J.Mycopathol.Res. 63(3) : 521-535, 2025, ISSN : 0971-3719 (Print), 2583-6315 (Online) 10.57023/JMycR.63.3.2025.521

REVIEW

Microbial bioremediation for waste water treatment

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Received : 20.03.2025 Accepted : 26.05.2025 Published : 29.09.2025

Earth has only 3 percent of fresh water of which only about 1.2 percent can be used for drinking purpose. This small portion too is deteriorating significantly due to anthropogenic activities which in turn leads to serious problem i.e., water pollution. One of the major concerns includes waste water problem due to the large amount of untreated waste water being released into fresh water bodies leading to oxygen depletion, bio magnification and water borne pathogens. This results in the disturbance of aquatic ecosystem, transmission of diseases and unavailability of clean drinking water. There are various sources of waste water such as sewage, industries, agricultural etc. To cope up with this problem there are various conventional methods but they are not cost effective and sustainable. Bioremediation using bacteria is an eco-friendly, affordable, sustainable and researched to be efficient strategy.Researchers have explored many bacterial species having biodegradation potential for waste water treatment depending upon their ability to degrade different contaminants. In this chapter bioremediation by different bacterial communities, their target contaminant, their mechanism of biodegradation and factors affecting will be discussed.

Keywords : Bacteria, Bioremediation, Sustainable, Waste water.

INTRODUCTION

In the modern era, as we confront the escalating challenges of pollution and environmental degradation, the imperative for sustainable solutions has become more pressing than ever (Lu *et al*., 2015). Among these challenges, the contamination of water bodies due to industrial, agricultural, and domestic activities stands out as a critical issue with far-reaching consequences for both ecosystems and human health (Chakraborty and Chakraborty, 2021). In response, the field of bioremediation has emerged as a promising avenue for mitigating water pollution while also harnessing the inherent power of nature to restore balance (Kapoor and Shah, 2023).

Central to the success of bioremediation efforts is the pivotal role played by bacteria, the microscopic powerhouses that drive numerous biochemical processes essential for life on Earth (Thirumalaivasan*et al*. 2024). Previous reviews have also focused on the potential of bioremediation for waste water treatment (Saeed *et al*. 2022).

In the context of wastewater treatment and resource recovery, bacteria exhibit remarkable capabilities to degrade and detoxify a wide range of pollutants, transforming them into harmless byproducts or valuable resources(Maqsood *et al*. 2023). From organic compounds to heavy metals, these versatile microorganisms can target various contaminants with precision and efficiency, offering a cost-effective and environmentally friendly alternative to traditional remediation methods (Sharma *et al*. 2022).

Characteristics of Wastewater

The characteristics of wastewater significantly affect the treatment approach to be pursued, as

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well as the reactor design selection process. For such characteristics, the most important are concentration for suspended solids, organic strength (BOD or COD), temperature, pH, and inhibitor presence (Asthana *et al*., 2017).

Sources of Wastewater

On the basis of the source from which the wastewater is being generated, there are various types of wastewater, some of them are listed below :

Domestic Wastewater

- Sewage Sludge
- Diary Wastewater
- Winery Wastewater
- Tannery Wastewater
- Textile Wastewater
- Food Wastewater
- Phenolic Wastewater
- Carpet Mill Wastewater
- Slaughter House Wastewater
- Pharmaceuticals Wastewater
- Beverage Wastewater
- Paper industry Wastewater
- Oil Mill Wastewater

Bioremediation

Bioremediation is a process that uses naturally occurring organisms to break down hazardous substances into less toxic or non-toxic substances(Abatenh *et al*. 2017). It's a form of environmental cleanup that harnesses the power of living organisms, such as bacteria, fungi, or plants, to degrade or remove contaminants from soil, water, or air (Gianfreda *et al*.2016).There are different types of bioremediation techniques like biostimulation involves adding nutrients or other substances to the contaminated area to stimulate the growth of naturally occurring microorganisms that can degrade the pollutants(Udume *et al*. 2023). In bioaugmentation specific microorganisms are introduced to the contaminated site to enhance the degradation of pollutants (Nwankwegu *et al*. 2022). Phytoremediation involves use of plants to remove, stabilize, or degrade contaminants in the soil, water, or air. Certain plants have the ability to absorb and accumulate heavy metals or other pollutants in their tissues (Jeevanantham *et al*. 2019). Bioventing involves enhancing the activity of naturally occurring microorganisms in the soil by providing them with additional oxygen (Anekwe and Isa, 2021). In composting organic materials are used to degrade contaminants in the soil through the activity of microorganisms (Masciandaro *et al*. 2013).

