Energy, Ecology and Environment
https://doi.org/10.1007/s40974-024-00335-7

REVIEW PAPER

Microbial bioremediation of dyes, metals, and microplastics for ecological sustainability

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Received: 19 March 2024 / Revised: 5 July 2024 / Accepted: 9 July 2024

Abstract

The adverse consequences of hazardous environmental contaminants, at minimal concentration also constitute a major threat to both human health and the ecosystem. Multiple techniques are investigated to remove contaminants. Among these techniques, microbial bioremediation has emerged as an appealing method because of its removal efficacy, affordability, and environmental friendliness. This review is an overview of the major environmental pollutants such as plastics, heavy metals, and dyes with their source and toxicity towards both humans and the environment. The summary of the beneficial microbes like bacteria, fungi, and algae that employ remediation techniques like biosorption, bioaccumulation, bioleaching, biodeterioration, bio-fragmentation, and biotransformation to convert the toxic compounds to non-toxic compounds has been discussed. During the degradation process factors like temperature, pH, initial concentration, O_2 concentration, N_2 addition, soluble salts, pollutants both chemical and physical structure, and hydrophobic properties play a major role. The enzyme present in the microbes helps in the quick and complete breakdown of the pollutants, emerging advancement techniques like genetic engineering are implied to generate desired compounds or enzymes to attain pollutant removal. As with other removal techniques, like immobilization, the recent advancements are also explained. The review majorly states the efficiency of microbial remediation toward environmental sustainability.

Keywords Bioremediation · Pollutants · Hazardous · Microbes · Immobilization

1 Introduction

Anthropogenic activities, which include industrialization, metropolitan, and farming, have developed globally in recent years due to the wide range of chemicals introduced into our environment. This exposure to chemicals has resulted in many types of pollution like air, water, and soil pollution, which has numerous effects on the environment and human health (Akhtar et al. 2021; Kaur et al. 2019). Many compounds like organic and inorganic can cause environmental pollution. Organic compounds include polycyclic aromatic hydrocarbons, petroleum hydrocarbons, volatile organic compounds (VOCs), polychlorinated biphenyls (PCBs), and pesticides. Inorganic compounds consist of heavy metals (HMs) as well as salts, nitrate, and phosphate. (Paul et al. 2021). These polluting agents tend to affect the human nervous system, impacting the mental state of a healthy individual (Ventriglio et al. 2021).

Recent civilizations have resulted in producing a major polluting agent called dyes, this chemical substance can accumulate in humans (Thakur et al. 2024). Certain dyes have tendencies to mutate the genes which results in various health defects, whereas dyes also affect our systems which likely causes endocrine disruption, respiratory problems, infertility, cancer-causing, preterm birth, Alzheimer's disease, Parkinson's disease, heart disorders, asthma, renal failure, and Skin issues (Bertero et al. 2020; Hassaan and El Nemr 2020).

Every country worldwide has faced emerging hazardous pollutants called microplastics (MPs) in recent years. The accumulations of these microplastics in the soil are majorly affecting the soil quality which influences plant growth and metabolisms. The distribution of these microplastics in the air is also causing severe health defects (Athulya et al. 2024). Due to the distribution of these microplastics in the environment, the accumulation of these pollutants in humans takes

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place through three ways of exposure: ingestion, inhalation, and dermal contact, this exposure, leads to inflammation that can be linked to cancer, heart disease, inflammatory bowel disease, rheumatoid arthritis, etc., genotoxicity, chronic diseases such as atherosclerosis, cancer, diabetes and autoimmune disorders (De-la-Torre 2020). In animals, ingestion of the MPs results in disturbances to the system like a blockage in the digestion system which finally leads to exhaustion of energy stores, interference with reproduction, alteration of the ratio, loss of weight, alteration in the distribution of cholesterol ratio, growth reduction, and nutritional deficiency (Saeedi 2024; Osman et al. 2023).

Eliminating these pollutants using wild strains of microbial colonies is considered one of the agents for bioremediation. This method is cost-effective, and these microorganisms react promptly to fluctuations in the pH, temperature, terrestrial inputs, patterns of light, sea level rises, tropical storms, etc. in the environment, which makes them suitable for possible bioremediation purposes due to these behaviors (Kour et al. 2021). Recent research has combined the physiological, biochemical ecological, genetic, and metagenomics bases of microorganisms with various characteristics, including photosynthesis, anaerobic methane oxidation, and phosphorus Sulphur and nitrogen cycle uptake (Meng et al. 2022). Research has shown that using multiple living organisms will probably produce better and more effective results. Further investigation into the diversity of microbial life is also made feasible by this, which will enable bioremediation initiatives to produce the best results (Sharma et al. 2018).

