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BIOREMEDIATION OF WATER POLLUTANTS FROM WASTEWATER

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ABSTRACT
Environmental pollution caused by xenobiotics and other persistent compounds has been recognized as a significant threat to both human health and the natural environment. These pollutants, which include heavy metals, polychlorinated biphenyls, plastics, and various agrochemicals, are toxic and resistant to biodegradation. Bioremediation is an emerging and effective method for cleaning contaminated environments by removing toxic waste. This technique utilizes a range of microorganisms, both aerobic and anaerobic, to treat polluted sites. Microorganisms are crucial in bioremediation as they degrade, detoxify, and immobilize hazardous wastes and pollutants, transforming them into less toxic forms. Depending on factors like cost, pollutant type, and concentration, bioremediation can be conducted ex-situ or in situ. Consequently, the appropriate bioremediation method is selected based on these factors. This review addresses the major issue of contaminants in water, including its sources, effects on the ecosystem, remediation strategies using different biological processes that change the pollutants into less hazardous, source and types of pollutants, the principle of bioremediation, bioremediation strategies, and technologies, microorganisms in bioremediation, case study and application, monitoring, and assessment of bioremediation process, environmental impacts and sustainability, future perspectives, and challenges.

Keywords: Bioremediation, Pollutants, Wastewater Treatments, Removal, Microbes

INTRODUCTION

Due to excessive human activity, the globe has seen difficulties with a wide spectrum of deterioration of the environment during the past few decades (Kshirsagar, 2013). Natural environments are polluted due to human activities, such as the discharging of sewage into the environment, and the dumping of crabs, broken bottles, plastics, industrial waste, and pesticides. These make our land to become polluted land and drain into water bodies to contaminate our drinking water.

Water pollution is the contamination of water bodies like rivers, lakes, oceans, and groundwater by harmful substances. This degradation of water quality negatively impacts ecosystems and human health. Sources of water pollution include industrial discharge, agricultural runoff, household waste, and chemical spills (Figure 1). Problems associated with water pollution are numerous for instance diseases such as cholera, dysentery, and typhoid (Kshirsagar, 2013). Toxic chemicals like lead and mercury cause poisoning and long-term health issues (Azubuike, et al. 2016). Pollutants harm aquatic life, reducing biodiversity and disrupting food chains. Economically, water pollution affects industries like fishing, tourism, and agriculture, leading to significant losses. It also exacerbates water scarcity, making clean water less available and reducing natural landscapes' aesthetic and recreational value (Azubuike, et al. 2016).

Various methods are used to remove pollutants from water. Physical methods include sedimentation, which allows particles to settle at the bottom, filtration, which uses barriers to remove impurities, and flotation, which removes suspended matter with air bubbles (Amin, et al. 2013). Chemical methods involve coagulation and flocculation to clump small particles into larger ones, oxidation to break down contaminants, and neutralization to adjust pH levels (Amin, et al. 2013). Other methods include biological treatments like the activated sludge process, which uses microorganisms to decompose organic matter, and trickling filters, which use beds of materials where microbes break down pollutants. Membrane technologies such as reverse osmosis and ultrafiltration remove ions, molecules, and larger particles. Advanced oxidation processes use strong oxidants like ozone, hydrogen peroxide, and UV light to degrade pollutants. Older methods, such as simple sedimentation, basic filtration, and chlorination, often fail to remove modern pollutants like pharmaceuticals, heavy metals, and persistent organic pollutants (Deshmukh, et al. 2016). These traditional methods were designed for more straightforward contaminants and are inadequate for the complex mixtures found in contemporary wastewater. Bioremediation has emerged as an effective and sustainable solution for water pollution. It is eco-friendly, resulting in minimal secondary pollution, and cost-effective, especially for large-scale applications. This process uses microorganisms, plants, or microbial enzymes to detoxify and remove pollutants. Bioremediation is efficient as microorganisms break down complex organic pollutants into less harmful substances (Singh, P., et al. 2020). Additionally, bioremediation can be tailored to treat specific pollutants by selecting appropriate microorganisms or plants (Harekrushna, & Kumar,–2012). Examples of bioremediation techniques include phytoremediation, which uses plants to absorb and metabolize pollutants, bio augmentation, which adds specific strains of bacteria to degrade contaminants, and biostimulation, which enhances the growth of native microbial communities by adding nutrients. While traditional methods have been useful, they often fall short in dealing with the diverse and complex contaminants present in modern wastewater. Bioremediation offers a promising and versatile solution, leveraging natural processes to effectively clean polluted water. As research advances, bioremediation is likely to become increasingly pivotal in ensuring access to clean and safe water (Abatenh, et al. 2017).

The area of contaminated water has expanded due to the global population boom. The amount and caliber of garbage manufactured and released into natural water sources have thus been taken into account, and the necessity of various approaches to address issues with the purity of water in the areas has been emphasized (Harekrushna, S., & Kumar, D. C. 2012). Global water pollution is a serious issue that causes the spreading of diseases such as cholera from one geographical area to another. Natural pollution, inorganic contamination, and microbes are the three main groups into which the issue of contamination can be broadly divided (Coelho, et al. 2015). Urbanization, significant pollutants in industry, and contemporary economies are the main factors causing the quantity of water pollution expansion, and the population of humans has grown enormously (Amin, et al. 2013). The process enhanced competency, environmental friendliness, and affordability (Singh, P., et al. 2020). A natural substitute for tactics like burning, using adsorbents, catalytic breakdown, physical removal, and destroying pollution is bioremediation. The technique is known as "bioremediation," which uses microorganisms' innate ability to break down or eliminate contaminants from the surrounding environment (Harekrushna, S., & Kumar, D. C. 2012). This strategy became well-known because of its economical and environmentally beneficial methods of cleaning polluted areas.

This review addresses the major issue of contaminants in water, including its sources, effects on the ecosystem, remediation strategies using different biological processes that change the pollutants into less hazardous, source and types of pollutants, the principle of bioremediation, bioremediation strategies, and technologies, microorganisms in bioremediation, case study and application, monitoring, and assessment of bioremediation process, environmental impacts, and sustainability. Traditional bioremediation methods face significant limitations, such as inefficiency in removing recalcitrant pollutants, inability to handle emerging contaminants (e.g., pharmaceuticals, PFAS), and limited adaptability to complex wastewater systems. This review highlights recent advancements like microbial consortia, genetically engineered microbes, and biosorption techniques, which address these shortcomings and offer sustainable, eco-friendly solutions. It emphasizes the urgent need for the research community to integrate these innovative methods into wastewater management to tackle modern environmental challenges effectively. By addressing these technical gaps, the review demonstrates that bioremediation is not just an option but a critical, scalable solution to eliminating environmental pollutants.

Principle of Bioremediation

A technique called bioremediation uses biological processes to reduce, degrade, alter, eliminate, immobilize, detoxify, mineralize, or change the quantity of pollutants in an environment that is neither harmful nor dangerous (Abatenh, et al. 2017). The best method of treating polluted water depends on the kind of contaminants, which can include chemicals, recyclable plastics, toxic metals, petroleum products, dyes, carbon monoxide, halogen elements, agricultural products, heavier metals, and lubricants. The microbes must attack pollutants enzymatically and convert them into harmless products for the procedure of bioremediation to be successful. The success of bioremediation depends on surroundings that allow microorganisms to develop and function (Amin, A et al. 2013). The key to solving the majority of the problems with contaminated environments is the existence of numerous native microorganisms.

Types of Bioremediation

Bioremediation encompasses several types shown in Figure 1, each utilizing different biological agents and processes to address pollution.

