Review Article

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Eco-Restorative Solutions: Unveiling Bioremediation's Impact on Water Quality Enhancement

Niki Desai*, Hetal Chenva, Ganesh Parmar and Varda Mehta
Department of Life Sciences, Hemchandracharya North Gujarat University, Patan, GJ, India
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*desainikky4@gmail.com

ABSTRACT

As a result of the world's growing industrialization and urbanization, developing nations have the densest populations worldwide. Due to numerous anthropogenic activities, this population growth has resulted in the generation of huge quantities of waste and reclaimed water. The main challenge is creating approaches so that they support wastewater treatment. Therefore, bioremediation is regarded as one of the most environmentally friendly, economical, safer and cleanest technologies for cleaning up sites contaminated with a variety of contaminants, including heavy metals, inorganic pollutants, organic pollutants, oil spill, dye and pesticides. The use of microorganisms found in nature, such as bacteria, fungus, and microalgae has emerged as an ecofriendly method. Using their unique molecular biodegradation pathways, novel bioremediation organisms offer innovative and useful insights. Enzymes, metabolites, and other bioactive chemicals produced by bacteria involved in water treatment can be identified primarily through the use of metagenomics techniques. This review speeds up research on the role of bioremediation in water purification while also providing a brief discussion of the environmental effects of water pollution.

Keywords: Bioremediation; Metagenomics; Water pollution; Contamination.

1. INTRODUCTION

Considering the growing shortage of water resources in the twenty-first century, water quality is an essential issue. Degradation of water quality frequently has severe effects on ecosystems, public health, and the economy, as well as harms society and the environment. It can be caused by natural phenomena, such as global warming, extreme weather events, or anthropogenic activities, such as pollution and resource over-exploitation (Pacheco *et al.* 2020). Improving water quality is a major priority of the 2030 Agenda and Sustainable Development Goals, since it is acknowledged as a global issue that needs to be addressed on a global scale to support society's sustainable development (Menger-Krug *et al.* 2012; Mohamad *et al.* 2017; Pacheco *et al.* 2020). For all living things to survive, water is necessary. Humans require water not just to survive but also to do their everyday activities. However, the introduction of various hazardous and deadly chemicals into water sources nowadays renders clean water inaccessible to humans. In addition to this vital need of the modern world, another difficulty is dealing with the wastewater or effluent that is produced (Puyol *et al.* 2017; Sakhuja *et al.* 2020; Bhatia *et al.* 2020). People's quality of life on Earth is directly affected by the overall state of water resources. Water needs in the home are estimated to be at least 7.5 liters per person per day for drinking, cooking, and personal hygiene. At least 50 gallons per person per day are needed to cover all needs for personal hygiene, laundry, housecleaning, and food hygiene (Cheng, 2014). A major concern for humanity in the twenty-first century is poor quality of water (Gernaey *et al.* 2004). A vast array of chemical compounds are introduced into the aquatic environment when untreated or inadequately treated wastewater is released into rivers, lakes, aquifers, and coastal waters. These compounds can affect aquatic organisms directly by causing negative effects or indirectly by changing some of the physicochemical characteristics of the medium (such as pH, redox potential, oxygen concentration, and nutrient concentration) (Menger-Krug *et al.* 2012; Mohamad *et al.* 2017; Pacheco *et al.* 2020). In general, organic chemical contamination, inorganic compound contamination, and microorganism contamination are the three main categories of water pollution, which is a significant worldwide issue (Ojha *et al.* 2021). As a result, the amount and kind of waste generated and released in water bodies that are natural have been taken into account and the necessity of various approaches to address issues with water quality in the affected areas has been emphasized (Ojha *et al.* 2021). Intentional or unintentional oil spills have a significant influence on environmental damage (Safiyanu *et al.* 2015). An important environmental risk has been identified as resulting from both nearby and distant oil spills and oil tanker spills. The habitat of fish, marine mammals, and seabirds is thought to be destroyed by the oil leak (Safiyanu *et al.* 2015). Ecosystems are severely harmed by oil spills, which also increase the risk of fire, ground water contamination via seepage, and air pollution from evaporation (Safiyanu *et al.* 2015). The physical and chemical content of contaminants varies depending on where they originate. They are frequently produced by home, agricultural, and industrial effluents (Emparan *et al.* 2019; Wollmann *et al.* 2019; Pacheco *et al.* 2020) metals and nutrients like phosphate (Chowdhury *et al.* 2016) and nitrate (Menció *et al.* 2016) are the most commonly discovered substances. Further, because conventional wastewater treatment plants (WWTP) are not yet equipped and suitable to remove these new contaminants, the occurrence of emerging organic and inorganic pollutants, such as microplastics (Eerkes-Medrano *et al.* 2019) pharmaceuticals (Muñoz *et al.* 2009), flame retardants (Sutherland *et al.* 2019), personal care products (Norvill *et al.* 2016), hazardous and noxious substances (Wang *et al.* 2016) has been increasing. Tanneries, distilleries, and pulp and paper are a few of the quickly expanding sectors that pose significant environmental dangers (Jayakumar *et al.* 2016; Tripathi *et al.* 2021). The wastewater produced by the Indian tannery, pulp and paper, and distillery industries was roughly 25,000 kilolitres per day (KPD), 50,000 m^3 per day, and 5–10 million per day, with significant levels of organic contaminants (Wang *et al.* 2016; Tripathi *et al.* 2021). By far the biggest threat to the atmosphere and living things is industrial heavy metal release. Large volumes of wastewater released by industry have the potential to contaminate groundwater, sediments, and aquatic life (Sharma *et al.* 2021a). One of the major hazards to the ecosystem is water contamination from dye spills from the textile sector (Ihsanullah *et al.* 2020). Since they cause cancer, dyes in water, even at low amounts, can have a negative effect on the ecosystem. Adsorption, filtration, flocculation, coagulation, precipitation, oxidation, ion-exchange, microbial degradation, and membrane separation are a few of the physicochemical and biochemical treatment methods that have been tried to treat textile effluents. Several traditional technologies have inherent drawbacks and restrictions, including low efficiency, high operating costs, complex procedures, large volumes of sludge produced, and limited commercial (Ihsanullah *et al.* 2020). The industrial revolution states that extensive use of pollutants leads to dangerous health issues. In addition to bringing their undesirable companions along, industrial and technical advancements also pollute and degrade the environment. Toxic gasses, chemicals, and xenobiotics are released into the environment both purposefully and unintentionally as a result of these revolutions. Human health will be impacted by the ongoing problem of environmental pollution. This problem nevertheless remains concerning even after many methods have been employed to identify and resolve it. These risks have an impact on the environment and people everywhere. To protect people and the environment from the harmful consequences of environmental contamination, one of the cutting-edge technologies that should be developed is bioremediation (Raghunandan *et al.* 2014; Raghunandan *et al.* 2018).