Bioremediation of the pollutants occurs naturally using wild strains of the microbial colonies which are very slow. To overcome this disadvantage, researchers genetically modified the suitable strains and showed us more successful and faster degradation comparatively. The genetic modification method consists of hybridization, induced mutation, and substitution. Many researchers found that genetically modified bacteria show highly positive results in the elimination of environmental pollutants (Jacob et al. 2018; Ahmad et al. 2023). The recent studies, in which there is a beneficial relationship between the bioremediation agent's cell growth rate and the rate of pollutant breakdown, retaining a large population of bacteria is one of the keys to the process's effectiveness (Narayanan et al. 2023). As a result, bioremediation agents must be immobilized in a matrix to improve their capacity to endure in polluted environments. Here the microbial colonies are immobilized onto the suitable carrier using Vander Waal's force, cross-linkage, covalent bond, and encapsulation (Mehrotra et al. 2021).

In bioremediation methods, beneficial microbial communities are essential because the suitable microbes may have a variety of metabolic capacities that enable them to break down a variety of contaminants. Designing specialized microbial consortia adapted to certain contaminants is the current area of research emphasis (Maqsood et al. 2023). These consortia can effectively digest a variety of contaminants by selecting and integrating microorganisms with compatible metabolic pathways. Synthetic biology, metagenomics, Meta transcriptomics, bioaugmentation and biofortification, nanobiotechnology, phytoremediation-microbial interactions, omics technologies, and machine learning are some breakthroughs in this important sector (Saravanan et al. 2023). The goal of the study is to enhance the effectiveness, accuracy, and ecological viability of pollution removal from the environment by the incorporation of these novel technologies into bioremediation strategies. These developments have a great deal of potential for tackling the problems caused by various environmental contaminants and promoting long-term ecological sustainability.

2 Environmental pollutants: sources and toxicity

Groundwater, surface waters, air, and below-ground soil have been impacted by potentially dangerous substances that deliberately or unintentionally enter the environment during the monitored or unplanned discharge of industrially contaminated effluent (Rasheed et al. 2020). Those effluents mainly consist of pharmaceutical products, cosmetic products, dyes, Heavy Metals, and Microplastics. Resources like air, water, and soil are essential for all living organisms in an environment. This pollution is created minimally by environmental factors, but it is heavily influenced by human activity. The pollutants are majorly depleting the quality of these resources, making our environment unsuitable for living, while causing damage to humans and other organisms (Roy et al. 2021). Figure 1 shows the sources and toxic effects of environmental pollutants, and the illustration was referred from Sharma et al. 2023.

When the accumulation of Heavy Metals in a healthy human exceeds, they become toxic, leading to damage to other important organs like kidneys, brain, lungs, blood, and liver. Prolonged exposure can also cause hypertension, insomnia, skin rashes, diarrhea, tiredness, and high blood pressure. It also imitates the process of neurological diseases like multiple sclerosis, Alzheimer's, muscle dystrophy, and Parkinson's (Guzzi et al. 2021).