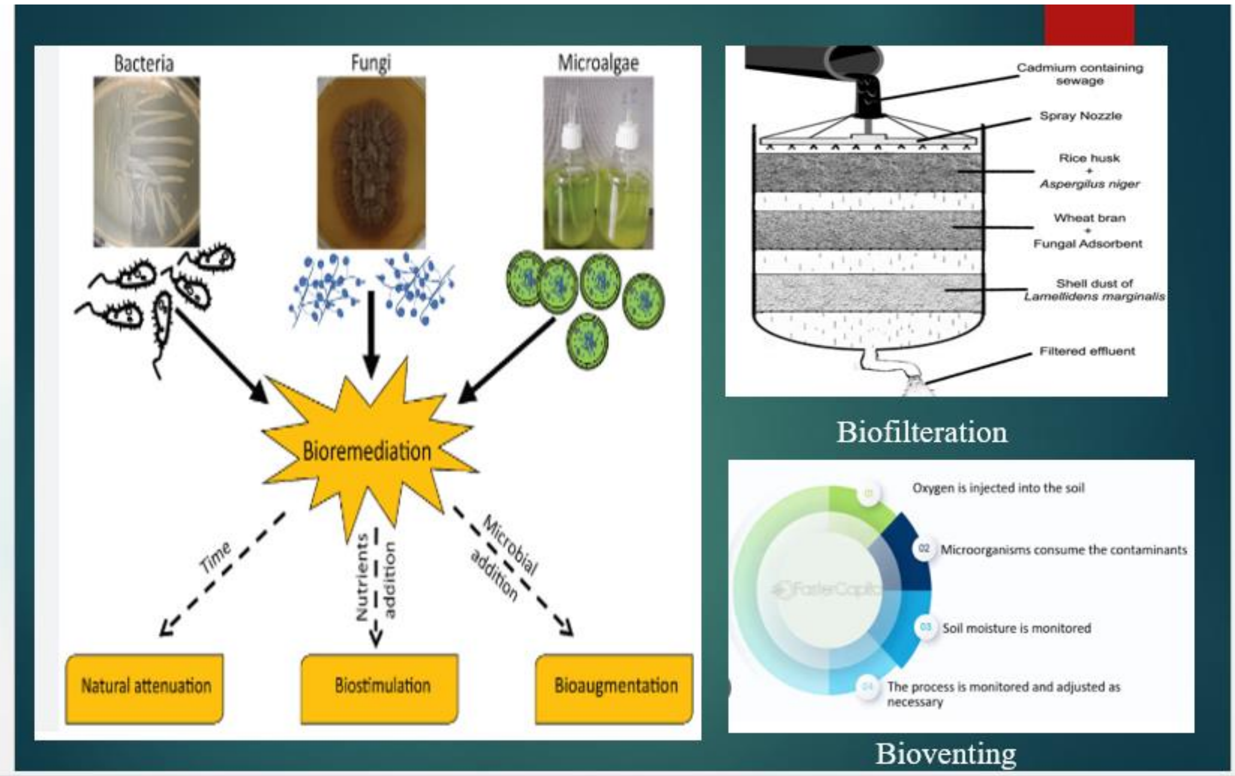

Figure 1: Types of Bioremediation

Microbial bioremediation entails employing microorganisms to break down and detoxify contaminants, including bacteria, fungus, and yeast. Organic pollutants are broken down by microorganisms into less dangerous compounds (Figure 1). They might be created genetically to target particular contaminants or they can be naturally present. This approach offers a flexible solution for a range of environmental contaminants and is frequently used to treat sewage, industrial waste, and oil spills (Kour, et al. 2021). Because of its well-known capacity to break down hydrocarbons, the bacteria Pseudomonas putida is helpful in the cleanup of oil spills. In order to degrade organic solvents and heavy metals, Deinococcus radiodurans has undergone genetic modification. White rot fungi, such as Phanerochaete chrysosporium, are excellent for degrading persistent organic pollutants (POPs) because they produce enzymes that can break down complicated organic compounds like lignin. Certain yeast species are helpful in the treatment of industrial effluent because they can break down organic substances like alcohols and esters. Certain algae can help clean up eutrophic water bodies by absorbing nutrients and heavy metals from the water. According to Sun, Reynolds, and Belcher (2020), microbial bioremediation can take place ex situ, or away from the site of pollution, or in situ, at the site of contamination. In-situ techniques, like biosparging, use underground injections of nutrients or air to promote microbial activity. Excavating contaminated soil and treating it in a controlled setting is the process of ex-situ methods, including biopiles (Sun, G., Reynolds, E., & Belcher, A. 2020).

Phytoremediation utilizes plants to clean up, store, and absorb contaminants from water and soil. The capacity of certain plants to absorb particular pollutants, including organic compounds or heavy metals, is taken into consideration while choosing them. Large-scale applications in contaminated land and water bodies are appropriate for phytoremediation because it has the ability to extract, stabilize, and degrade contaminants.

Bioaugmentation entails introducing particular microbial strains to contaminated areas in order to accelerate the breakdown of contaminants. These microbes were chosen since it is well known that they can efficiently break down particular pollutants. In situations where native microbial populations are either insufficient or inefficient at degrading contaminants, bioaugmentation is especially helpful. It can be used in projects involving the cleanup of both water and soil. This method works especially well in settings where the local microbial population is too small or unable to efficiently break down pollutants (Zhang, et al. 2021).

Biostimulation enhances the microbial populations already present in the contaminated environment by introducing nutrients, oxygen, or other materials that support the development and activity of microorganisms. Biostimulation has the potential to expedite the removal of contaminants like hydrocarbons and nitrogen compounds from the environment by augmenting the inherent biodegradation processes. This approach is economical and adaptable to particular environmental circumstances. This procedure speeds up the breakdown of contaminants and promotes microbial development (Wu, et al. 2019).

Mycoremediation utilizes fungi, especially their mycelium, can break down organic contaminants. Fungi are useful for removing pollutants like hydrocarbons and pesticides because they produce enzymes that can break down complicated organic compounds. Mycoremediation can aid in the restoration of soil health and is effective in both soil and water environments. This technique can be used in conjunction with other bioremediation strategies and is especially helpful for breaking down persistent organic contaminants. Fungi are useful in gaining access to and breaking down contaminants because their mycelium can infiltrate both soil and organic substances.

Bioventing is an in-situ remediation method that includes adding oxygen or air to polluted soil to encourage the growth of natural microorganisms and speed up the biodegradation of contaminants, particularly hydrocarbons (Figure 1) (Smith, J., Gaito, S., & Koons, B. 2023). Remediating locations affected by petroleum typically involves the use of bioventing. It is a versatile and efficient technique for in-situ soil remediation since it can be adjusted to different soil types and contamination concentrations.

Composting involves combining organic materials and microbial inoculants with contaminated soil to promote aerobic microbial activity and the degradation of organic contaminants. Composting enhances the fertility and structure of the soil while lowering the concentration of pollutants. It is a useful technique for cleaning up organic waste and agricultural areas. It also encourages the recycling of organic materials, which helps to promote a circular economy. Organic components like manure, plant leftovers, or food waste are combined with contaminated soil (Tran, et al. 2021). These various bioremediation methods leverage the natural capabilities of biological agents to address and mitigate pollution, offering environmentally friendly and sustainable solutions to contamination issues (Tekere, M. 2019 and Muttaleb, W., & Ali, Z. 2022).

Sources of Water Pollutants

Sources and origins of pollution, in water-polluting substances originate from both naturally occurring and artificially created environments on Earth. Among the natural contaminants include nitrogen, oxides, hydrocarbons, heavy metals, and radioactive materials. There are two main source of water pollutants namely organic pollutants and inorganic pollutants.

Organic Pollutants

Organic pollutants can be found in Sewage, manufacturing industries, food processing facilities, slaughterhouses, paper and pulp mills, tanneries, and other sources all contain organic substances in different suspended, colloidal, and dissolving forms. Organic compounds are made up of carbon, hydrogen, oxygen, nitrogen, and sulfur. These compounds deplete oxygen, which leads to anaerobic conditions in aquatic habitats. Chemical pesticides, detergents, food additives, medications, insecticides, dyes, synthetic fibers, plastics, solvents, and volatile organic compounds are examples of manufactured organic contaminants that are not removable and remain in rivers and lakes for a long time (M. Syafrudin, et al. 2021).

Marut et.al reported the elimination of organic contaminants by using microalgae. Using a descriptive bibliometric approach, they studied the mathematical applicability vs. practicality of the bioremediation process of developing organic pollutants. The effective methods for the bioremediation of various Organic contaminants describe the possibility of using microalgae to biologically remediate microscopic pollutants in a cost-effective and environmentally beneficial way (Jain, Marut et al. 2022).

Table 1: Emerging organic pollutants and their bioremediation techniques.

S/No.	Contaminants	Remediation Methods	Microorganisms	Reference
1.	Polychlorinated biphenyl (PCB)	Bioreactor	Bacteria: Paraburkholderia xenovorans LB400	(Bakoli et al., 2022)
2.	Trinitrotoluene (TNT)	Phytoremediation, Biopiling	Eurasian water milfoil	(Thiado et al., 2020)
3.	1,2,4-trinitro-1,2,4-triazine (RDX)	Phytoremediation	Mycorrhizal Fungi	(Jompson and Molebiski, 2022)
4.	Total Oil hydrogen carbon (TPH)	Phytoremediation	Aerobic Microbes	(NcIntosh et al., 2020)

Polyfluoroalkyl

Polyfluoroalkyl substances (PFASs) are a family of water-soluble compounds that are distinguished by several fluorine atoms inside an alkyl chain. During the past 60 years, PFAS compounds have been extensively employed in many different industries, such as food packaging, foams, Teflon coatings, waterproof fabrics, wax products, and dyes. They are also present in contaminated soil as well as water, which is commonly linked to specific locations such as airports, fire stations, oil refineries, and other facilities that utilize or manufacture PFAS. PFAS chemicals have been used in this process. PFOA also referred to as PFOA, and a compound known as perfluorooctane (PFOS) are two of this class's most widely used compounds. These lubricants are fluorinated and possess both phobic and philic properties. Organic contaminants that linger, including PFOS and PFOA, are unable to degrade in surroundings and instead progressively accumulate in ecosystems and human beings. Numerous medical conditions, including thyroid disorders and thyroid cancer (liver, testicular, and pancreatic adenocarcinoma), pregnancy-related hypertension, weakened immune response to vaccinations, asthma, premature birth, lower levels of bone minerals, and abnormalities in neurological development have all been linked to exposure to per- and poly-fluoroalkyl substances (PFASs) (Y. Hu, G. Liu, et al. 2019 and S. Iftekhar, A et al. 2023).