2. Principle of Bioremediation

Bioremediation is a more efficient and environmentally friendly method of eliminating pollutants from the environment (Saikia *et al.* 2005; Tegene *et al.* 2020). This approach to removing dangerous pollutants is typically less expensive. The concept of bioremediation is a contemporary and optional approach to managing environmental pollution. It involves the use of byproducts of microorganisms to break down, eliminate, immobilize, or detoxify various chemical wastes and physically harmful substances from the surrounding habitat. Biological agents, such as yeast, actinomycetes, fungus, and bacteria, can be used in bioremediation to reduce or eliminate contamination (Seshadri *et al.* 2005; Tegene *et al.* 2020). Bioremediation requires three fundamental ingredients. These are the three elements: food, nutrients, and microbes. The bioremediation triangle is made up of these three essential elements. The most common missing component preventing successful bioremediation is a lack of food and nutrition. The food that microorganisms consume is found in the water or soil where they reside. But, if a contaminant is present, it may provide as an extra source of food for the microbes. For the microorganisms, the contamination fulfills two beneficial functions. To begin with, the contamination offers a supply of carbon that is required for growth. Second, the microorganisms transfer electrons from the pollutant and break chemical bonds to obtain energy. This type of reaction is called oxidation-reduction. Although oxygen is the most common electron acceptor used by microbes, they can also frequently use nitrate, sulfate, iron, and CO_2 (Holliger *et al.* 1996). With differing degrees of success, bioremediation has been applied in several locations across the world, including Europe and North America. Undoubtedly, bioremediation holds significant promise in addressing specific forms of site contamination (Cheng *et al.* 2014). Wastes from industries contain a variety of biological and inorganic materials. Consequently, there is a critical need to create a natural system that can treat such wastewater by using multiple microbial strains, leading to the formation of a consortium (Tare *et al.* 2003; Sharma *et al.* 2021a). Microbial consortiums are extremely beneficial in bioremediation because they provide a more robust metabolic mechanism that may be sustained and used for pollution remediation. Within a complex waste site with multiple contaminants, every consortium member microbe will specifically rule out a specific metal. Consequently, it is possible to successfully and environmentally friendly remove several pollutants at once (Mishra *et al.* 2014; Sharma *et al.* 2021a) (Fig. 1). Depending on where the contaminated materials are treated, these treatment techniques are divided into two main categories: in situ and ex situ treatment. Ex situ technologies are those that transfer pollutants to an outside facility for treatment, whereas in situ bioremediation technologies treat pollutants where they are found and are thought to reduce material handling and expenses (Frascari *et al.* 2015; Okoh *et al.* 2020).