Bioremediation is often preferred over traditional cleanup methods because it is generally more cost-effective, environmentally friendly, and can often be carried out in situ, meaning the contaminants can be treated without being removed from the site (Kumar *et al*. 2018). However, its effectiveness can vary depending on factors such as the type of contaminant, site conditions, and the presence of suitable microorganisms(Abatenh *et al*. 2017).

Bacteria for Bioremediation

Bacteria play a crucial role in bioremediation of water contaminated with various pollutants. *Pseudomonas* species are known for their versatility in degrading a wide range of organic pollutants, including hydrocarbons, pesticides, and aromatic compounds(Mediæ *et al*.,2022). They are commonly used in bioremediation of oil spills and contaminated water bodies.While *E. coli* is often associated with water contamination and can be harmful, certain strains of *E. coli* have been engineered or selected for their ability to degrade specific pollutants, such as phenols and chlorinated compounds(Sharma *et al*.2024). These strains can be used in bioremediation applications under controlled conditions. *Rhodococcus* species are known for their ability to degrade complex hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs), which are common contaminants in water bodies. They can also degrade pollutants like gasoline, diesel, and crude oil (Kuyukina and Ivshina, 2019). *Bacillus* species are known for their robustness and ability to survive in diverse environmental conditions. They are capable of degrading a variety of pollutants, including hydrocarbons, heavy metals, and pesticides (Sarker*et al*. 2021). *Bacillus subtilis*, for example, has been used in the bioremediation of oil-contaminated water

(Safdari *et al*. 2017). *Alcaligenes* species are capable of degrading a wide range of organic compounds, including aromatic hydrocarbons, chlorinated solvents, and pesticides. They have been used in the bioremediation of industrial wastewater and contaminated groundwater (Patel *et al*. 2022). *Nitrosomonas* and *Nitrobacter* spp.These bacteria are involved in the biological oxidation of ammonia to nitrate in a process known as nitrification (Noofan *et al*. 2009). They play a crucial role in waste water treatment by converting toxic ammonia to less harmful nitrate. Denitrifying bacteria, such as *Paracoccus denitrificans* and *Pseudomonas denitrificans*, are capable of reducing nitrate and nitrite to nitrogen gas under anaerobic conditions. This process, known as denitrification, is important for removing excess nitrogen from water bodies and waste water (Medhi *et al*. 2017). *Dehalococcoides* species are anaerobic bacteria capable of dechlorinating chlorinated compounds, such as chlorinated solvents like trichloroethylene (TCE) and polychlorinated biphenyls (PCBs), which are common groundwater contaminants. They play a critical role in the bioremediation of chlorinated solvent-contaminated sites through a process called reductive dechlorination (Dutta *et al*. 2022).*Sphingomonas* species are known for their ability to degrade various aromatic compounds, such as polycyclic aromatic hydrocarbons (PAHs), which are often found in water bodies contaminated by industrial activities or urban runoff. They possess enzymes capable of breaking down complex aromatic structures into simpler compounds that can be utilized by other microorganisms or mineralized into harmless byproducts (Premnath *et al*. 2021). *Methylococcus* species are methanotrophic bacteria that can utilize methane as their sole source of carbon and energy. Methane is a potent greenhouse gas and can also be a significant component of contaminated ground water or landfill leachate (Strong *et al*. 2017). *Methylococcus* spp. can mitigate methane emissions from water bodies by oxidizing methane to carbon dioxide and water under aerobic conditions (Jung *et al*. 2020). *Acinetobacter*species are versatile bacteria known for their ability to degrade a wide range of organic pollutants, including hydrocarbons, aromatic compounds, and industrial chemicals. They are commonly used in bioremediation of oil spills and wastewater contaminated with petroleum hydrocarbons(Pandolfo *et al*.,2023). *Shewanella* species are capable of reducing metals and metalloids, such as chromium, uranium, and arsenic, through microbial processes. They play an important role in the bioremediation of metal-contaminated water bodies by converting toxic soluble metal ions into less toxic or insoluble forms that can be precipitated or immobilized (Shukla *et al.* 2019). Certain phototrophic bacteria, such as purple non-sulfur bacteria and green sulfur bacteria, can utilize light energy for the degradation of organic pollutants and the removal of nutrients from water bodies(Lu *et al*., 2021). These bacteria are capable of photosynthetic metabolism and can thrive in environments with sunlight exposure (George *et al*. 2020).Biofilms, which are communities of microorganisms attached to surfaces and encased in a matrix of extracellular polymeric substances, play a crucial role in the bioremediation of water bodies by providing a microhabitat for diverse microbial populations involved in pollutant degradation processes (Patel *et al*. 2022). Bacteria capable of forming biofilms, such as *Pseudomonas aeruginosa* and *Bacillus subtilis*, contribute to the effectiveness and resilience of bioremediation systems (Mishra *et al*. 2022).