Adenike et al. used microbes to bioremediate PFAS-contaminated environments. Because of their hydro- and oleo/lipophobicity, heat resilience, and non-degradability, a vast class of over 9,000 fluorinated carbon compounds known as per- and poly-fluoroalkyl substances (PFAS) find widespread use in both commercial and consumer applications. Consumer uses include non-stick cookware, shampoos, cleansers, paints, and food packaging materials; industrial applications include aqueous film-fighting foams, coatings, and surfactants (Schaider LA et al. 2017 and Hogue C 2021). Since PFAS continue to be used by consumers and industries, they have contaminated soils, groundwater, rivers, lakes, drinking water, other healthcare, and environmental concerns (Figure 3). Environment by interfering with the biological activities of microbial populations in water and soil, they have an impact on a variety of settings, encompassing people and a microbiome as well as species in the higher trophic level of the food chain (Senevirathna STMLD et al. 2022). This specifically influences their advantageous symbiosis connection to the metabolic processes of animals and humans by facilitating the immune response's manufacture of vitamins, neutralizing medications, and the gut's ability to break down and utilize minerals (Chen L, et al 2019). Though little is known about PFAS-induced microbial dysbiosis and metabolic syndrome in people, research toward similar outcomes in humans is being driven by findings in animal models (Chen L, et al. 2019). As time goes by, various ecological remedial techniques have been developed to break down environmental PFAS pollutants (Lim X 2021). This covers the use of reverse osmosis in-home water use and nanofiltration technologies (Tang CY, et al. 2017). As well as biodegradation. Because of their highly fluorinated domains, PFAS are difficult to degrade and pose an important obstacle for government organizations, lawmakers, and researchers who are working to develop active remediation methods (Lim X 2021). Microbial breakdown is one approach that could be pursued since it has shown promise in the removal of the most prevalent industrial byproducts, petroleum spills, and chlorine chemicals at a low cost (Shittu, et al. 2023).

Jessica et al, Presented the idea of using biological remediation as a remedy for poly-fluoroalkyl remediation. With more information becoming accessible about the possible risks and widespread amount of pollution, polyfluoroalkyl substances (PFAS) have drawn increasing attention. To lessen exposure to perfluoroalkyl substances (PFAS), remediation plans are presently being created. These plans are particularly focused on aquifers beneath sites where the widespread use of aqueous film-forming foam (AF) for fire suppression and/or fire training has led to PFAS pollution. Due to the resistant nature of PFAS and the lack of known organisms capable of fully degrading PFAS into non-toxic byproducts, microbiological treatment, or biological remediation, has not yet been explored as an option for therapy for PFAS. However, according to current research, the function of our comprehension of the procedures taking place in polluted areas where the conversion of PFAS precursors to terminal end-products has been identified may benefit from an examination of microbes. Topics of particular significance to bioremediation as systems, are covered in the current state of knowledge about the biotransformation of PFAS by microorganisms (LaFond, et al. 2023).

Pesticides

Water pollution rises as a result of inappropriate use of insecticides, primarily herbicides and pesticides (Figure 2). The causes of this type of contaminants in water include inappropriate submission of pesticides in high quantities, inappropriate mixing of pesticides, and inappropriate handling of pesticide-containing toxic substances may lead to contamination of water. Pesticide residues are readily absorbed by plants and rivers close to agricultural land. Aquatic eventually make their way into the nutrient chain of humans. Pesticide-induced increased generation of reactive oxygen species is a significant and practical contributor to cell damage, the contamination from pesticides and herbicides causes serious problems to aquatic life which may lead to death (E. Nazarzadeh Zare et al. 2021).

Jesus et al employed a cylindrical, semi-closed horizontal photobioreactor (PBR) to extract insecticides in agricultural wastewater. In July, the study was conducted to examine its effectiveness in the optimal setting—that is, with the maximum amount of sun radiation. A comprehensive analysis was conducted on 51 pesticides, comprising 10 transformation products, taking into account their ecological significance and rate of usage. There were sixteen of them found in the agricultural runoff, and the predicted removal efficiency varied from zero for three compounds (terbutryn, diuron, and medication) to one hundred percent for ten components. The usual clearance of the corrosive chemical MCPA was 88%, but the removal rates of the insecticides 2, 4-D, and diazinon varied and ranged from 100% to negative, Zare et al. 2017).

Baba et al employed biological remediation methods to remove insecticides from the environment. The start of the Industrial Revolution and the development of numerous pesticides have undoubtedly increased agricultural goods productivity and shielded almost all of our crops from pests. Since such pests can't lead us to lose the majority of our crops. Although pesticides currently help our farmers succeed by increasing productivity and provide financial support, their usage in agricultural fields is a major source of concern. There is cause for serious concern regarding the rise of soil contamination. Numerous pollutants, among which pesticides are one of the main worries, seriously endanger both human beings and the environment. The mechanical or chemical methods now in use are either expensive or insufficient. Bioremediation offers a new method or instrument. Chemical decontamination can be accomplished economically, environmentally, and effectively via a bioremediation process (Uqab, B., Mudasir, S., & Nazir, R. 2016).

Dyes

One of the most predominant substances in our economy and everyday lives is dye, yet people are becoming progressively reliant on synthetic colors due to the shortage of natural dyes and progress in industries' dye technology. On the other hand, issues with conservational pollution are also getting worse. Many industrial procedures, including sulfonation, nitration, diazotization, oxidation, reduction, and acidic deposition (salts), as well as elements of synthetic colorants, such as chromophore groups that include aromatic assemblies, nicotine groups, nitrogen-consisting groups, and anthraquinones, among other, are plausible possessions for this contamination. The transfer of light interferes with water plants' ability to photosynthesize. Dyes are frequently carcinogenic because they contain chemical groups (organic aromatic compounds containing halogen nitro, phenol, and amine groups) (S. Ben Hamida, et al 2018 and F.R. Abe, et al. 2017).

Shanmugam et al demonstrated bioremediation of textile dyes, including their categories, their contamination, and the use of algae and bacteria in the bioremediation of toxic textile industry effluent. Worldwide concern over the contamination of the environment resulting from wastewater discharged by textile manufacturers is growing. The textile industry generates vast amounts of effluents that are largely made up of dyes and other compounds. Such effluents cause pollution that negatively impacts aquatic life when they are released into water bodies (Figure 3). Synthetic dyes are aromatic compounds with complicated structures that have a high physiological and physiological demand for oxygen as well as mutagenic and carcinogenic qualities. This intricate aromatic structure is resistant to breaking down using standard methods. The biological removal of harmful pollutants from wastewater from factories is known as bioremediation. Biological treatment techniques are economical, efficient, and environmentally benign, and they generate little or no sludge. Microbes, primarily bacteria, and microscopic algae, but occasionally Microfiber dye chemicals are decolored into basic, non-toxic chemical substances by yeast, fungus, and enzymes (Sudarshan, et al. 2023).

Mehvish et al. presented biophysical methods for dye removal in textiles cleanup. Azo colorants are a very common synthetic color class used in industrial manufacturing. They are aromatic compounds with one to several –N=N– groups. Azo dyes are harmful to aquatic organisms as well as human well-being when they are introduced into the environment through textile waste. Remediation of these contaminants has gained significant interest as a result of their durability and release through the surroundings, which have become global issues. Numerous biophysical techniques, including the coagulation process chemically flocculation, and filtering, have already been applied to the treatment of textile waste. Even while these traditional methods work well, they are expensive and cause heavy waste to accumulate, which poses a second disposal issue. Utilization of microbes is an efficient, cost-effective, environmentally safe, and biocompatible method (Ajaz, M., Shakeel, S., & Rehman, A. 2020).

Manikant et al. discussed the most recent advancements in innovative biologically, physically, chemically, and environmentally friendly techniques for effectively reducing dye pollution and the associated difficulties in the environment. Significant environmental risks are posed by the dye in sewage, which also has detrimental effects on the health of other parts of the ecosystem as well as human health. The area's residents and other species are exposed to the possibly dangerous effects of wastewater discharge from textile and industrial manufacturing due to the growth in textile-related industries. Various kinds of colors released by textile materials harm the aquatic ecosystem. Several techniques, such as chemical, biological, and physical approaches, are used to lessen the quantity of dye pollution that enters the natural world. It is essential to create cost-effective, environmentally friendly, and efficient methods for cleaning waste that contains dyes. Microbial ecosystems have been demonstrated to have a great deal of possibilities for safely and sustainably remediating toxic dyes. Many innovative techniques, such as those based on nanotechnology, microbial biosorbents, bioreactor technology, microbial fuel cells, and genetic engineering, have been used to increase the effectiveness of color treatment (Tripathi, et al. 2023).