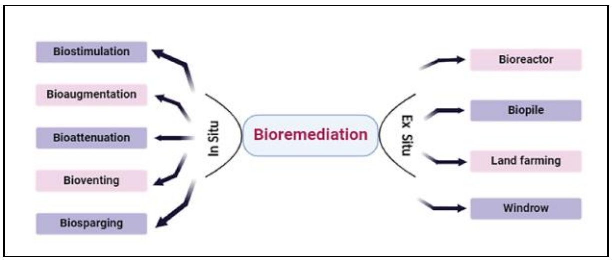

Fig. 1: Various bioremediation techniques

The numerous interactions among the following three factors are crucial to bioremediation: the environment factors, organisms, and pollutants. The ways in which these variables interact impact biodegradability, bioavailability, and physiological requirements all of which are critical in determining whether bioremediation is feasible. The most crucial factors influencing biodegradation processes include:

- Pollutant bioavailability: The way a pollutant interacts with its surroundings might alter its bioavailability, affecting how accessible it is to organisms that can break it down. The degree to which a pollutant is free to enter or adhere to an organism varies depending on the species and organism. This is known as bioavailability. The organic pollutant's bioavailability and the catabolic activity of microorganisms determine how organic pollutants are broken down in situ by bacteria.
- Salinity, pH, pressure, oxygen, temperature, water activity, nutrients, and moisture availability are environmental elements that impact bioremediation. These factors vary from site to site and act to restrict the growth of bacteria that break down contaminants. If unfavorable surroundings are present, bacteria either grow slowly or die, and pollutants are not removed. The availability of nutrients affects microbial breakdown and elimination of pollutants. This includes the enzymatic activity of the organisms that break down contaminants and the direct suppression of the growth process.
- The number of microorganisms and their catabolic potency determine the capacity of the soil microbial population to break down pollutants in a contaminated area (Kumar *et al.* 2018).

2.1 Bioremediation through Metagenomic Approach

In order to quickly investigate any sample, such as water or soil, for the advancement of sequencing technology, genomic analysis is a technique that is independent of culture. The last several decades have seen the development of next-generation sequencing (NGS), which has made it possible to analyze microbial communities in great detail using genomic, metagenomic, and bioinformatic techniques. This has provided previously unattainable insight into the primary bioremediation mechanisms (Sharma *et al.* 2021a). Nucleotide databases and in silico techniques are valuable resources for research on the role of microorganisms in pollution degradation and the identification of novel genes responsible for microbial remediation. Apart from providing fresh insights into the complexities of the affected area, metagenomic studies are an invaluable resource for analytical and graphical support when examining the connection between soil microbiota and environmental activities. The method known as "metabolomics" is used to examine genetic material that has been directly isolated from environmental samples. Thus, metagenomic uses sequence- and function-based research methodologies to reveal information on the microbial communities of non-cultivable organisms in a niche ecosystem (Sharma *et al.* 2021a).