Mechanism of bacteria for degradation of waste water pollutants

Bacteria employ various mechanisms for the degradation of pollutants in wastewater. These mechanisms involve a combination of biochemical pathways, enzymatic reactions, and metabolic processes (Mathew *et al*. 2022). Here's an overview of some common mechanisms used by bacteria for the degradation of wastewater pollutants:

Aerobic degradation

Many bacteria degrade pollutants under aerobic conditions, where oxygen is present. In aerobic degradation, pollutants such as organic compounds are oxidized by enzymes, such as oxygenases and dehydrogenases, into simpler compounds like carbon dioxide, water, and biomass (Saravanan *et al*. 2021). This process often involves the sequential action of multiple enzymes to break down complex organic molecules step by step.

Anaerobic degradation

Some bacteria can degrade pollutants in the absence of oxygen through anaerobic respiration or fermentation. Anaerobic degradation typically occurs in environments where oxygen is limited or absent, such as deep within wastewater treatment systems or in anaerobic digesters (Nguyen and Khanal, 2018).This process is divided into three stages, namely hydrolysis and fermentation, acidogenesis and acetogenesis, and methanogenesis; which illustrate the sequence of microbial activities that occur in the process biogas production (Menzel *et al*., 2020).

Biodegradation

Biodegradation is the process by which bacteria enzymatically break down organic pollutants into smaller molecules that can be metabolized as carbon and energy sources (Maier and Gentry, 2015). Bacteria secrete extracellular enzymes to hydrolyze complex organic compounds, such as proteins, carbohydrates, and lipids, into soluble intermediates that can be transported into the bacterial cell for further degradation (Kumari and Das, 2023).

Co-Metabolism

Co-metabolism involves the degradation of pollutants by bacteria using secondary metabolic pathways that are not directly involved in the growth and maintenance of the bacterial cell(Espinosa-Ortiz *et al*. 2022). In co-metabolism, bacteria metabolize pollutants using enzymes and pathways originally evolved for the degradation of natural substrates. This process can result in the transformation or mineralization of pollutants into less toxic or inert compounds(Kumari and Das, 2023).

Enzymatic transformation

Bacteria produce a diverse array of enzymes capable of transforming specific classes of pollutants. For example, oxygenases are enzymes that catalyze the incorporation of oxygen into organic molecules, facilitating their degradation (Lap *et al*. 2024). Dehydrogenases are enzymes involved in the removal of hydrogen atoms from organic compounds, leading to their oxidation. Other enzymes, such as reductases and hydrolyses, play roles in the reduction and hydrolysis of pollutants, respectively(Saravanan *et al*.,2021).

Synergistic Interactions

Bacteria often work synergistically within microbial communities to degrade pollutants more efficiently. Synergistic interactions involve the exchange of metabolic byproducts, signaling molecules, and energy sources among different bacterial species (Zhou *et al*. 2023). Cooperative behaviors, such as cross-feeding and metabolic cross-talk, enhance the overall degradation capabilities of microbial consortia and enable the degradation of complex mixtures of pollutants (Ibrar*et al*.2022).

Adaptation and evolution

Bacteria have the ability to adapt to changing environmental conditions and evolve new metabolic capabilities for the degradation of pollutants(Bhatt *et al*. 2021). Through genetic mutations, horizontal gene transfer, and selection pressures imposed by pollutant exposure, bacteria can acquire novel enzymes and metabolic pathways that enhance their ability to degrade specific pollutants(Khan and Rao, 2019). These mechanisms highlight the diverse and versatile strategies employed by bacteria for the degradation of wastewater pollutants (Aragaw, 2021). By harnessing the metabolic potential of bacteria and optimizing environmental conditions, wastewater treatment systems can effectively remove pollutants and mitigate environmental contamination (Sahu*et al*. 2023).

Heterotrophic bacteria

Heterotrophic type of bacteria uses several inorganic and organic macronutrients to build their cells (Graeber *et al*. 2021). The effect of dissolved inorganic phosphate (PO_4^{3-}) and dissolved organics from biomass containing phosphorus such as adenosine triphosphate (ATP), glucose-6-phosphate, 2-aminomethyl phosphonic acid, collectively is very important for bacteria growth and to undertake bioremediation (Aragaw, 2021). Wastewater supplemented with phosphate, heterotrophic bacterial production, and the abundance of the different microbial components is enhanced (Feng *et al*. 2022). Inorganic phosphate alone does not simulate enough for most of the heterotrophic bacteria, but the addition of phosphorus-containing biomass like ATP has a significant change in the bacteria productivity and biomass (Wu *et al*. 2021). The heterotrophic microbial communities compete for organic molecules containing phosphorus to mollify their cellular requirements and are likely carbon and phosphorus co-limited (Aragaw, 2021). The ammonium nitrogen (NH_4^+-N) and total nitrogen (TN) elimination in wastewater by checking the quality of treated water tells that the occurrence of a certain biochemical reaction such as nitrifcation and denitrifcation with heterotrophic bacteria (Zehr and Ward, 2002). The targeted heterotrophic bacteria have tremendous removal eficiency for NH_4^+-N and TN in the optimum concentration from the influent (Man *et al*. 2022). But, many competitive heterotroph species, such as *Pseudomonas* sp. which can inhibit the NH_4^+-N conversion into nitrate which resulted in decreasing efficiencies in such a way that swelled with fluid carbon consumptions (Yang *et al*. 2019). However, it is possible to increase the overall performance by using a mixed culture system such as nitrifying and denitrifying bacteria, even though the operation is not as easy as that of a pure system (Di Capua*et al*. 2022).