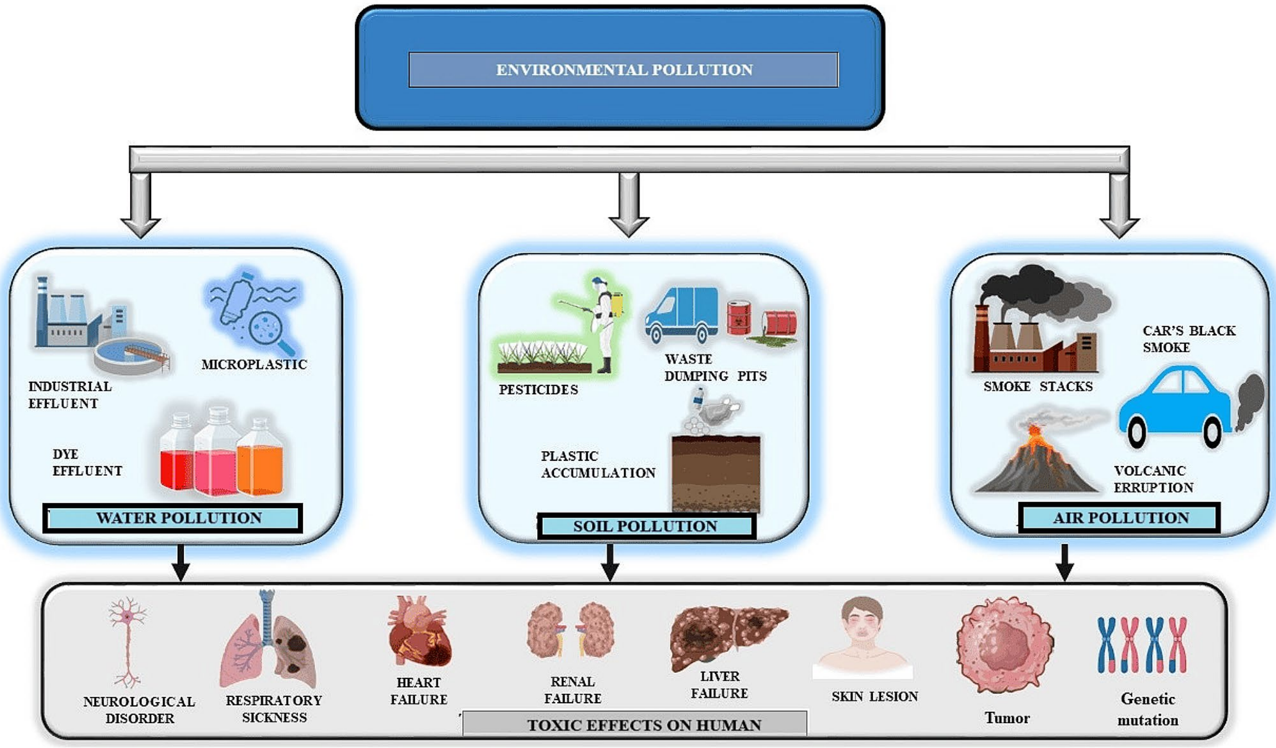

Fig. 1 Sources and toxic effects of environmental pollutants

2.1 Dyes

The textile, cosmetic, plastic, photographic, pharmaceutical, food, and paper industries use dyes that give different colors to the fibers used, these dyes are natural or synthetic materials. Usage of these dyes is based on their reliability on stability over time, having the ability to dye the fibers with the color using reproducible methods while maintaining color intensity, staying inactive to the chemical, physical, and biological deterioration, and should be at low cost (Al-Tohamy et al. 2022). Dyes can be classified based on their chromophore structure, Henceforth they are classified as Azo dyes (methyl orange, Congo red, orange G), anthraquinone (Remazol brilliant blue R, Alizarin Red S, Reactive Blue 4, Reactive Bright Blue X-BR,), triphenylmethane (Malachite green, Crystal violet, Light green SF, Crystal violet), nitro and nitroso (Naphthol yellow s, disperse yellow 26, disperse yellow 14), Indigoid (Ciba blue 2B, indigo Carmine), Xanthene (fluorescein, rhodamine 6G, rhodamine 123), Phthalein (o-cresol phthalein, phenolphthalein, thymolphthalein,) and Acridine (basic yellow 9 and acridine orange) (Ardila-Leal et al. 2021).

Dyes, being non-biodegradable, accumulate in soil, water, and air from industrial effluent, causing pollution that damages plants by reducing protein content, photosynthesis, and CO_2 absorption. This soil contamination triggers oxidative stress, which inhibits plant growth (Varjani et al. 2020). When discussing exposure to dyes in the aquatic environment, can have a huge impact on the food chain and inhibit the aerobic microbes' biodegrading process (Alonso et al. 2018). Humans get chronic diseases due to exposure to these dyes for a long period, the chemicals present in the dyes can cause an impact on all the vital organs which includes the brain, renal, liver, and heart. The immune system, reproductive system, and respiratory systems are being suppressed due to this exposure. It is also possible for illness to arise either directly by breathing in, such as asthma, nausea, skin, eye irritation, and dermatitis, or indirectly through the food chain, such as tuberculosis (TB), heart illness, genetic mutation, bleeding episode, and tumor (Islam et al. 2023).

2.2 Microplastic

Plastic particles that are less than size 5 mm are considered Microplastics (MPs), these plastics have been available in the environment for the past 100 years due to the consistent nature of their chemical property. MPs are of different types like Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), polypropylene (PP), polystyrene (PS), Polyethylene terephthalate (PET), and polyvinyl chloride (PVC) (Frias and Nash 2019). These MPs enter our environment from the two major sources that are classified into primary and secondary. Primary pollutants originate from plastics in cosmetics and personal care products, while secondary MP sources include degraded plastic particles from wastewater treatment plants and household/industrial discharge (Kurniawan et al. 2021).

In the aquatic environment, exposure to chemicals from the MPs affects the food web by stopping the photosynthesis process of algae. Thereby, an increase in Reactive Oxygen Species (ROS) occurs due to the oxidative stress caused by the accumulation of the MPs in the algae (Huang et al. 2022; Ugya 2021). Through biological absorption, MPs can pass through zooplankton and onto larger animals at the top of the food chain. Accumulation of these microplastics leads to severe damage to the human body, Neurological damage is caused due to the blocking of neurotransmitter signals, and endocrine disturbance which affects the reproductive system, and digestive system, some of the dye's chemicals that have an allergic nature and also can mutate the gene (De-la-Torre 2020; Ma et al. 2020). Figure 2 depicts the various toxic impacts of environmental pollutants in agriculture referred from the source (Ahammed and Li 2022).