In bioremediation, microbes are employed to remove pollutants from the environment (Malla *et al.* 2018). Handelsman et al. employed metagenomics for the first time in 1998. It is a relatively promising field of molecular biology (Handelsman *et al.* 1998). These techniques currently provide new insights into the world of microbes by expanding our understanding of the environments of non-culturable bacteria. Finding new ecosystems is made fascinating by the function-focused metagenomic technique, which promotes the discovery of new genes and provides genetic analysis (Tripathi *et al.* 2018). The bioremediation approach also includes the microbial diversity and particular genes identified by metagenomic research that may function as pollution biomarkers. With the aid of bioactive substances and enzymes that have been identified through metagenomics techniques, a variety of microorganisms play a significant role in the cleanup of contaminants. The discovery of bioactive substances, compounds, and enzymes produced by microbes involved in the treatment of water is greatly aided by the application of metagenomics techniques.

Numerous microorganisms, including bacteria and anaerobic-aerobic fungus, are involved in the bioremediation process. The complete application of microorganisms in the removal, immobilization, or detoxification of many types of pollutants from waste materials is the main focus of the field of bioremediation. (Sharma *et al.* 2021b). In a variety of damaged situations, metagenomic approaches can identify microbial species that are beneficial for bioremediation. Metagenomics is starting to incorporate a number of advances in life science understanding.

2.2 Bioremediation through Fungi

It is well known that fungi break down most organic compounds found in the environment. (Akerman-Sanchez *et al.* 2021). Additionally, because of their versatility, declining enzymatic capacities, and capacity to operate in a wide range of pH settings, bioremediation using fungi is superior to bioremediation using bacteria (Khursheed *et al.* 2011; Tomasini *et al.* 2019). Since the 1980s, soil and water bioremediation systems have made use of fungi, namely those in the White-Rot Fungi (WRF) family (Tomasini *et al.* 2019). Comprising an eco-physiological group of fungus with the ability to degrade lignin, the WRF is primarily made up of basidiomycetes (Hale *et al.* 1985; Rodríguez-Rodríguez *et al.* 2013). The lignin-modifying enzymes (LME) that this fungus group possesses are responsible for the degradation of lignin and the breakdown of wood (Rodríguez-Rodríguez *et al.* 2013). Pharmaceutical compounds (PhCs) are biodegraded by WRF fungus mostly by the action of LME, which uses oxidoreductase enzymes to chemically alter xenobiotic substances (Pointing *et al.* 2001; Gernaey *et al.* 2004; Dhouib *et al.* 2006),WRF enzymes are potentially useful instruments for the bioremediation of medications and antibiotics due to their diversity and non-specificity (Ryan *et al.* 2007; Ellouze *et al.* 2016; Haroune *et al.* 2017). Moreover, PhCs and other compounds can attach to the surface of WRF hyphae or internalize within the cell, whereupon they are kept rather than transported into the water, promoting biosorption and further water filtration (Khursheed *et al.* 2011; Tomasini *et al.* 2019). Moreover, the hyphal shape of WRF can aid in the biosorption of PhCs and other chemicals, which attach to their surface or internalize within the cell to be kept rather than carried into the water, helping to purify the water (Kumar *et al.* 2011; Lu *et al.* 2016).

2.3 Bioremediation through Microalgae

Microalgae are especially beneficial for bioremediation because they can use solar energy to create biomasses and absorb elements like nitrogen and phosphorus that contribute to eutrophication during photosynthesis (de la Noue *et al.* 1988). Microalgae's great capacity for inorganic nutrient uptake makes them an efficient and economical solution for the removal of pollutants and excess nutrients from tertiary wastewater, while also producing biomass that may have economic value (Bolan, 2004; Muñoz *et al.* 2006). According to (Zhang *et al.* 2008). Scendesmus sp. shown a high capacity for removing inorganic nutrients from synthetic residential secondary effluents. Because photosynthesis raises pH, phosphorus precipitation and NH3 stripping can also improve nutrient removal (Oswald, 2003). Physical adsorption is the rapid process by which metals are absorbed by algae by adsorption over their cell surface, occurring in a matter of seconds or minutes. After that, a process known as chemisorptions allows these ions to enter the cytoplasm gradually. According to (Chaisuksant *et al.* 2003) and (Akhtar *et al.* 2004), microalgae are effective heavy metal absorbers. Thus, the ability to absorb heavy metals has applications in the treatment of wastewater and other combinations of water samples, including well, sea, and sewage (El-Sheekh *et al.* 2016). When Chlorella pyrenoidosa was cultivated on sewage sludge, it produced a high protein content and the aqueous extract held relatively low levels of certain heavy metals, such as Cu^{2+}, Mn^{2+}, Fe^{2+}, and Zn^{2}.