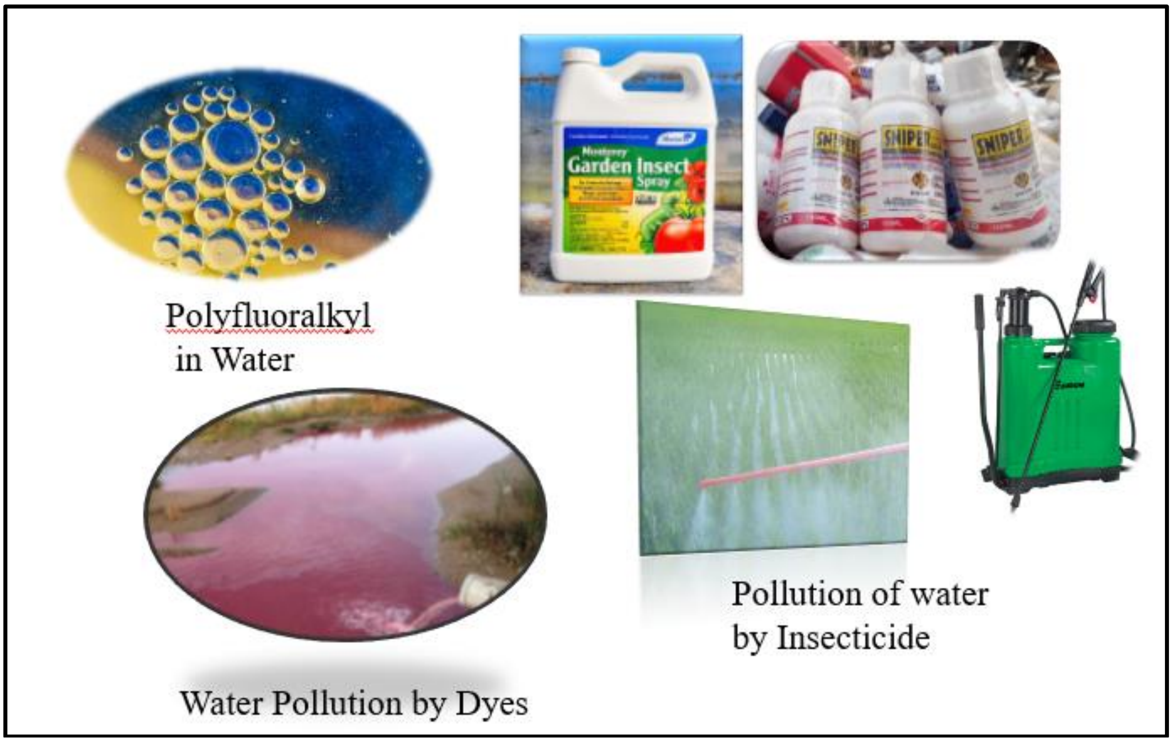

Figure 2: Common Organic Pollutants

Inorganic Pollutants

The pollution of water for drinking by dangerous constituents like ammonium ion nitrate, and heavy iron is a worry for countries with poor infrastructure. Many health matters can arise from high amounts of nitrogen contaminants (nitrates, nitrites, and ammonium ion) and inorganic phosphates in river water, which are carried on by the outflow of pollutants from cities or industries as well as the discharge of water from farms and ranches (Figure 4). Naturally toxic, nitrites increase the danger of the lungs, liver, and intestine cancer as well as increase the body urea concentrations (E. Nazarzadeh Zare, et al. 2018). Particularly, inorganic substances are important for the chemical composition of factory contaminants and their possible effects on the environment. Synthetic contaminants, as opposed to organic ones, are defined as chemical compounds devoid of carbon-hydrogen (CH) bonds. The contaminants come from a variety of industrial processes, including raw materials, chemical reactions, and production apparatus. They can be metals, metalloids, acids, bases, salts, or other chemicals derived from minerals, among other forms. Typical instances of inorganic substances are lead and other heavy metals. (E.N. Zare, M.M. Lakouraj, N. Kasirian 2017). Suhail et al. illustrated how to use biological remediation procedures to get rid of colors, heavy metals, both inorganic and organic contaminants, and other pollution. The need for sustainable materials is rising as a result of several factors, including those related to the economy, long-term viability biological compatibility, and being biodegradable as well as the environment. This has led to the emergence of new academic disciplines that heavily emphasize natural product development. Gum polysaccharides are one of the most widely used natural polymers. They are utilized in many different industries and are frequently exudates from microorganisms or plants. In contrast to their synthetic counterparts, hydrogels derived from carbohydrates provide various beneficial attributes. Hydrogels derived from natural gums possess the capability to yield environmentally sustainable goods and mitigate pollution in the environment (Ahmad, et al. 2023).

Liping et al used biochar and composites based on biochar to eliminate both natural and artificial contaminants. Because of its low cost, high surface area, developed pore structure, and the broad availability of raw materials, biochar (BC) has shown considerable potential in the removal of water pollutants. Nevertheless, there are a lot of restrictions on using BC for water restoration. An increasing number of investigators have worked to create BC-based materials for composites, motivated by the strong desire to overcome adverse variables. These efforts have enhanced BC's physical and chemical characteristics and produced a new composite material that combines the benefits of BC along with additional supplies. This paper examined earlier studies on BC and BC-based composite substances, and covers based on the fundamental adsorption mechanisms, the performance of pollutant removal, the physicochemical characteristics, and preparation techniques. Next, a thorough assessment of current research findings on the removal of organic and inorganic contaminants by BC and BC-based materials was conducted. Even though BC-based composite compounds have demonstrated excellent efficacy in eliminating of both organic and inorganic pollutants, it is still necessary to be aware of and do additional research on potential hazards (such as stability and biological toxicity) (Liang, et al. 2021).

Nitrate (NO_3)

Nitrate is commonly found in water and nitrogen in the forms of nitrate, nitric oxide, nitrite ion, and ammonium ion, may be one of the most common pollutants in groundwater (Figure 4). Moreover, water naturally contains minuscule levels of nitrate. In water in the ground, nitrate has the capacity to linger and accumulate. Since nitrogen is necessary for plant growth, farmers heavily treat their plants with nitrogen to increase crop production (Li, D et al 2020).

Mahboobeh et al reported that lower collection costs can be achieved by using immobilized and biofilm growth as substitute culture techniques for nitrate removal. Both land-based agriculture and aquatic algal rearing systems require a steady supply of macronutrients, specifically phosphorus (P) and nitrogen (N), along with a variety of micronutrients, to produce growth. Large-scale algal production using industrial fertilizer significantly raises the cost of generating algae. The wastewater may be effectively cleaned of ammonia, nitrate, nitrite, and other mixed contaminants by using algae. Methods: By digesting nutrients in wastewater, the algae provide an efficient way to recycle nutrients in storm-water and turning into cellulose using inorganic nitrogen. Combining Various Algal Strains for Nitrate Elimination and Cellulose Formation Previous studies have shown that different species of microalgae may absorb and assimilate different quantities of N and produce energy. However, because the methods used for experimentation varied, it is difficult to assess and understand the results. These include the use of different algae strains and varieties, the type of media (which can include stipulated natural media and wastewater waste), and the amount of increased and decreased N, humidity, light intensity, diurnal light systems, BOD levels, and CO_2 concentration. For example, Sacristán de Alva et al. (2013) created Scenedesmus cactus in municipal wastewater after two phases of remediation: primary activation treatment of sludge and secondary settlements (primary remediation). The main effluent supported twice as much biomass and had almost twice as much COD, phosphates, and reduced N as the secondary treatment effluent. They managed to achieve a low nitrate removal rate of 0.59. Ten differences in the ingestion of nitrates were found using the same microorganisms (Doria et al. 2012).

Kwiyong et al. offered a generic approach to a completely electrified reaction-separation pathway for the synthesis of ammonium and flexible nitrates treatment. A common aqueous contaminant from industrial and agricultural processes is nitrate. Simultaneously, the nitrogen cycles environmental and energy challenges can be effectively addressed by the conversion of nitrate to ammonium, which turns contaminants into a vital chemical raw material and a carbon-free energy source. Because of the diluted concentration of nitrate, mass transport restrictions pose a significant challenge to the efficient conversion of nitrate to ammonia from water streams. Here, we create bifunctional in-nature, catalysts that combine an electrocatalyst (copper oxides) for nitrate-to-ammonium conversion into a nitrate-selective redox-electrosorbent (polyaniline) transformation. We show that nitrate can be reactively separated in a synergistic manner using only electromechanical control. It is possible to produce electrochemically reversible nitrate uptake of more than 70 mg/g, and spectroscopic investigations and electronic configuration simulations shed light on the fundamental function of hydrogen bonding in nitrate selectivity. We show that, in comparison to direct electrolysis in the dilute flow, the dual-functional electrode may produce an 8-fold up-concentration of nitrate, a 24-fold enhancement of ammonium production rate, and an enhancement in energy efficiency using agricultural tile drainage water containing diluted nitrate (0.27 mM). For modular nitrate remediation and ammonia synthesis, our study offers a generic approach for a completely electric reaction-separation system (Kim, K., Zagalskaya, et al. 2023).

Heavy Metals

Metals with an atomic number larger than 20 and an essential density higher than 5 g per cubic centimeter are considered heavy metal ions, and even at very low levels, it is frequently supposed that these metals are dangerous. Heavy metal ions can be initiated from both man-made and natural sources. Rare earth and contaminants from substantial metals can be originate in water that is naturally occurring. Moreover, these metal particles are added to ground water via human activities such as the wide prevalent use of insecticides, manures in agriculture, paints, and incorrect dumping of sewage from cities and industries. (P.K.Rai, S.S.Lee, et al. 2019).

R.K. Goswami et al. offered information on the latest cutting-edge nanomaterials methods for heavy metal removal, as well as the principles underlying the absorption of heavy metals by algae and their potential to remediate.