3 Microbial bioremediation

Restoration of the recalcined biosphere and the control of pollutants via detox and mineralization has been the goal of the technological advances process referred to as bioremediation. Microbes are very eco-friendly, economical, innovative, and optimistic (Haripriyan et al. 2022). The bioremediation method employs microbial species from bacterial, fungal, yeast, and algal ecosystems, these organisms employ enzymes or additional metabolic procedures dependent on the microbe's development and metabolism which breaks the contaminant's organic components (Pushkar et al. 2021). Certain Microbes possess enzymes that have the ability capable of breaking down a large number of toxic contaminants in the environment such as laccases, hydrolases, oxidoreductases, oxygenases, and lipases (Narayanan et al. 2023). These enzymatic remediation processes also have constraints i.e. only selective organisms possess the nature of degrading the contaminants and consume more time (Saravanan et al. 2022). Due to this limitation, scientists have modified the gene of the microorganism under a controlled environment. The microbes play a role in the bioremediation treatment due to their broad spectrum of enzymes, ability to alter DNA, and unique metabolism (Rathore et al. 2022). By undergoing reactions as part of their processes of metabolism, living things change pollutants. Numerous methods can be used to apply the principles of bioremediation, including land farming, biostimulation, bioaugmentation, composting, biofiltration, bioventing, and bioreactors (Patel et al. 2022). Table 1 shows the data containing bacterial, fungal, and algal communities with bioremediation potential.

Some enzymes are responsible for the bioremediation process which includes cytochrome P450 (employs the reduction or oxidation of heme iron to carry out catalysis

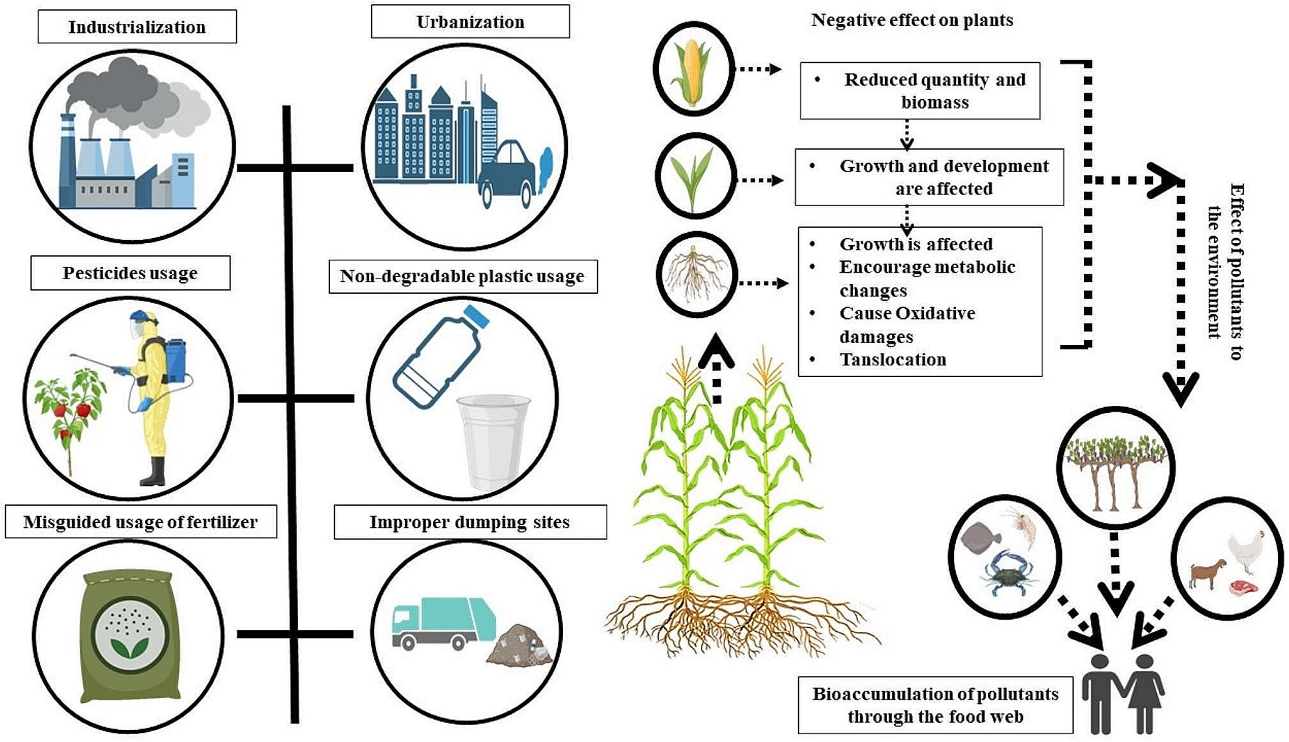

Fig. 2 Toxic impacts of pollutants on agriculture/horticulture

Table 1 Role of bioremediation potential in microbial communities such as algae, fungi, and bacteria

