metals simultaneously. To sum up, ecologists still face a significant difficulty when it comes to removing heavy metal pollution. This study aimed to shed light on bioremediation technology, including its significance, mode of action, and potential.

Sharma, Pallavi et al., (2023) Bioremediation is a new and exciting field of technology that uses microorganisms to remove hazardous contaminants from polluted areas, therefore reducing pollution levels. The air, water, and land all contribute to the environment's complicated factors. Humans and all other forms of life, including plants, animals, and bacteria, are here because of the positive connection that the environment makes. Pollution of the air, land, and water—essential components of human existence—has resulted from technological progress in industrialised nations. Management of groundwater resources in emerging nations is becoming more difficult due to the world's growing population, increased urbanisation, and fast industrialisation. As a result of these causes, the whole environment is now polluted due to the massive volumes of solid waste produced in a variety of harmful forms. The use of living creatures, namely microorganisms, to detoxify polluted water and soil is known as bioremediation, and it's an exciting new field of study. It calls for a method to identify species that can absorb or secrete enzymes that can break down these contaminants. The use of biological materials in bioremediation techniques allows for the direct application at the site of contamination, eliminating the need to transport contaminating materials. This makes them more effective than conventional tactics. Biodegradation may be achieved in bioremediation using either bacterial alone, bacterial consortia, or a mix of bacteria and algae, fungi, etc.

Kuzmanović, Ana et al., (2021) Because metal ions are persistent, bioavailable, and poisonous, heavy metal contamination is a major environmental hazard. Environmental cleanup has long made use of a wide variety of tried-and-true physical and chemical methods. The employment of live organisms, also known as bioremediation, is on the rise as an alternative to traditional approaches, which have a number of disadvantages. Numerous microbial strains have been shown to be effective in eliminating heavy metals, and the biotechnological use of microbes is both established and constantly evolving. This study outlines the interactions between microorganisms and heavy metals and gives an overview of their major properties. The article outlines the primary concepts and kinds of heavy metal bioremediation technologies, including specifics on pilot size bioreactor experiments that were effective, and it goes on to define important processes by which microorganisms resist these metals. Because they have evolved to survive in contaminated settings and have developed resistance mechanisms, native bacteria should get extra care when they are extracted from such sites. Using bacterial biofilms or consortia might be beneficial since they have more tolerance and can use many metabolic routes, which means they can potentially remove multiple heavy metals at once. Nanotechnology, genetic engineering, metagenomics, and other cutting-edge technologies are being used to enhance bioremediation processes, as discussed in this article. In conclusion, bioremediation offers a promising strategy for environmental clean-up.

APPLICATION OF IMMOBILIZED MICROORGANISMS AND BIOREACTOR SYSTEMS FOR WASTEWATER TREATMENT

Toxic heavy metal-contaminated industrial wastewater may now be effectively and sustainably treated using bioreactor systems that use immobilised microorganisms. Microorganisms like bacteria, fungus, algae, or mixed microbial cultures may be immobilised by entrapping or attaching them to appropriate supporting materials in a way that preserves their biological activity. Sequestration, adsorption, encapsulation, cross-linking, and covalent attachment are some of the most common methods for immobilisation. To create an environment conducive to microbial growth, materials may be used, including alginate, agar, activated carbon, silica, charcoal, polymeric matrices, and porous ceramics. Biosorption, bioaccumulation, biotransformation, precipitation, and enzymatic reduction are some of the mechanisms by which immobilised microbes may detoxify heavy metals. It is simpler to separate them from treated water, they are more resistant to harmful metal concentrations, they may be used again or continuously, and they are more stable for microbes than free microbial cells. Because bioreactors provide regulated environments for microbial activity, they significantly improve the efficacy of immobilised microbial therapy. An assortment of reactor designs may be tailored to meet the specific needs of wastewater treatment, including as packed-bed, fluidized-bed, continuously stirred tank, membrane, and sequencing batch bioreactors. Contaminated wastewater may travel through the reactor and interact with the active biomass in packed-bed systems because the immobilised biomass is maintained inside a fixed support material. Because the support particles in a fluidized-bed reactor are continually suspended, it increases the amount of contact time that wastewater has with immobilised microorganisms. The effectiveness of a treatment is greatly affected by operational parameters such temperature, pH, hydraulic retention duration, dissolved oxygen, nutrition availability, starting metal concentration, and microbial loading. If these parameters are optimised correctly, the effectiveness of metal removal may be enhanced while the microbial activity is maintained. Continuous industrial wastewater treatment is a potential use for immobilised microbial bioreactors due to its ability to decrease biomass washout and enable long-term operation. Problems including blockage, limited mass transfer, support degradation, suppression of microbes, and replenishment of depleted biomass must be resolved, however. In conclusion, a greener, more cost-effective, and time-saving way to lessen the presence of harmful heavy metals in industrial effluent is to combine microbial immobilisation with state-of-the-art bioreactor technology.