The ecosystem and all living things on land, in the air, and in water are seriously threatened by drinking water and wastewater contaminated with toxic metals. Various methods, including natural, sophisticated nanomaterials-based and traditional approaches, have been used to treat metals. Microalgae are a significant class of microorganisms that are useful in numerous ecological applications and can remove heavy metals from wastewater when used in biological processes. It also offers a lot of benefits over traditional cleanup techniques. These algae cells are used as a source of nutrients to control the metabolism of heavy metals and are capable of absorbing them through a variety of physical and biological processes, ultimately leading to the formation of biomass. Additionally, an improvement in the elimination of heavy metals, several techniques, including the fixation of algal cells, the formation of algal groups, and the creation of materials for microalgae-based nanocomposite materials, can be used to increase efficiency. It can also make a big difference in the preservation of the environment now and in the future. Wastewater may be able to have contaminants removed by microalgae. It has been the subject of numerous studies that indicate it may remove multiple heavy metals in various kinds of wastewater (Goswami et al. 2020). (Oyebamiji et al. 2019) assessed the potential for heavy metal and dye removal by cultivating six distinct microalgae in textile effluent. This shows that chromogenic coating (4710–7003%) and heavy metals (V, Se, Pb, Cu, and Al) were eliminated from textile effluent by algae belonging to the Chlorellaceae family. There is a huge quantity of harmful material in the alkaline wastewater. Metals such as lead or acid mine wastewater that is directly discharged into the water body system damage aquatic ecosystems and have detrimental effects on the degradation of the environment. Nonetheless, by eliminating the hazardous heavy metals present in these mines, microalgae can cure acid mine wastewater (Samal et al. 2020). (Mullins and Richards 2013), extracted contaminants from both high-saline waste and local waste using microalgae Chaetoceros muelleri, Tetraselmis chuii, Pavlova lutheri, and a species of Nan gaditana. The outcome demonstrated that 90% of the pollutants in both sewages were eliminated by phytoplankton. Via living or dying cells, phytoplankton can remove pollutants from the environment. Nevertheless, additional changes to the system are needed to improve the removal efficiency and biomass utilization (Cheng et al. 2019). Numerous investigations into the immobilization of microalgae biomass for sewage treatment have been conducted. This method was also used to remove heavy metals. For instance, Tetraselmis chuii was immobilized using calcium alginate by (Moreno-Garrido et al. 2020). In order to extract Cd and Cu from ocean water. The outcome demonstrated that cells were immobilized and eliminated 20 and 100% of Cd and Cu, in that order. The suspended alga cell based on Lufa the cylindrical or loofa sponge has the ability to remove contaminants from the environment. Chlorella sorokiniana cells immobilized in L. cylindrica as well as free C. sorokiniana cells were tested for

Cd removal efficiency by (Akhtar et al. 2019). According to the findings, immobilized C. sorokiniana removed 979% of Cd at the initial level of 10 mg l1 Cd, whereas free C. sorokiniana cells removed 927% of Cd. Immobilizing microalgae improved metal removal effectiveness. Additionally, (Shen et al. 2020). Proposed that a fermentation technology can be used by phytoplankton to recover and immobilize Cd ions. It has been noted that a mixture of metal oxides, such as Fe2O3, likewise achieves the goal of immobilization of ions and aids in the more effective removal of heavy metals.

Liuwei et al examined the innovative amendments for soil and those greener methods of remediation critically. The sustainable use and management of soil resources is threatened by the accumulation of metalloids and heavy metals in the soil, which may have harmful impacts on ecosystems and human health. The immobilization, removal, or detoxification of heavy metals in soil can be achieved through a variety of treatment innovations, including chemical oxidation/reduction, soil cleaning, electrokinetic restoration, and solidification/stabilization (S/S). However, the social, economic, and environmental implications of these conventional methods limit their overall efficacy and durability. As the "green and sustainability restoration" (GSR) trend has grown, more efforts are being made to optimize the "net ecological impact" in a number of methods, such as resource recovery, adopting nature-based solutions (NBS), and energy conservation. Because iron-based additions have the best stabilization performances for both metal ions and oxyanions and cause very little disruption of the earth, they are one of the appealing possibilities for environmental treatment. In contrast, even if waste-derived materials are inexpensive, they have a longer-term risk of releasing contaminants, which lowers their general stability. It has been discovered that natural amendment-based S/S and phytoremediation are usually the "greenest" remediation techniques; however, prudent choices must be based on the outcomes of case-specific sustainable assessments. Lastly, it is suggested that combining a number of green remediation strategies could improve restoration effectiveness in a complementary way (Wang, et al 2021).

Radioactive Contaminants

Radioactive pollutants usually occur from the planet's crust, dangerous elements settle on the shallow of the earth and ultimately dissolve in drinking water. Water contaminated by radioactive compounds typically comes from nuclear fusion swaps, leftovers from uranium extraction, nuclear weapons testing, medical research, and unintentional leaks and explosions in industrial effluents (Figure 3) and nuclear reactors (S.K. Verma 2019). Radioactive sickness, cancer, and genetic abnormalities are just a few of the health risks that can result from consuming water contaminated with radioactive elements. Adsorption, ion exchange, and a process called reverse osmosis are examples of sophisticated water treatment methods that can be used to decrease radioactive pollution in water. In order to prevent and regulate harmful pollution, routine inspection and tracking of water sources is required (S.K. Verma 2019).

Adam J. et al Investigated the state of the art in radionuclide biogeochemistry principles and bioremediation process, and connections are made to enable the application of these ideas to the cleanup of radioactive effluent in the future.

Humma et al, talked about many biological remediation techniques for managing radioactive contamination, including microbes, plants, and myco-remediation. Large amounts of radioactive substances are used to meet demand for energy in a variety of industries, including nuclear power plants. As a result, nuclear installations and their spent sources—such as mining operations, the reuse of nuclear arms, and the generation of nuclear energy—produce a huge amount of radioactive waste. The extensive release of radioactive materials into the environment and subsequent movement poses health dangers to living things, which is a worldwide problem. For the efficient handling of radioactivity nuclide wastes, environmentally friendly methods must be adopted. One eco-friendly and viable method for treating radioactive material is biological remediation (Cheema, 2023).

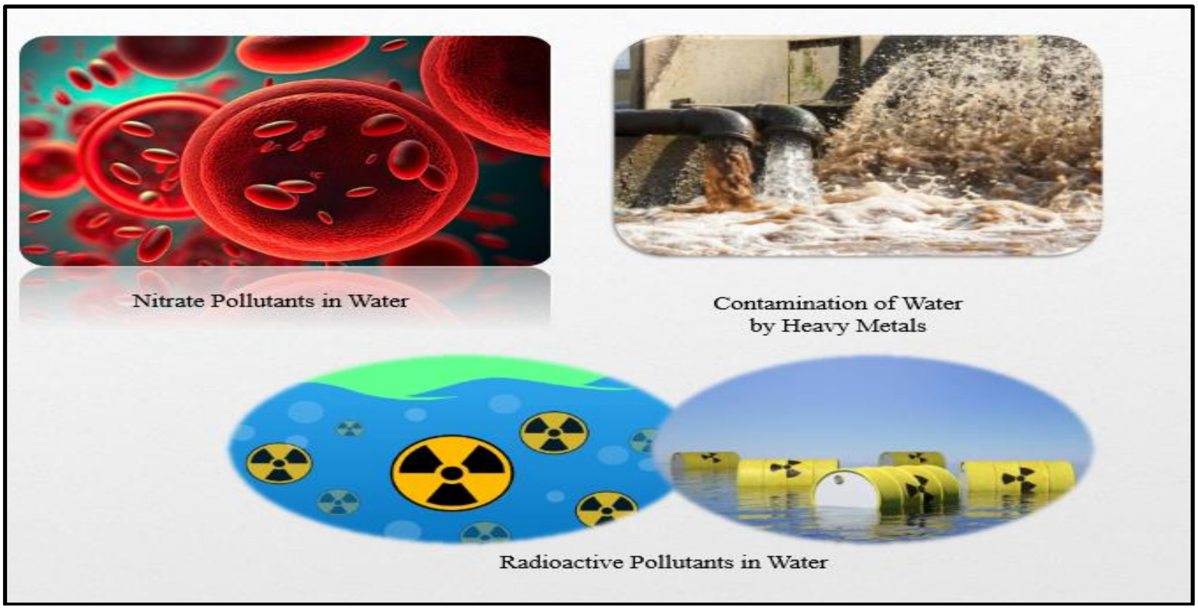

Figure 3: Contamination of water by inorganic pollutants

Pathogens

Microbes are microscopic creatures responsible for illness, such as viruses, bacteria, fungi, and some pests. The majority of germs found in contaminants typically cause hepatitis, and among their predominant pathogens are the pathogenic fungi Candidacies (N.J. Ashbolt at al 2019). Water can get polluted by pathogens due to a several of reasons, including sewage spills. Water-borne diseases can be produced by bacteria and virus such as Shebelle, Campylobacter, salmonella, and Cryptosporidium that are existing in manufacturing effluent. A number of prevalent diseases that affect people due to microbiological pollution include waterborne illnesses like cholera, typhoid, dysentery, polio, and hepatitis. Infection of microorganisms by heterotrophic bacteria with higher levels of pathogenic agents can be observed in aquatic ecosystems when untouched stagnant wastewater is contaminated with bacteria and Escherichia coli, as evidenced by certain research. Examples of germs found inside water include fecal streptococci, coli forms, E. coli, and coli forms, which are brought about by the contamination of feces. It's interesting to note that sewage pathogens can lead to serious gastrointestinal diseases (N.J. Ashbolt at al. 2019).

Darmawati et al, developed and applied a basic plate-based pathogenicity selection scoring technique for evaluating the infectiousness of 26 naturally occurring hydrolytic bacteria that were extracted from the untreated sewage of two hospitals located in Semarang, the heart of Java, Indonesia. Finding an affordable bioremediation process agent for hospital wastewater is essential because the existing global approaches to treating biological waste are still expensive and unfriendly to the environment. Hydrolysis bacteria have been used as bioremediation agents before, but it's crucial to make sure they meet safety regulations. On MacConkey Agar Plate (MAP), Blood Agar Plate (BAP), and Chocolate, in addition to Agar Plate (CAP), bacterial cultures were conducted concurrently, DNA sequencing was then performed. Following this, a method of grading was established using based on the isolation's capacity to generate violet color on the MA and the bacteria's hemolytic properties on the BAP and CAP media (Darmawati, Sri, et al. 2021).