Microbial species	Microorganism	Pollutants	Remediation mechanism	Environmental conditions			Removal efficacy (%)	Reference
				pH	Time	Initial Concentration		
Chlorella Vulgaris	Bacteria	Methylene blue	Electrostatic interaction (adsorption)	2	1 h	100 mg/L	83.04	Chin et al. (2020)
Spirulina platensis	Microalgae	Chromium	Bio adsorption	1	2 h	500 mg/L	82.5	Nithya et al. (2019)
Oscillatoria sp.	Microalgae	Malachite green	Phytoremediation	-	120 h	1–5 mg/L	93	Gelebo et al. (2020)
Bacillus sp. K1	Bacteria	Cd (II)	Electrostatic interaction (Biochar-microbe)	7	12 h	50 mg/L	95	Wang et al. (2021c)
Pseudomonas citranellolis	Bacteria	Phenol	π-π London dispersion force adsorb phenol on biochar micropore	6.5–7.6	72 h	400–1200 mg/L	46–99	Zhang et al. (2018)
Scenedesmus almeriensis	Microalgae	Arsenic	Adsorption	9.5	3 h	100 mg/L	40.7	Saavedra et al. (2018)
Sphingomonas sp.	Bacteria	4-bromodiphenyl ether	Electrostatic interaction (Biochar-microbe)	7	24 h	500 mg/L	93	Du et al. (2016)
Shewanella oneidensis	Bacteria	Cr (VI)	Bioreduction	7	24 h	50 mg/L	34-56.3	Ri et al. (2022)
Maugeotia genuflexa	Microalgae	Arsenic	Biosorption	6	5–90 min	10–400 mg/L	96	Abdelfattah et al. (2022)
Penicillium simplicissimum	Fungal	malachite green crystal violet cotton blue methyl violet	Biodetoxification	5	2 h	50 mg/L	94.1 97.5 98.7 96.1	Mian et al. (2024)
Aspergillus sp.	Fungal	Copper	Bioaccumulation	4–7	72 h	500 mg/L	85	Palanivel et al. (2023)
Sarocladium sp. M2	Fungal	Cadmium	Biodetoxification	-	216 h	200 mg/L	57.11 ± 4.45	Zhang et al. (2024)
Sarocladium sp. M6				-	192 h		48.35 ± 1.44	
Bacillus subtilis	Bacteria	Trypan blue Methyl red Neutral red Bromophenol blue	biosorption, bioaccumulation, biotransformation, and biomineralization	7	96 h	50 mg/L	95 80 70 70	Mandragutti et al. (2021)
Pseudomonas resinovorans	Bacteria	Comassie brilliant blue Gentian Violet	Biodetoxification	7	96 h	50 mg/L	60 95	Mandragutti et al. (2021)
Saccharomyces cerevisiae (Baker's yeast)	Yeast	Chromium	Biomass/Polymer Matrices Beads (BPMB) biosorption	3.5	2 h	200 mg/L	85	Mahmoud and Mohamed (2017)
Aspergillus niger	Fungal	Cadmium	Biosorption	6	4 h	10 mg/L	80	Bhateria and Dhaka (2019)

and the transfer of electrons) (Guengerich 2018). Enzymes like Laccase catalyze the breakdown of aromatic compounds and dehalogenase facilitates the removal of halogen atoms, both contributing to the bioremediation process by degrading pollutants into less harmful forms. Dehydrogenase and hydrolase are the enzymes that produce energy by oxidizing organic compounds and breakdown of both lipids and proteins (Kumari and Das 2023). Microbes that produce Protease, activate the disruption of peptide linkage of proteins. Whereas, lipase activates the disintegration of all mono-, di-, and triglycerides to glycerol and fatty acid, and is also used as an activator for the transesterification and esterification domino effect) (Bhandari et al. 2021). Figure 3 elucidates the remediation mechanism of pollutants by microorganisms.

3.1 Remediation mechanism

3.1.1 Heavy metals

The dangerous toxins in the environment can be broken down using organisms such as microbes and plants in an approach called bioremediation. The toxic organic or inorganic contaminants are biotically degraded during this process into harmless substances (Okoye et al. 2022). The procedure could succeed spontaneously or improve by inserting an acceptor of electrons, nourishment, or any additional components (Tan et al. 2022). Environmental bioremediation for Heavy metals contamination involves processes like biosorption, in this process, the outer cell shield gives the microbes their sorption features. Functional groups of compounds are discovered on the outermost layers of microbes that connect metals (Fathollahi et al. 2020). Metal cations react with active groups on cell structures of diverse microorganisms, facilitating ion transfer, despite variations in their chemical compositions (Aryal 2021). This mechanism has been implemented which includes sewage treatment procedures and the pharmaceutical sectors both use microbe biomass as a subsequent product, the ability of microorganisms to efficiently utilize metal is demonstrated by their ability to be cultivated and multiply on a particular basis, resorbent with a vegetable or animal origin (nutshells, sea plants, humus, moss peat, etc.) (Medfu Tarekegn et al. 2020).