Autotrophic bacteria

In the global nitrogen cycles and treatment processes, autotrophs play a crucial role in the process called nitrification(Nag *et al*. 2022). Therefore, some investigation that has been dealt with is mostly with *in situ* techniques by identifying the natural bacterial, autotrophs, community which have been used in the nitrification process. Ammonia oxidizing and nitriteoxidizing bacteria have been investigated by physiological and molecular *in situ* techniques (Lu *et al*. 2021). Identifying the exact distribution patterns of nitrifiers are difficult due to diferent biogenic and environmental factors resulting from the composition of its complex and diverse in mixed environments (Yang *et al*., 2021). Mostly, autotrophs play an important role in the activated sludge systems of the biochemical process, especially in the nitrification process, denitrification is also common in heterotrophs (Song *et al*., 2021). The growth system, operation strategies, and the degradation products formed in the autotrophs are still sparse as compared with heterotrophs in the activated sludge treatment process (Zheng *et al*. 2024). Nitrite is the dominant inhibitor for autotrophs in activated sludge treatment, especially oxidizing bacteria process which requires a considerable amount of energy during maintenance (Mo *et al*. 2023). A complete N-transformation activity of ammonia oxidation has been performed predominantly by aerobic autotrophs, especially chemolithotrophic in the activated sludge process (Grubba et al. 2022).

Interaction between contaminants and microbes

Bioremediation strategy for hydrocarbon contaminated water and soil

The contaminants included as BTEX (Benzene, Toluene, Ethylbenzene, and Xylenes) are compounds requiring strict attention since they are categorized as priority pollutants requiring strict regulation by Environmental Protection Agency. According to De Graaff *et al*. (2011), these compounds act as environmental factors affecting the bioremediation potential of microbes and are both carcinogenic and neurotoxic (Mishra *et al*. 2021). The structure and functioning of microbial communities is greatly affected by the release of BTEX compounds (Huang *et al*. 2021). In a system having multiple components the surplus components may affect the biodegradation of any components. So, hydrocarbon containing petroleum should be degraded by a bacterial consortium (Adamu *et al*. 2023).

Treatment of heavy metal contaminated water by bioremediation

Heavy metals are metals with relatively high density and include elements with atomic numbers greater than 20. Some of the heavy metals are required by organisms such as Co,