2.4 Bioremediation through Microbes

Some organic contaminants are mineralized by microorganisms into products like CO_2 and H_2O or metabolic intermediates, which serve as the primary fuel for cell growth. Microorganisms maintain a two-way defense system by:

(i) Generating enzymes that degrade the target pollutants; and
(ii) Blocking the presence of pertinent heavy metals.

Microorganisms are important for replenishing the environment in a number of ways, including binding, immobilization, oxidation, transformation, and volatizing heavy metals (Verma *et al.* 2019). Identifying the mechanisms governing the growth and activity of microbes in contaminated sites, their capacity for metabolism, and their response to environmental changes could potentially improve the efficiency of bioremediation process in specific locations through the application of the designer microbial method (Alvarez *et al.* 2017). The extracellular polymeric materials have a major impact on metal adsorption and acid-base characteristics, making them the most prominent reactive chemicals linked to bacterial cell walls (Guiné *et al.* 2006). Table 1 lists some of the microorganisms and the pollutants that can be removed the species.

Extracellular polymeric substances (EPS) exhibit a high degree of metal binding capacity towards complex heavy metals using several mechanisms, such as proton exchange and micro-precipitation of metals (Comte *et al.* 2008; Fang *et al.* 2010). According to recent studies, the protons were identified and measured, and the metals were adsorbed on bacterial cells and EPS-free cells so that they could determine the proportional importance of EPS molecules in metal breakdown (Fang *et al.* 2011). By using various techniques, such as proton exchange and micro-precipitation of metals, extracellular polymeric substances (EPS) exhibit an incredible metal binding ability towards complicated heavy metals (Comte *et al.* 2008; Fang *et al.* 2010). According to recent studies, the protons were measured and analyzed, and the metals were adsorbed on EPS-free and bacterial cells so that they could determine the relative importance of EPS molecules in metal breakdown (Fang *et al.* 2011). The primary cause impeding bioremediation research and application in the current context is the poor understanding of the genetics and genome level properties of the organisms that were used in the metabolic pathway and their kinetics as well as in metal adsorption (Kato *et al.* 1996; Haritash *et al.* 2009; Onwubuya *et al.* 2009; Gan *et al.* 2009).

Table 1. List of microbes capable of degrading pollutants

Microorganism	Pollutant	References
P. alcaligenes	polycyclic aromatic hydrocarbons	(Safiyanu *et al.* 2015)
P. mendocina and *P. putida*	toluene	(Safiyanu *et al.* 2015)
Lactobacillus plantarum, L. casei and *Streptococcus lacti* and Photosynthetic bacteria- *Rhodopseudomonas palustrus, Rhodobacter spaeroide*		(Divya *et al.* 2015)
Exiguobacterium aurantiacum	phenol and PAHs	(Jeswani *et al.* 2012)
Halobacterium piscisalsi *Halorubrum ezzemoulense* *Halobacterium salinarium* *Haloarcula hispanica* *Haloferax* sp. *Halorubrum* sp. *Haloarcula* sp.	*p*-hydroxybenzoic acid Naphthalene Phenanthrene Pyrene	(Erdoğmuş *et al.* 2013)
Staphylococcus pasteuri	Phenanthrene Fluoranthene Pyrene	(Liu *et al.* 2009)
Rhodococcus erythropolis	*n*-alkane	(Li *et al.* 2019)

2.5 Benefits of the Bioremediation Method

The bioremediation method has several benefits, some of which are listed below. It is a natural process that has no negative effects on environmental cycles or components.

2.5.1 Environmentally Friendly

Bioremediation typically uses natural processes and organisms to degrade or remove contaminants, making it a more environmentally friendly approach compared to chemical or mechanical methods (Omokhagbor Adams *et al.* 2020)

2.5.2. Cost-Effective

In many cases, bioremediation can be more cost-effective than traditional cleanup methods. It often requires fewer resources and can be implemented with minimal infrastructure (Anekwe *et al.* 2023).