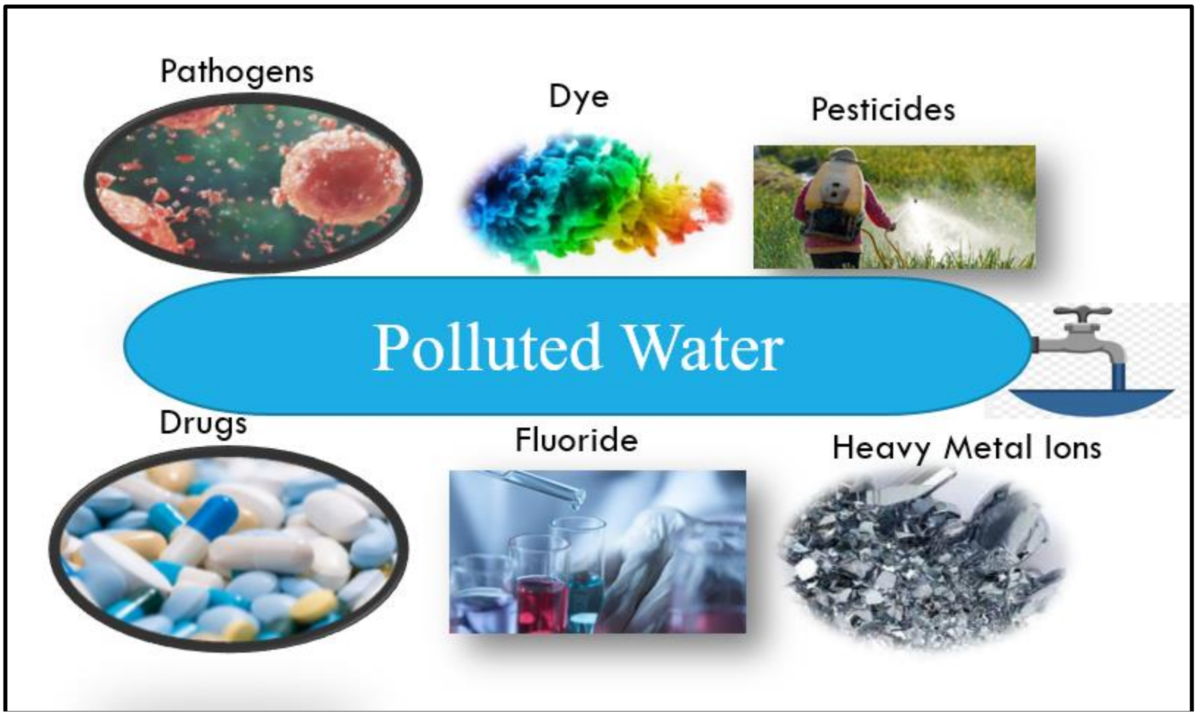

Figure 4: Some common water pollutant sources

Many chemical contaminants, including pesticides, polyaromatic hydrocarbons, halogenated petroleum hydrocarbons, nitroaromatic compounds, metals, and industrial solvents (Figure 4), have had their concentrations and toxicity reduced by the use of the bioremediation process technique (Dua et al., 2020). The domain According to the bioremediation process is made up of practical research fields such as biogeochemical assessment techniques, environmental attenuation, fate modeling, and metabolic methodologies, as well as fundamental study areas such as cometabolism, biotransformation kinetics, biotreatment, and biogeochemical or modeling. Both large-scale and smaller-scale applications of bioremediation have been successful; one notable example of bioremediation's usage for the removal of contaminants is the cleaning of the Alaskan oil spill (Boopathy, 2019).

Modupe S. et al advocated for the employment of microorganisms in the process of bioremediation. Numerous forms of pollution brought on by the discharge of hazardous substances entering the natural environment have increased as a result of the rapid rates of growth in urbanization and manufacturing. Manufacturing industries (such as detergent and dye), the agriculture sector (such as herbicides and insecticides), the mining sector (such as cyanide and sulfuric acid), and the building industry (such as cement and metals) are typically responsible for this. The health of plants, animals, and people is negatively impacted by these contaminants. Additionally, they cause the population of microbes to be destroyed in both land and aquatic ecosystems, which makes remediation necessary. While many remediation techniques, including both physical and chemical techniques, have been used for many years, their shortcomings and difficulties have encouraged the application of the bioremediation process as a replacement. Utilizing biological agents, such as microorganisms and plants, to eliminate or decrease the effects of environmental contaminants is known as bioremediation. Microorganisms are used more often than others because of their quick development and ease of manipulation, which improves their performance as biological remediation agents. Various cohorts of Algae, fungi, and bacteria are being used to clean up various natural environment pollutants (Ayilara, M. S., & Babalola, O. O. 2023).

M. Abdul et al, investigated that transnational contamination of the environment is a major problem that requires creative solutions for both reduction and remediation. In terrestrial biological remediation, microorganisms have proven to be vital instruments, providing adaptable and long-lasting solutions to diverse types of contaminants. This examines the critical role that microbes play in biological remediation tactics, showcasing cutting-edge methods and uses that maximize the ability of the world of microbes to efficiently fight contaminants. This thorough review raises hopes for the potential of microbial-based biological remediation as a major force in controlling pollution and restoration of the environment by discussing the basic mechanisms of microbial-mediated bioremediation, examining new technological developments, and presenting examples showing effective microbial treatments (M. Abdul Kapur, M et al 2024).

Classification of Microorganisms used for Bioremediation

Bioremediation employs various microorganisms, including bacteria, fungi, algae, and yeast, to degrade and detoxify pollutants. Bacteria such as Pseudomonas and Bacillus break down hydrocarbons and heavy metals. Fungi like Phanerochaete chrysosporium decompose complex organic compounds. Algae are used to absorb heavy metals and nutrients from water, while yeast like Saccharomyces cerevisiae helps in detoxifying industrial waste. These microorganisms are selected for their specific metabolic capabilities and environmental adaptability (Bala, et al. 2022).

Bioremediation of Pollutants by Yeast

A number of the most powerful species of microbes with significant potential as a bioremediating agent is yeast. Yeasts represent a diverse range of microorganisms with extensive functional applications in the biotechnology industry. They have gained recognition because they are inexpensive, simple to cultivate in inexpensive media for growth, readily available biomass supplies, and capable of withstanding the harshness of adverse environments. Furthermore, these species are widely distributed and can potentially remove heavy metals from contaminated water (Figure 7), contributing significantly to the ecosystem's return to its pre-contamination state. Yeasts are employed not only to remove metals but also should have the ability to decolorize and break down dyes from hazardous chemicals, petroleum products, and textile industry effluents. Yeast species belonging to the family Saccharomyces are thought to have numerous uses in the nutritional, medicinal, and bioprocess industries, as well as in the environmental domain. Although bioremediation with yeast sp. has many benefits, it is limited in certain ways by its particular use. Particular needs for the environment, the right amounts of nutrients for the biological processes, and worries about the type of product that is produced after the breakdown; this requires attention. We have covered the possible contribution of several species of Candida to the biological remediation of stormwater and several industrial contaminants in this review. Additionally, a recent update on the significance of Candida sp. in the bioremediation of various industrial wastes was provided by (Kramer 2020).

Table 2: Candida species used for degrading synthetic dyes, hydrocarbons, and petroleum

Species	Pollutants	Culture Conditions	Degradation Percentage (%)	Reference
Candida glabrata	Motor oil	Temperature-27°C, agitation speed-150 rpm for 24 hours, pH-5.7	85%	Luna et al. (2019)
Candida sphaerica	Motor oil	Temperature-27°C, agitation speed-150 rpm for 24 hours	68%	Daverey and Pakshirajan (2013)
Candida dibgoiensis	Petroleum hydrocarbon	Temperature-30°C, agitation speed-180 rpm for 7 days, pH-3	75%	Kolb et al. (2018)
C. vishwanathii	Petroleum Crude oil	Temperature-30°C, agitation speed-180 rpm for 72 hours	51%	Priya et al. (2015)
Candida catenulate	Diesel Hydrocarbon	Temperature-30°C, agitation speed-204 rpm for 6 days, pH-4.7	82.1%	Babaei and Habibi (2019)
C. tropicalis	Azo dye (Acid brilliant scarlet GR)	Incubation-160 rpm, temperature-35°C, concentration-20 mg/l	96.3%	Kolb et al. (2016)
Candia Catenulate	Diesel Hydrocarbon	Temperature-30°C, agitation speed-204 rpm for 6 days, pH-4.7	82.1%	Babaei and Habibi (2019)
Candida rugopelliculosa	Azo dye (Reactive Blue 13)	pH-2–8, temperature-28°C, concentration-50 mg/l	93%	Liu et al. (2012); Solís et al. (2014)
Candida boidinii	Azo dye (Reductive Black 5)	Incubation-250 rpm, pH-5.41, temperature-25°C, concentration-200 mg/l	98.26%	Martorell et al. (2016)
Candida cylindracea	Azo dye (Orange G)	Incubation-150 rpm, pH-3–8, temperature-20–40°C, concentration-500 ppm	92%	Alcantara et al. (2018)
Candida krusei	Azo dye (Reactive Brilliant Red K-2BP)	Incubation-200 rpm, temperature-28°C, concentration-50 mg/l	97%	Yu and Wen (2017)