Table 1: Microbes used for bioremediation against different water contaminants

Microbe	Contaminant	Reference
P. alcaligenes , *P. mendocina* and *P. putida* ,*P. veronii*, *Achromobacter* , *Flavobacterium*, *Acinetobacter*, *Pseudomonas*sp	Petrol and diesel polycyclic aromatic hydrocarbons toluene, polyurethane	Kumar and Chandra, 2017
Pseudomonas putida	Monocyclic aromatic hydrocarbons, e.g. benzene and xylene	Molina *et al*. 2020
Alcaligenesodorans, *Bacillus subtilis*, *Corynebacterium*, *Burkholderiacepaciapropinquum* , *Pseudomonas aeruginosa*	Phenol	Khaire*et al*. 2022
Cyanobacteria	Naphthalene	Zhang *et al*., 2018
Acinetobacter sp., *Pseudomonas* sp., *Ralstonia*sp., and *Microbacterium* sp.	Aromatic hydrocarbons	Premnath*et al*., 2021
Gleophyllum striatum	Striatum Pyrene, anthracene, 9- metil anthracene, Dibenzothiophene Lignin peroxidase	Yadav et al.,2011
Oil and grease contaminants		
Alcaligenesodorans, *Bacillus subtilis*, *Corynebacteriumpropinquum*, *Pseudomonas aeruginosa*	Oil	Singh *et al*.2013
Bacillus cereus A, *Pseudomonas aeruginosa* , *Pseudomonas cepacia* , *P. putida* , *Arthobacter*sp. and *Bacillus* sp., *Bacillus coagulans*	Diesel oil	Singh *et al*. 2022
B. brevis, *P. aeruginosa* KH6, *B. licheniformis* and *B. sphaericus*	Crude oil	El-Borai*et al*., 2016
Azo dye wastewaters		
B. subtilis	Oil-based paints	Phulpoto*et al*., 2018
Pseudomonas, *Flavobacterium*, *Achromobacter*, *Nocardia*, and *Bacillus cereus* , *Alcaligenes* sp., *Bacillus* sp., *Escherichia* sp., *Pseudomonas* sp., *Providencia* sp., *Acinetobacter*sp.	Industrial dyes	Ruikar and Pawar, 2022
Staphylococcus sp, *Micrococcus luteus* strain SSN2, *Providenciarettgeri* strain HSL1 and *Pseudomonas* sp. SUK1, *Pseudomonas fuorescensListeriadenitrifcans* and *Nocardiaatlantica*	Textile azo dyes	Monga *et al*., 2022
Bacillus spp. ETL-2012, *Pseudomonas aeruginosa*, *Bacillus pumilus* HKG212	Remazol Black B, Sulfonated di-azo dye, reactive red dyes	Khaire*et al*., 2022
Bacillus firmus , *Bacillus macerans* , *Staphylococcus aureus*, and *Klebsiellaoxytoca*	Vat dyes in textile efuents	Adebajo*et al*., 2017
Heavy metals		
Geobacter spp., *G. metallireducens* , *Pseudomonas syringae*, *Pseudomonas fuorescens* and	Manganese, iron, Copper, uranium, zinc, lead	Joshi *et al*., 2023

Pseudomonas aeruginosa, *Vibrio harveyi* *Lysinibacillussphaericus* CBAM5, *Bacillus safensis* (JX126862) strain (PB-5 and RSA-4)	Cobalt, copper, chromium, lead, and cadmium	Idrees *et al*., 2022
Pesticides		
Bacillus, *Staphylococcus aureus* , *Klebsiella pneumonia* KE-1, *Pseudomonas* sp. *Klebsiella* sp. M3, *Achromobacter* sp. M6, and *Rhodococcus* sp. M2	Endosulfan, Coragen	Patyal*et al*., 2022
Enterobacter Strain B-14, *PseudomonasResinovarans* Strain AST2.2, *Acenetobactor* sp.	Chlorpyrifos, methyl parathion and organophosphorus	Lourthuraj*et al*., 2022
Pseudomonas putida, *Acinetobacter* sp., *Arthrobacter* sp. *Rhodococcusrhodochrous*and*Sphingomonas* sp.	Ridomil MZ 68 MG, Fitoraz WP 76, Decis 2.5 EC, malation	Mónica *et al*., 2016

Cu, Fe, Mn, Mo, Ni, V, and Zn(Shah, 2021). Excessive amounts of these heavy metals may become deleterious to organisms, but minute quantities of these are required by microorganisms. Metals such as Pb, Cd, Hg, and As are harmful to both plants and animals (Inobeme, 2021). pH of the soil mainly contributes to heavy metal availability. Other factors contributing to heavy metal availability in soil includes density, soils relative surface area, type of charge in soil colloids, and degree of complexation with ligands (Oyewo *et al*.2020). Heavy metals also show antagonistic and synergistic behavior (Yang *et al*. 2023). Through the complex processes of biosorption, precipitation, surface complexation, and oxidoreduction, microbes can mobilize or immobilize or diminish the concentration of heavy metals (Priya *et al*. 2022;Rahman and Singh, 2020). In soils contaminated by heavy metals, microbes evolve and that is how resistance develops (Gorovtsov *et al*. 2018). Even very minute levels of heavy metals either in suspended or dissolved state can be removed by microbes by various processes such as bioaccumulation, surface complexation, and biosorption (Ghosh *et al*., 2021). When it comes to heavy metalcontaminated soil, bioremediation emerges as a nondisruptive method and makes the remediated site fit for growth of plants (Bhatt and Gour, 2018). Although heavy metals are preferentially removed by phytoextraction, the efficiency of bioremediation is enhanced when bacteria are used along with the plants (Sharma *et al*.2021).