Another remediation mechanism, Where the susceptibility of living things to toxins that are impacted by the toxicokinetic process, this process is known as bioaccumulation. The accepting capacity of bioaccumulation candidate microorganisms ought to improve from one or more pollutants to higher concentration levels (Tan et al. 2019). Furthermore, these may have strong bio transformational competencies, converting the dangerous material into a harmless form that allows the organism to reduce the damaging effects of the pollutants while keeping them isolated. This technique has been compared with biosorption which is distinct from it in that the expulsion of metals from cells and its subsequent

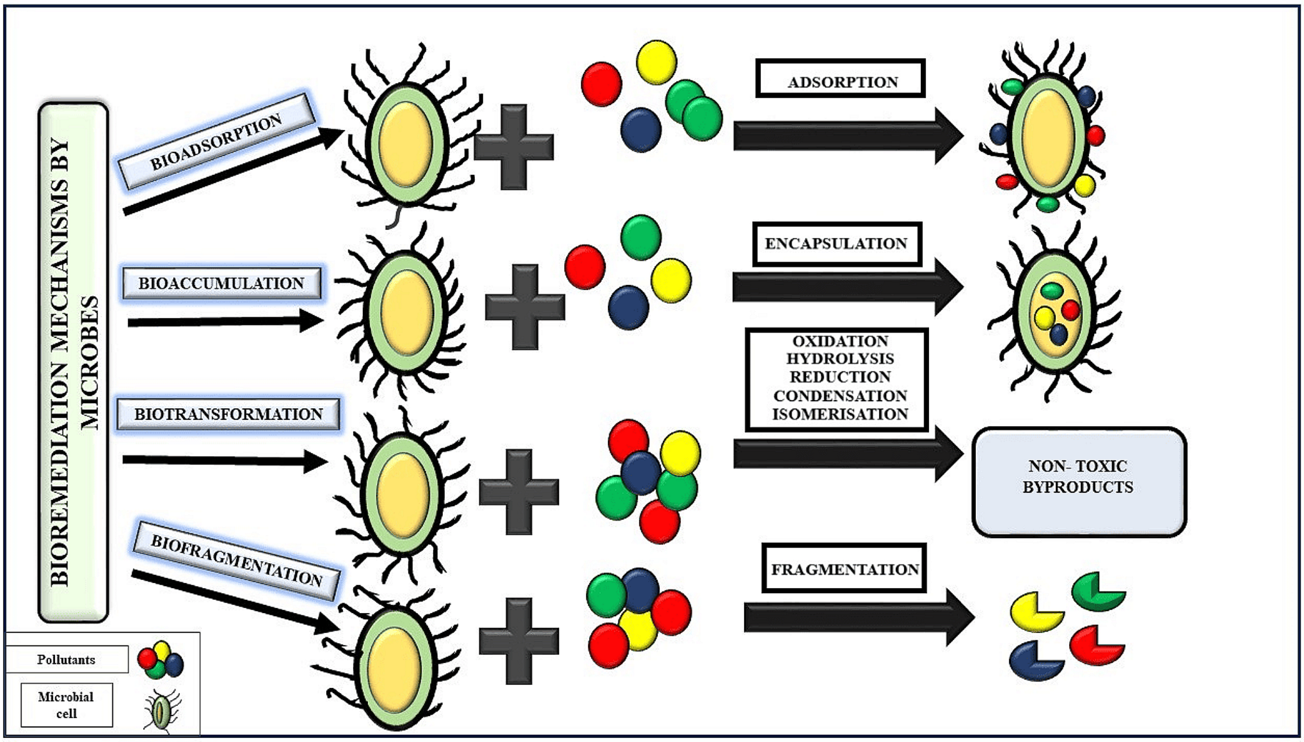

Fig. 3 Remediation mechanism of pollutants by microorganisms

recovery depends on cell structure modification (Yaashikaa et al. 2024). As a result, there aren't many cycles where biomass applications are possible. The capability to store significant quantities of Heavy metals in cells, the cell walls themselves, or regions restricted by the cytoplasm is a distinctive trait of numerous environmental species of bacteria (Medfu Tarekegn et al. 2020). Table 2 shows the potential of microorganisms for the removal of HMs.

Biotransformation is also another process, where the Heavy metals undergo oxidation, reduction, methylation, and demethylation reactions by microbes, it involves the enzymatic system of microorganisms (Mohsin et al. 2021). Practically beneficial reactions of extensively hazardous or highly valuable metal reduction include bacteria isolated from tanning plant sewers that reduced extremely hazardous chromium (VI) to less chromium (III), which may then be removed from the environment (Kholisa et al. 2021). Any type of bacteria or fungi that are microscopic can convert valuable metal ions such as gold or silver into metallic form. This process is capable of taking place in vacuoles, along the cell exterior, and in the environment outside of the cell, which is significant for the recovery of this metal (Nivetha et al. 2022).

Utilizing microorganism activity, bioprecipitation and biocrystallization are bioremediation methods that can precipitate or crystallize combinations of Heavy Metals, reducing their toxic effects while transforming the metal into a form that is rarely used. Some precipitation and biocrystallization procedures such as forming microfossils, mineralizing silver and manganese, and depositing iron and manganese involve themselves in biogeochemical patterns. Furthermore, due to the direct action of enzymes, secondary metabolites produced by galactosis can also result in the precipitation of metals on the surface or interior of the cell (Hussain and Mutag 2021).