Bioremediation of Pollutants by Bacteria

Scientists reported finding multiple bacterial strains that can bleach dyes for textiles that were recovered from polluted areas. Bacillus subtilis, Aeromonas hydrophila (Ogugbue and Sawidis 2020), and Bacillus cereus, among others (Ola et al. 2019) are bacteriological cultures that can breakdown down azo dyes. For the biological elimination of azo dye, Klebsiella pneumoniae RS-13 and Acetobacter liquefaciens S-1 were found to be capable of discolorizing textile industrial wastewater containing methyl red. A Pseudomonas bacterium that was effectively isolated from soil-degraded and discolored dyes that belonged to the azo and triplet methane groups. In aerobic circumstances (pH 6–8 and temperature 30–40 C), malachite green, fast green, brilliant green, Congo red, and methylene blue were decolorized to a range of 30–70%. E. coli and Pseudomonas species were used to decolorize Congo red and direct black 38 in anaerobic, aerobic, and microaerophilic environments (Isik and Sponza 2021). At the conclusion of the anaerobic incubation, the bacteria E. coli eliminated up to 98 and 72% of the color of the Congo red and direct black 37, accordingly absolutely no color was seen when using aerobic fermentation conditions, but E. coli eliminated the azo dyes, including the Congo red and influence black 38, under the microaerophilic conditions used. After five days of aerobic Pseudomonas species, the incubation processes the color was completely removed in 39 and 75% of cases, respectively. Furthermore, Aeromonas hydrophila showed the highest color removal efficacy with diverse dyes out of the six microbial strains that were isolated from sludge samples and mud lakes and had the capability to degrade textile dyes. In ideal circumstances (pH 5.5–10, temperature 20–35.8 C), in 8 dyes, at a dye concentration of 3000 mg/L, more than 90% of the discoloration of red RBN was observed (Isik and Sponza 2021).

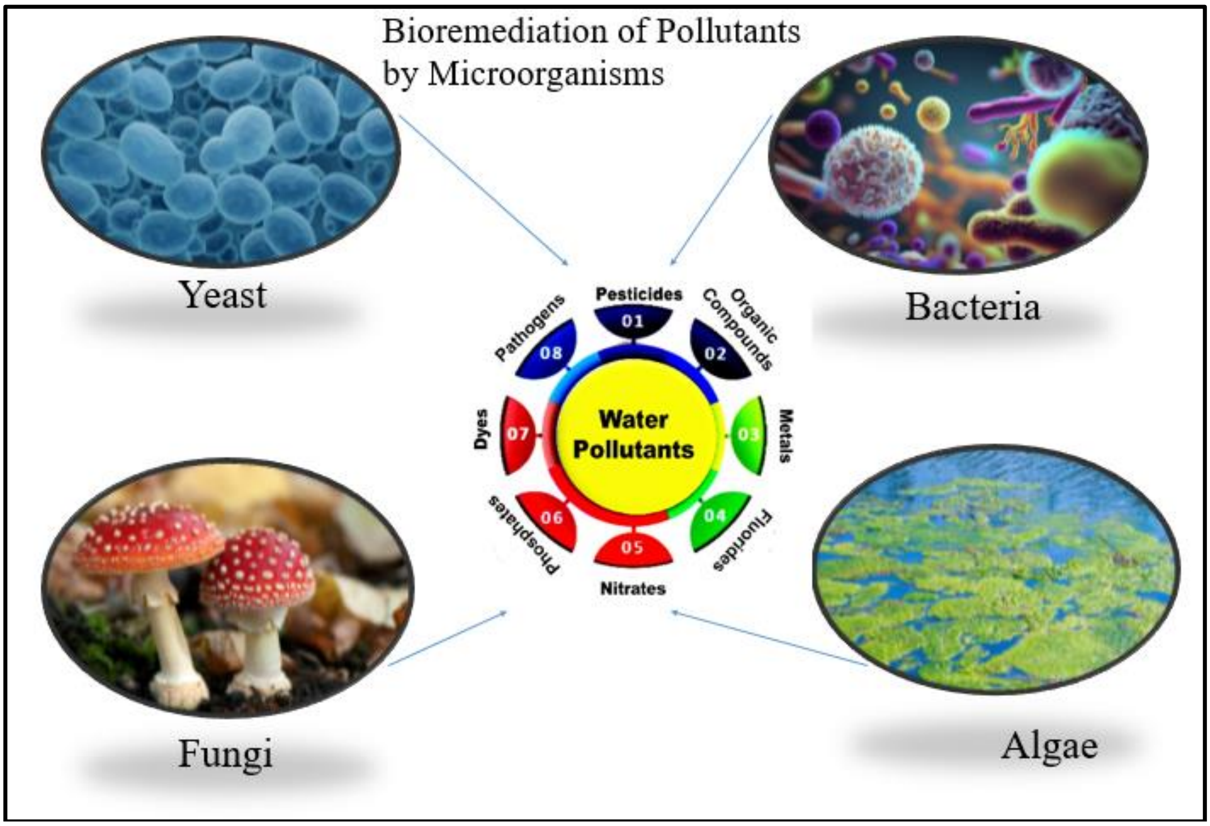

Figure 5: Bioremediation of pollutants using different microorganisms

Bioremediation of Pollutants by Fungi

Fungi have been shown to be an effective species for removing dye from textile wastewater (Figure 5). Due to the production of extracellular enzymes that solubilize solid materials, fungi mycelia have an additive advantage over single-celled organisms. Fungi have a higher ratio of cell to surface, which increases their enzyme and physical contact with the surroundings. A further benefit of the fungal enzymes' intercellular structure is their ability to withstand higher poison quantities. Numerous fungal taxa have been implicated in the different forms of discoloration of dyes used in textiles. The most effective white rot fungus in dissolving artificial dyes because these fungal organisms, which are primarily basidiomycetous and are capable of substantial aerobic lignin depolymerization and mineralization, belong to a broad ecophysiological group. These characteristic features from the WRFs create one or more extracellular lignin-modifying enzymes, which can degrade a variety of contaminants because they don't have particular substrates (Zhuo, R., & Fan, F. (2021).

Around the world, around two million metric tons of insecticides are used annually as a result of rising food demand and the need to reduce agricultural losses caused by pests (Sharma et al., 2019). The intentional application of insecticides eliminates weeds, insects, and rodents in particular as well as other living organisms that pose a hazard to the crops that are being cultivated. Nonetheless, according to (Tudi, et al. 2021), 90% of agricultural pesticides are thought to float around the environment rather than reaching the targeted organism. Insecticides are commonly found in the oceans, the groundwater, soil systems, and the atmosphere. Chemicals like organochlorines organic phosphate steroids, and carbonates are linked to negative outcomes like high environmental persistence, bioaccumulation, long-range transmission, and adverse effects to non-target organisms (Kumari et al., 2014; Kumar et al., 2019). For instance, being exposed to chemicals may result in various forms of body malignancy, mutagenic and genetically toxic imperfections, as well as hormonal and neurological disorders (Wołejko et al., 2020). This is due to a high level of population and highly modern methods of agriculture, some appear to have greater long-term health effects and environmental problems than acute fatal consequences (Tudi, M., et al 2021). According to Mansouri et al. (2017), the excessive use of the pesticide dichlorodiphenyl trichloroethane (DDT) during the 1940s had detrimental ecological effects that, in certain situations, took years to manifest. DDT continues in use in many nations and its derivatives are still present in the environment after decades of prohibition by the first countries that outlawed it in the 1970s. Numerous pesticides, such as carbonates, steroids, organochlorines, and organophosphorus or chemicals, have been shown to be degraded by fungi (Soares, P. et al 2021).

The use of fungus for the biological remediation of metallic substances, particularly toxic metals, has been studied more in terrestrial environments rather than aquatic ones (Chaurasia, P. et al 2022). Bioremediation has shown interest in reducing hazardous Cr (VI) to non-toxic Cr (III). Within six months, 94% of the Cr (VI) in soil contaminated with chromium was eliminated by the brown-rot fungus Gloeophyllum sepiarium. It has been demonstrated that isolates of Neocosmospora spp., Aspergillus spp., Penicillium spp., and Rhizopus spp. from soils contaminated with arsenic can withstand concentrations of sodium arsenate up to 10 g/L. In a different investigation, Aspergillus and Trichoderma species tolerated up to 10 g/L of arsenate, furthermore demonstrated resistance to up to 10 g/L of arsenate, as did representatives of the genera Chaetomium, Myrothecium, Stachybotrys, Rhizomucor, Fusarium, Rhizopus, and Microdochium. Arsenic has been demonstrated to bioaccumulate in the cells of Trichoderma asperellum, F. oxysporum, and Penicillium janthinellum (Ceci, A et al 2020). Aspergillus fumigatus and Aspergillus niger-coated nanoparticles with magnetic properties were employed as a biosorbent to remove Cr(VI) in aquatic settings, magnetic nanoparticles have a removal efficacy of 249.9 mg/g, which makes them a potential Cr(VI) removal material for aquatic settings. The elimination was impacted by glucan or chitin levels polymers. These have been demonstrated to have ionizable functional groups (such as carboxyl, sulfate, or phosphate) that can facilitate possible binding sites for ion exchange and metal chelation. According to a number of studies, a species' ability to absorb metals through biosorption may vary (Dusengemungu et al., 2020). However, selected binding of metals affinity was demonstrated in the order of Cu(II) > Pb(II) > Cd(II) in metal sorption tests with Cu, Pb, and Cd and A. fumigatus (Dusengemungu et al., 2020). Additionally, most of the fungal isolates come from the families of Aspergillus, Penicillium, Alternaria species, Geotrichum, and Fusarium resistance to Pb, Cr, Cu, and Zn was found in water and sediment samples from five polluted sites in the Moghogha River (Tangier, Morocco) (Ceci, A et al 2020). There aren't many reports on marine fungi as possible agents for heavy metals biological remediation, but what is known appears to be encouraging. For example, the species Yarrowia lipolytica is a viable option for a number of biotechnological uses, such as the processing of crude oil, palm oil plant pollutants, and 2, 4, 6-trinitrotoluene (TNT) (Hamdan, A et al 2021). Idd1 and Idd2, two marine strains of Yarrowia spp., demonstrated remarkable Hg removal efficiency.