Degradation of dye using bioremediation

Effluents from textile-processing industries and dyeing industries contains up to 50% of the originally used dye concentration(Uddin, 2021). Along with the dye, there are various other constituents including dispersing agents, fixatives, heavy metals, and inorganic salts(Sharma *et al*. 2021). Dyes in water lead to reduction in dissolved oxygen. Decreased light penetrance also diminishes photosynthetic capacity of submerged plants (Natarajan *et al*. 2018). Various processes such as adsorption, precipitation, flocculation, and oxidation followed by filtration and electrochemical methods are used to remove color from the waste water. However, these methods are not too pocket friendly and there are operational troubles involved too (Rajoria *et al*. 2022). Dyes that are discharged along with the waste water constitute 90% of the reactive dyes (Rosa *et al*. 2015). Treatment of water containing dyes also demands plenty of expensive chemicals and extensive power consumption(Katheresan *et al*., 2018). In light of the difficulties discussed previously, bioremediation of effluents containing dues is gaining momentum (Saha *et al*. 2021). In order to achieve enhanced biodegradation, manipulation of the bacterial genome is also being carried out in various labs worldwide (Dvoøák *et al*., 2017). Dye degradation can be carried out under various aerobic and anaerobic conditions. Depending upon the microorganisms contained in the consortium and the chemical nature of the dye, the degradation of latter can be fine-tuned (Tiwari *et al*. 2024).

Biodegradation of pharmaceutical and personal care products

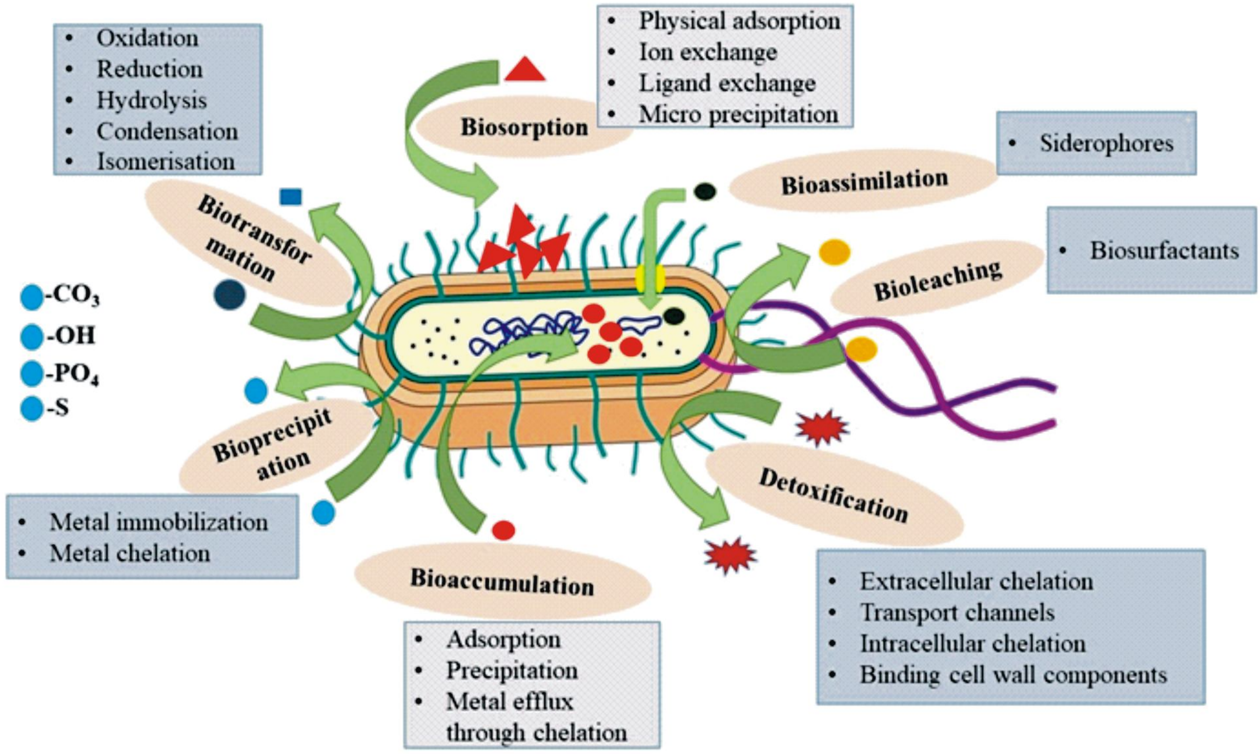
Past few years have witnessed the contamination of water sediments and biota by the unintentional release of pharmaceutical and personal care products (PPCPs) (Ebele *et al.*2017). PPCPs find extensive use in human and veterinary medicine and so released continuously in the environment (Chopra and Kumar, 2018). Biodegradation of PPCPs is possible through pure cultures of several organisms. Sulfamethoxazole, including various other sulfonamides, can be mineralized by *Achromobacter denitrificans* (Nguyen *et al*. 2017). Paracetamol can be mineralized by *Delftia tsuruhatensis* (De Gusseme *et al*. 2011; Palma *et al*. 2018). Few PPCPs are not compliant with certain microorganisms so do not get degraded by pure cultures. This may be attributed to the substrate specificity of the microorganisms involved (Carneiro *et al*. 2024). Maintenance of vital metabolic functioning of the microbes requires carbon and energy sources. Sometimes breakdown of carbamazepine that is not completely degraded by any microorganism because of its stability, the breakdown is possible by a mixed consortium consisting of a basidiomycete member which has not been identified as yet (Efremenko *et al*. 2024) and Streptomyces MIUG (Singh *et al*. 2020) when glucose was supplemented. One constituent which needs mention here is diclofenac, which finds extensive use in pain relief tablets. Diclofenac exhibits extreme resistance to degradation in activated sludge. However, it is possible to completely degrade diclofenac by using white rust fungus (Hedar *et al*. 2023). It is essential to understand microbes must synthesize specific enzymes. For instance, for the faster degradation of triclosan, the bacteria *Nitrosomonas europaea* must synthesize ammonia monooxygenase (Nandikes *et al*. 2022). It is also essential here to highlight that certain PPCPs, such as ciprofloxacin, tetracycline, and trimethoprim do not undergo biodegradation because they do not induce microbes to produce degradative enzymes (Kumar *et al*. 2023). It has been, however, found that mixed cultures are more efficient in degrading PPCPs. The degradation of a single PPCP is slower as compared to mixed PPCP (Hena *et al*.2021).