Bioleaching in this bioremediation process where biohydrometallurgy is the principal application of biological processes of leaching. Metals leaching from sulfide and oxide minerals can be accomplished through microbial approaches. This method's foundation is built on converting environmental metal compounds between slightly soluble forms into easily soluble types, making Heavy Metal removal simple. Metals like Arsenic, antimony, bismuth, zinc, cobalt, gold, lead, copper, molybdenum, nickel, vanadium, and other metals are recoverable (Saldaña et al. 2023).

3.1.2 Dyes

Industries like cloth, leather, or wood use long-lasting coloring agents called dyes, these dyes are either natural or manmade. There are different types of dyes classified according to their structure (Acid, direct, azo, dispersion, sulfur, fiber reactive, basic, oxidation, mordant, developed, vat, pigment, and solvent dyes are some examples of dyes (Bharathi et al. 2022). Due to their multifaceted chemical constitution of coloring agents, dyes can endure adverse conditions and continue to be "pinned" to the materials to which have been applied (Dahiya and Nigam 2020). The process of decomposition of these organic dyes can be carried out by microbes either under aerobic conditions or anaerobically. The adsorption of the dye molecules onto microbial biomass or dye breakdown by bacteria are two ways that microbes can lead a dye to become discolored (Bharathi et al. 2018).

In wastewater remediation, mixed microbial cultures or pure cultures are employed. Due to the result of a synergistic metabolic effect, mixed microbial culture demonstrated excellent dye degradation. Comparatively, there is more biodegradation and mineralization as a result of microbial co-metabolic activities (Rane and Joshi 2021). The consortium of microorganisms has been proven to successfully biodegrade refractory substrates when compared to individual pure strains. A *Pseudomonas mendocina* MCM B-402 strain's aerobic degradation of the triphenylmethane color methyl violet. Methyl violet, which is used as a bacterial culture and histopathological color, served as the isolate's main source of carbon and energy. Through a series of unidentified metabolites, *Pseudomonas mendocina* converts the dye to phenol, which subsequently enters the β- ketoadipic acid pathway (Varjani et al. 2020). The bacteria's cell wall is essential to the biosorption process, bacterial cell surfaces that are negatively charged exhibit strong electrostatic attraction to the positively charged dyes.

Gram-positive bacteria are better at attracting color pigments than Gram-negative bacteria. The thickened cell wall of Gram-positive bacteria is composed of peptidoglycan, teichoic, and teichuronic acids. In Gram-negative bacteria, only the peptidoglycan layer is present as a thin layer (Lellis et al. 2019). When employing azo dyes as their only provider of carbon for cell development, certain bacteria were able to break azo (-N = N-) bonds (Ardila-Leal et al. 2021). Fungal species have also demonstrated the ability to degrade dyes; using these fungi in the restoration process can be both economically advantageous and a successful replacement for dye degradation. Methods like biosorption, biodegradation, and bioaccumulation are also conducted as essential processes. When dyes are exposed to fungal enzymes, it degrades into a variety of metabolites. As their primary means of discoloring textile colors, fungi rely on biodegradation. Laccases, peroxidase, Mn peroxidase, lignin, and azo-reductase are some of the enzymes involved (Lellis et al. 2019). The cell wall's negative charges stem from carboxyl groups and phosphate (from glucuronic acid), while positive charges originate from amino groups (from chitosan) (Bharathi et al. 2022). Hence these functional group