FACTORS AFFECTING BIOREMEDIATION EFFICIENCY, CHALLENGES, AND FUTURE PROSPECTS

Several biological and physicochemical parameters determine how well microbes can remediate heavy metal-contaminated industrial effluent. The availability of functional groups involved in metal binding, surface charge, microbial growth, and metal solubility are all affected by pH, making it one of the most crucial factors. Biosorption and biotransformation rates, as well as metabolic activity in microbes, are temperature dependent. Heavy metals may hinder microbial growth and metabolic activities at high concentrations, therefore their initial concentration and chemical form can greatly impact clearance effectiveness. various bacteria, fungus, and algae have various metal-binding capabilities and resistance mechanisms, thus it's necessary to consider both the kind and density of microorganisms. In addition to these factors, microbial performance may be affected by organic matter, dissolved oxygen, salinity, nutrient availability, and hydraulic retention time. The elimination of some pollutants may be facilitated or impeded by interactions between certain metals. Practical wastewater treatment presents a number of obstacles for microbial bioremediation, notwithstanding its promise. Microbes may experience decreased biomass activity or cell death if toxic metal concentrations above their tolerance limits. Treatment stability and repeatability may be impacted by variations in the content of industrial effluent as well. Large-scale applications may be constrained by mass-transfer restrictions, microbial contamination, biomass separation, and the challenges of sustaining active microbial populations during long-term operation. Biosorption also has the potential to move metals from water to biomass instead of completely removing them, which means there has to be a way to regenerate, recover, or dispose of biomass in a safe manner. Immobilised microbial systems with greater stability, microbial consortia, genetically or metabolically modified microorganisms, and strains of microbes resistant to metals are all areas that might be explored in the future. Bioremediation could be even more effective if combined with nanotechnology, biochar, electrochemical processes, membrane filtration, and adsorption. To optimise microbial activity and enable improved management of environmental conditions, advanced bioreactors integrated with automated process control and real-time monitoring are being considered. Predicting treatment success under complicated wastewater circumstances and identifying efficient microorganisms may also be possible with the use of omics technology and artificial intelligence. Reliable, scalable, cost-effective, and ecologically sustainable heavy metal bioremediation systems will need a combination of biological treatment with complementing technologies to overcome current operational limits.

CONCLUSION

When it comes to cleaning industrial wastewater that has been polluted with harmful heavy metals, microbial bioremediation is a viable, long-term, environmentally safe option. By using biosorption, bioaccumulation, biotransformation, precipitation, and enzymatic activities, microbial therapy is able to decrease metal pollution with very few secondary pollutants, in contrast to many traditional physicochemical techniques. Metals including lead, cadmium, chromium, mercury, nickel, and copper may be tolerated and removed by a wide variety of bacteria, fungus, algae, and microbial consortiums. Continuous wastewater treatment is possible with the help of bioreactor systems and immobilised microorganisms, which increase treatment efficiency, operational stability, and biomass recovery even further. But you have keep a tight rein on things like pH, temperature, metal content, microbe activity, nutrient availability, and the makeup of the wastewater. There are still issues with toxicity, managing biomass, scaling up, and long-term stability. Performance may be improved by future integration with biotechnology, automated treatment systems, and sophisticated materials. When it comes to improving environmental protection and removing heavy metals in a sustainable manner, microbial bioremediation is a promising option.

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