Removal of pesticides by bioremediation

Bioremediation is a technology, whereas biodegradation is a natural process. Both of them are somehow related as they involve metabolism of pesticides by microorganisms (Abioye *et al*. 2021).As regards the pesticides, their extensive use harms the natural environment as well as it affects human life (Alengebawy *et al*. 2021). Of special mention here are the organochlorine compounds. These compounds are nonbiod-egradable, so they undergo bioaccumulation at various trophic levels. Too much use of these pesticides has led to the development of pesticide resistance and hazardous effect on nontarget organisms (Sharma *et al*. 2020). A bacterial strain should be chosen that can degrade maximum amount of pollutant to the minimum level in a limited time frame. However, difficulty arises due to very limited knowledge about the population dynamics of degrading organisms in relation to other microorganisms that reside in the same habitat (Bodor*et al*. 2020).

Factors affecting bioremediation and bacterial population

Monitoring physical and chemical properties of soil is time taking. Instead the extent of soil pollution may be measured by evaluating microbiological and biochemical properties of soil after contamination (Lee *et al*. 2020). According to Zhang *et al*. (2020), in order to achieve enhanced benefits of the bioremediation process, it becomes essential to consider the factors affecting the process. The complexity of the process magnifies due to noxious and hydrophobic nature of the hydrocarbons contained in the petrochemicals (Jain *et al*. 2024). The intricacies are further diversified due to prevailing environmental conditions and microbial community diversity. Various physical, chemical, and biological factors seem to limit the bioremediation process as evident from the literature (Patel *et al*. 2023). pH, temperature, nutrient status, dissolved oxygen content, presence of electron donors and acceptors,



dissolved oxygen content, contaminant load, etc. all affect the efficiency of the bioremediation process (Patel *et al*. 2022). Degradation rates of individual contaminants are also affected by substrate interactions (Lipczynska-Kochany, 2018). Bacterial metabolism is greatly affected by substrate interactions at different concentrations. It has been found that catabolic enzymes can improve decomposition rates of various components of the contaminant due to synergistic actions (Kebede *et al*. 2021). The BTEX compounds beyond a certain concentration, due to their complex interactions, show inhibitory effect to microbial actions (Li *et al*. 2024).

Factors affecting biodegradation

Concentration of the contaminant Concentration of the contaminant affects the microbial activity. If the concentration of the contaminant is low, bacterial degradation enzymes are prevented from induction(Bhatt *et al*. 2021). Toxicity effects are, however, manifested by very high concentrations of contaminant (Javed and Usmani, 2019). The decomposition rates of catabolic enzymes are improved by the synergistic interactions between different components of a contaminant. At high substrate concentration, in batch culture, the growth rate of *Pseudomonas putida* was found to be decreased (Mediæ and Karadžiæ, 2022). Due to complex microbiological interactions BTEX compounds showed inhibitory effect to the biodegradation process (Mello et al. 2019).