2.5.3 Targeted and Specific

Bioremediation can be tailored to target specific contaminants, allowing for more precise cleanup efforts. This specificity reduces the risk of unintended consequences and minimizes disruption to the surrounding environment. (Anekwe *et al.* 2023).

2.5.4. Versatility

Bioremediation can be applied to a wide range of contaminants and environmental settings, including soil, water, and air. It is applicable to both organic and inorganic pollutants, offering versatility in addressing various types of contamination (Kuppusamy *et al.* 2016).

2.5.5. Long-Term Solution

Bioremediation can lead to the long-term remediation and stabilization of contaminated sites. By promoting natural processes of degradation and detoxification, it can prevent contaminants from persisting or re-accumulating over time (Tyagi *et al.* 2021).

2.5.6. Minimal Site Disruption

Unlike some traditional cleanup methods that involve excavation or large-scale engineering, bioremediation often requires minimal site disruption. This can reduce the impact on surrounding ecosystems and communities.

2.5.7. Promotes Soil Health

Bioremediation processes can improve soil quality and fertility by stimulating microbial activity and enhancing nutrient cycling. This can lead to ecosystem restoration and sustainable land use after contamination has been remediated (da Silva *et al.* 2020).

2.5.8. Potential for Public Acceptance

Bioremediation is often viewed more favorably by the public and stakeholders due to its natural and non-invasive approach. This can facilitate regulatory approval and community support for cleanup projects (Taffi *et al.* 2014).

2.5.9. Reduces Waste Generation

Unlike some traditional cleanup methods that generate large amounts of waste or secondary pollutants, bioremediation typically produces minimal waste. The process often results in the complete degradation or transformation of contaminants into harmless byproducts (Sahota *et al.* 2022).

2.5.10. Adaptive and Evolving Technology

Bioremediation techniques continue to evolve with advancements in biotechnology and microbiology. Researchers are constantly discovering new microbial strains and metabolic pathways that can enhance the efficiency and effectiveness of bioremediation processes (Ayele *et al.* 2021).

2.5.11. Disadvantages

- There are concerns that the biodegradation products could be more hazardous or persistent than the original chemical.
- Biological processes are frequently very specialized.
- A favorable environment for growth, the availability of metabolically competent microbial populations and the right amounts of toxins and nutrients are all crucial site requirements for success.
- It is restricted to non-biodegradable chemicals. Not every substance degrades quickly and entirely (Abatenh *et al.* 2017).

3. CONCLUSION

When wastewater is discharged into the environment, cleanup and a successful approach are required, along with regular monitoring. One extremely effective and advantageous option for microbial activity to improve, purify, regulate, and replenish methods for cleaning and repairing contaminated surroundings is bioremediation. Microorganisms are an extremely effective way to remove various pollutants from wastewater since they also help to assimilate carbon, phosphorous and nitrogen. Microbe-mediated methods like metagenomics and omics have a high potential for adsorbing even minute amounts of heavy metals, making them perfect for heavy metal removal. The current study demonstrated that white-rot fungi and algae species both have excellent capability to lower the hazardous level of every physico-chemical parameter. These biological agents are excellent for use in wastewater treatment processes due to their easy handling and versatility in breaking down difficult chemicals. In contrast to chemical and physical procedures, biological methods are more specific and convenient for in situ methodologies (such as ignoring high energy or adding harmful chemicals).

4. FUTURE PROSPECTS

Environmental restoration with bioremediation is a rapidly expanding discipline that offers flexible and environmentally beneficial treatment options. One of the limitations of the bioremediation process is that some bacteria inhibit microbial activity because they are unable to change harmful heavy metals into non-toxic forms. Genetic engineering is therefore used to increase the biodegradation capability of microorganisms. By using bimolecular engineering, it is possible to create genetically modified bacteria that have enhanced capacities to break down various pollutants. Furthermore, the scientific fields of analytical chemistry, molecular biology, environmental engineering, microbiology, biochemistry, and others have all contributed to the advancements in bioremediation. These several sectors, each using a unique technique, have made significant contributions to improving the development of the bioremediation process.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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