In a medium containing 16 mg/mL Hg+2, Yarrowia spp. eliminated more than 97% of the mercury 49–83% of the removal was accomplished via the most common removal route, which was absorption to the cell wall. But vaporization and biological accumulation were also significant processes in the Hg removal process (Oyetibo et al., 2019). However, the ability of Yarrowia lipolytica (NCIM 3589 and 3590) to remove pollutants was not investigated (Bankar et al., 2018). Moreover, the species demonstrated a high resistance to a variety of harmful ions. It was discovered that Saccharomyces candidus, which was separated from the city coast of the oceans, could withstand arsenic (Bankar et al., 2018).

Bioremediation of Pollutants by Algae

Algae can acquire plant nutrients, heavy metals, pesticides or herbicides, organic and inorganic hazardous chemicals, and radioactive compounds in the mitochondria, cyanobacteria have emerged as important microorganisms for the natural cleaning of waste (Figure 5). The use of microalgae in biological wastewater treatment systems has grown significantly over the past 50 years, and it is now generally acknowledged that these systems can treat wastewater just as well as more traditional techniques for wastewater treatment. Due to these unique characteristics, algal wastewater treatment systems are now a viable, reasonable alternative to more complicated, costly systems for treating wastewater, specifically for the purpose of purifying. The damage to the environment caused by the effluent discharge into water sources may be mitigated by producing biomass from microalgae from textile-related wastewater. Within three months of the incubation process, 50–70% of the color was eliminated from both pure and combined microalgae cultures. The pigment decrease system revealed a quick rate of elimination period, and then a declining removal rate phase. Three fundamentally distinct methods of assimilative chromophores that use for biomass, CO_2, and H_2O generation were responsible for color elimination through microalgae chromophore absorption on algae biomass and the conversion of colored compounds into noncolored ones. According to a study by (Dong, et al 2019), algae that can break down azo dyes using an induced version of azo reductase were able to effectively remove color. Azo dyes could be broken down into their aromatic amino acids by a number of Chlorella and Oscillatoria species, which could then be further broken down into simpler chemical compounds. Some may even get all of the carbon and nitrogen they need from azo dyes. Since these algae are crucial for the elimination of aromatic amines, (Oscillatoria tenuis, C. vulgaris, and Chlorella pyrenoidosa) has also been evaluated (Dong, H et al 2019). Furthermore, the algae may directly contribute to the azo dyes' breakdown, chlorine bacteria can biosorb multiple reactive colorants. Both the process of biosorption and the bioconjugation processes can be used by dehydrated spirogyra and rhizopus to decolorize acid red 274 dye. The amounts of dye removed reduced as the percentage of S. rhizopus rose, whereas the quantity of dye eliminated decreased (Ozer et al. 2021).

Table 3: Decolorization of dye with algae isolated from contaminated areas

S/N	Algae	Dye	Conditions	Removal Efficiency	Reference
1.	Algae biomass	Malachite green	pH 4-6, temp. 49°C, 45 min	84%	Gajare and Menghani (2014)
2.	Cholera sp.	Basic green 4	pH 7.0, temp. 23°C	97%	Khataee et al. (2012)
3.	Cosmarium sp.	Malachite green	pH 9.0, temp. 25°C, static, 24 h	93.3%	Daneshvar et al. (2012)
4.	Green algae	Monazo and diazo dyes	Temp. 25°C, 2 days	70%	Omar (2019)
5.	Green algae	Indigo	pH 8, temp. 24°C, salinity at 15 G/L, 6 days	88.2%	Elisangela et al. (2017)
		Remazol brilliant orange		77.2%	
		Crystal violet		74.6%	
6.	Lyngbya sp. BDU 9001	Textile dye	pH 7, temp. 29°C, 15 days	75%	Henciya et al. (2015)
7.	Shewanella aquimarina	Azo dyes including acid red 26, methyl orange, acid orange 8, reactive red 121, direct blue 70	Temp. 30°C, aerobic, 200 rpm	-	Meng et al. (2018)

Researchers looked into the possibility of using the algal species Cosmarium sp. as a workable biological material for the biological removal of malachite gemstone green and triplet methane dye. According to (Mohamed, Z., Alamri, S., & Hashem, M. 2021), immobilized thermophilic cyanobacteria strain Phormidium sp. has good decolorization activity in a thermophilic condition. The capacity of the test biosorbent to eliminate azo dye from the aqueous phase at acid pH 2 at the ideal temperature of 30 C and a concentration of dye 5 mg/L was demonstrated by mixed batches adsorption carried out on algal and fungus Sp 102 C, vulgaris Culture in the textile pollutant effluent presented that this microalga may be used to produce biomass, remove dye and COD, and improve color. The highest specialized rate of growth μmax and optimum cell concentrations Cmax were observed in wastewater at levels of 5.0% and 17.5%, respectively, when C. vulgaris was cultivated (Kong, et al. 2021).

Current Challenges and Research for the Generation of Value-Added Products from Wastewater

Many of the polluted water operational challenges, like the use of dependable and environmentally friendly equipment, reduced operating costs, fewer carbon emissions, potential power savings, and minimizing chemical inputs, are still a challenge for the majority of wastewater treatment facilities today. There have been several stages to the treatment, and there isn't a single procedure unit that can be used to treat someone properly and efficiently. The economics of treating stormwater have been a barrier, but they can be overcome by gathering cellulose to create value-added goods. In the exclusive manufacturing of valuable products like biofuels, it is not commercially possible to produce a category called poly using algae traditionally for colors. To be cost-effective in a sustainable biorefinery strategy, the novel techniques for producing goods with value were incorporated into large systemic components, including wastewater treatment and other procedures. These methods effectively utilize effluent and lessen competition for agricultural land. The second-generation effluent of stormwater contains approximately 110 mg/L of phosphorus and 2040 mg/L of nitrogenous ammonia (Fayyaz, M. et al. 2020). Cultured N. oleoabundans in dairy fertilizer that had been anaerobically absorbed, the buildup of 90%95% of nitrogen and 10%30% (by weight) of fatty acid methyl ester (FAME) was generated. The mixotrophic culture of C. vulgaris produced more biomass than photoautotrophic and heterotrophic approaches, it also led to a release of acetate in aerobic digestion effluents (Laraib, N. et al. 2021).
Development of phototrophic algae that produces the astaxanthin and heterotrophic bacterium Bacillus subtilis. In starch-rich food effluent, Haematococcus pluvialis formed 2.2 g/L of biomass, which resulted in 65% astaxanthin (Bohutskyi et al., 2018). The waste-activated sludge contains γ-Proteobacteria, Pseudomonas sp., and a cultured bacteria called Cellvibrio sp. These bacteria use xylose as a major source of carbon and collect 32% PHA of dry cell weight. These bacterial consortiums provide a stable PHA system output (Kouřilová, X et al. 2020). Batch aerobic fermenters' ability to produce biogas may depend critically on the ratio of substrate to inoculum. S. platensis, Chlorella, and other species were grown in diluted fermenter effluents that were metabolized anaerobically. This protein-rich algae can be fed to fish and aesthetic crustaceans (Llamas, M et al 2020).
The purpose of this review is to address the critical challenges in wastewater management by highlighting innovative approaches for generating value-added products from wastewater, thereby aligning with sustainable development goals. While traditional wastewater treatment techniques focus on pollutant removal, they often face economic and operational barriers, such as high chemical inputs, energy consumption, and limited scalability. This review explores novel methods that integrate wastewater treatment with the production of value-added products, such as biofuels, fatty acid methyl esters (FAME), and biomass-derived materials, addressing these challenges holistically. This review also emphasizes integrating these methods into a systemic biorefinery strategy, which effectively utilizes effluent, reduces competition for agricultural land, and mitigates economic barriers, such as the cost of stormwater treatment. By synthesizing these insights, the review provides actionable guidance for researchers and industries to transition from pollutant mitigation to a circular economy approach.

CONCLUSION

The application of microorganisms is self-sufficient and active for the secondary and tertiary effluent treatment methods in a single step. It also offers advantages for treating continuously flowing waste effluents by replicating a natural ecosystem. Additionally, the absence of aeration requirements and community integration together increase the efficiency of nutrient elimination, bioremediation of toxic components, etc., by a synergistic performance. Current technologies helped in better investigation of consortia leading to a proper understanding of their relationship. The use of innovative tools is also helpful in accessing both the genomics and metabolic stability of consortia under diverse stress situations leading to enhancement of the control process. The economics of wastewater treatment at a large scale is still a hurdle, different reports show the significance of bacteria in wastewater treatment and other pollutants such as pesticides, heavy metals, hydrocarbons, dyes, nitrates, etc. To harness the economic viability of wastewater treatment technology, biorefinery approaches can be applied by the current PBRs for proper biomass cultivation, generation of value-added products as well as protection of the microorganisms against any inhibitory effects.

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