Nutrient availability

Microbes require nutrients such as carbon, nitrogen, phosphorus, potassium, and calcium for their growth. In addition to this, the relative concentrations of the available nutrients also impact degradation of the contaminant. A negative impact on biodegradation resulted due to excess of nitrogen, potassium, and phosphorus on the degradation of hydrocarbons (Kebede *et al*. 2021). The rate of biodegradation is also determined by whether organic pollutants are accessible to microorganisms, which is also referred to as bioavailability. When mass transfer is a limiting factor, higher biotransformation is not achieved in spite of high microbial conversion (Leung *et al*. 2019). It has been found that certain surfactants of food grade can overcome the bioavailability problem (Karthik *et al*. 2017). pH

pH of the contaminated site is related to the contaminant and optimal pH is required for the bioremediation process. Generally, a pH range of 6-8 (International Centre for Soil and Contaminated Sites, 2006) is considered optimal (Burges *et al*. 2018). It also needs to be emphasized that at the contaminated site, microorganisms are tolerant of the site conditions and may metabolize polyaromatic hydrocarbons at high pH (Premnath *et al*. 2021). Neutral pH is favorable for the mineralization of petroleum hydrocarbons. As per the available studies, biodegradation process may be affected by even the temperature range of 15ºC-20ºC (Lahiri *et al*., 2022). It has been observed that increased temperatures enhance the solubility of organic hydrocarbons in the medium, making the petrochemical hydrocarbons readily available to a slight variation in pH (Mohammadi *et al*. 2020). According to Alegbeleye (2018), biodegradation potential of certain fungi and acidophilic microbes are higher in acidic environments.

Temperature

The degradation of the contaminant specially the hydrocarbon under both *in situ* and *ex situ* conditions is affected by temperature (Hussain *et al*.2022). It has been observed that higher temperature ranges such as 30ºC-40ºC enhance soil biodegradation and the same is true in aqueous or marine environments in microorganisms (Lahiri *et al*.2022).

Oxygen availability

The availability of oxygen decides whether the bioremediation process is aerobic or anaerobic(Bandyopadhyay *et al*. 2018). The few initial steps of aerobic metabolism of PAH oxygen is required for the action of monooxygenase and dioxygenase enzymes in the oxidation of aromatic ring (Aydin *et al*. 2017). During anaerobic oxidation of aromatic compound, ferrous iron, nitrate, and sulfate in their substituted form are required as electron acceptors. However, the process leads to emission of sufficient levels of phosphorus and ferrous ion, which in turn again contaminated the ecosystem (Dhar *et al*. 2020). The anaerobic degradation of petrochemical hydrocarbons release greenhouse gases such as methane and nitrogen dioxide along with increased pH (Saranya *et al*. 2025). Bioremediation in submerged marine sediments and aquifers occurs mostly by anaerobic process (Fragkou *et al*. 2021).

Strategies and Mechanisms for Recovery of Renewable Energy Products from Waste Water Biogas

Biogas produced through bacterial bioreme-diation harnesses the natural ability of microorganisms to break down pollutants, offering a sustainable solution for both waste management and renewable energy production (Bhatia *et al*. 2020). Algal biomass cultivated in waste water treatment ponds presents a valuable resource for Biogas production, alongside its potential for lipid extraction(Bhandari *et al*. 2023).

Bioelectricity

Bioelectricity generated through bacterial biorem-ediation harnesses microbial metabolism to convert organic pollutants into electrical energy, offering a sustainable and eco-friendly approach to waste management while simultaneously producing renewable power(Hoang *et al*. 2022). This innovative process not only addresses environmental concerns but also contributes to the diversification of clean energy sources, paving the way for a greener and more sustainable future (Su *et al*. 2023).

Biofertilizer

Biofertilizer produced through bacterial bioreme-diationtechniques utilize microbial activity to convert organic waste into nutrient-rich additives, enhancing soil fertility and promoting sustainable agriculture practices (Vurukonda *et al*. 2024**).** By harnessing the natural processes of microorganisms, Biofertilizer offer an eco-friendly alternative to chemical fertilizers, minimizing environmental impact while supporting crop growth and soil health (Kumar *et al*.2022).

A list of microbes which can be used in bioremediation against water pollutants have been given in Table 1.

CONCLUSION

Microbial bioremediation represents a promising and sustainable approach for wastewater treatment and resource recovery. Through the utilization of various microorganisms, pollutants can be effectively degraded, resulting in reduced toxicity and enhanced water quality. The versatility of microbial communities allows for the simultaneous removal of multiple contaminants, including heavy metals, organic pollutants, and nutrients, making this method highly adaptable to different wastewater compositions. Moreover, the integration of bioremediation processes with resource recovery techniques can lead to the production of valuable by-products, such as biogas, biofertilizers, and other renewable resources. This not only addresses environmental concerns but also contributes to the circular economy by maximizing resource efficiency. However, challenges remain, including the need for better understanding of microbial dynamics, optimization of operational conditions, and scalability of bioremediation technologies. Future research should focus on enhancing microbial consortia through genetic engineering and other innovative techniques, as well as exploring the synergistic effects of combining bioremediation with other treatment methods. In summary, microbial bioremediation offers a viable pathway for improving wastewater management practices while promoting environmental sustainability and resource recovery. As research advances and technology develops, its application could significantly contribute to cleaner water systems and a more sustainable future.

DECLARATION

Conflict of Interest. Authors declare no conflict of interest.

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