Table 2 The potential of microorganisms for the removal of HMs

Microbes	Metal pollutant	Operating conditions				Removal efficiency	Isotherm/kinetics	References
		Temp (°C)	pH	Initial conc.	Contact time			
Acinetobacter junii	Pb (II)	30	7	500 mg/L	48 h	1071 mg g^{-1}	Pseudo first order	Kushwaha et al. (2017)
Sporosarcina pasteurii	Pb (II)	28	9.40	-	72 h	98.71%	-	Jalilvand et al. (2020)
	Cd (II)					97.15%		
	Zn (II)					94.83%		
Aspergillus fumigatus	Cr (VI)	35	5.5	50 mg/L	120 h	96%	Freundlich/ Pseudo first order	Dhal and Pandey (2018)
Trichoderma	Cd (II)	25	6	50 mg/L	2 h	21.7 mg g^{-1}	Freundlich/ Pseudo second order	Bazrafshan et al. (2016)
Bacillus cereus	Cr (VI)	37	7	1500 mg/L	24 h	81%	-	Nayak et al. (2018)
Bacillus subtilis	Cr (VI)	35	8	25 µg m/L	1 h	96%	Langmuir and Freundlich	Rizvi et al. (2020)
Microbactan	Cd (II)	28	7	100 mg/L	24 h	97 mg g^{-1}	Langmuir	Camacho-Chab et al. (2018)
B. firmus						141 mg g^{-1}		
Pseudomonas azotoformans	Cd	30	6	25 mg/L	4 h	98.57%	Pseudo second order	Choińska-Pulit et al. (2018)
	Cu					69.76%		
	Pb					88.58%		
Sphingobacterium and *Bacillus*	Mn (II)	30	7	100 mg/L	168 h	98.5%	Pseudo second order	Wan et al. (2020)
Synechococcus sp.	Cd	25	9	100 mg/L	24 h	55%	-	Zhou et al. (2020)
Penicillium chrysogenum	Pb	60	5	1.0 mg/L	4 h	56%	Langmuir and Freundlich	Alothman et al. (2020)
	Cu		6		2 h	53%		
	Cd		5		4 h	91%		
Aspergillus ustus	Pb	60	7	1.0 mg/L	4 h	42%	Langmuir and Freundlich	
	Cu		6		4 h	52%		
	Cd		5		1 h	84%		
Aspergillus fumigatus and *Synechocystis* sp.	Cd (II)	30	7	2.0 mg/L	24 h	98.89%	-	Wang et al. (2021a)
Aspergillus penicillioides	Pb (II)	32	8.85	0.5 mg/L	5.74 h	73.14%	Pseudo second order	Paria et al. (2022)
Trichoderma brevicompactum	Pb (II)	30	7	30 mg/L	2 h	96%	-	Zhang et al. (2020a)
				50 mg/L		97.54%		
				100 mg/L		81.11%		
Fungal-extract-based	Cu (II)	25	5	5 mg/L	3 h	71%	Langmuir / Pseudo second-order	Yildirim et al. (2020)
	Ni (II)		6	1.5 mg/L	1 h	80%		
Lycium barbarum	Cu (II)	25	6	10 mg/L	12 h	7.27 mg/g	Langmuir, Freundlich, and Temkin / Pseudo second-order	Guan et al. (2022)
	Cr (III)					6.29 mg/g		
	Cd (II)					11.53 mg/g		

Table 2 (continued)

Microbes	Metal pollutant	Operating conditions				Removal efficiency	Isotherm/kinetics	References
		Temp (°C)	pH	Initial conc.	Contact time			
Bacillus cohnii	Zn	28	7	-	96 h	175.53 mg/L	-	Marzuki et al. (2021)
	Fe					172.65 mg/L		
	Cu					168.66 mg/L		
Pseudomonas stutzeri	Zn			-		165.06 mg/L		
	Fe					162.02 mg/L		
	Cu					158.66 mg/L		
Rhizobium sp.	Cr (VI)	28	-	0.01 mg/L	0.5 h	44%	-	Alfadaly et al. (2021)
	Cd (II)					52%		
Rhodotorula sp.	Cr (VI)		-	0.01 mg/L		36%		
	Cd (II)					63%		

gets attached or absorbed to the surface of these cell walls for example *Aspergillus flavus and Aspergillus fumigatus* use biosorption techniques for pollutants like methylene blue and methyl orange (Varjani et al. 2020).

3.1.3 Microplastics

The two types of plastics that exist are thermoplastic and thermosetting plastics. Thermoplastic materials need heat to become pliable and to retain their shape after cooling. Such materials don't significantly alter in characteristics even after being heated and reshaped multiple times. Meanwhile, thermosetting plastics go through chemical reactions to generate a permanent shape that cannot be remelted or reformed; rather, these compounds break down or deteriorate when heated to high temperatures. Plastics that are thermosets cannot be reprocessed. In the process of biodegradation, the microbial colonies tend to change neither their chemical nor physical properties (Elahi et al. 2021). Microbes like actinomycetes, bacteria, and fungi can degrade plastics. Most often in the process of biodegradation, the microbes get attached to the out layer of the polymer, where these microbes use them as a carbon source by secreting enzymes that degrade the plastics and use them for their survival (Alshehrei 2017). The degradation of microplastics by the microbial strains and its analysis methods is tabulated in Table 3.

The bioremediation of MPs also takes place in different mechanisms and one of the mechanisms is the biodeterioration mechanism, in this remediation process the microbes alter the polymer's chemical, physical, and functional properties. The microorganism impacts the outer surface of the MPs due to the alteration of these properties (Vivi et al. 2019). Bio-fragmentation, which involves after biodeterioration, where the enzymes of the bacteria act on the polymer that cleaves the oxygen molecule and are attached to the carbon chains which results in the production of low-toxic products like peroxyl and alcohol (Zhang et al. 2022).

Beyond these mechanisms, another approach for MPs biodegradation is mineralization in which the fragmented polymers get inside the microbes via the cell membrane, where the monomer of smaller size enters the microbes, is later oxidized, and helps in producing energy that is employed in biogas or biofuel production (Jaiswal et al. 2020). Assimilation involves transporting secondary metabolites to other microbes for degradation, yielding CO_2, N_2, and H_2O as byproducts (Elahi et al. 2021).

3.2 Factors influencing bioremediation

The architecture of the microbial cell wall, the chemical compounds on the cell wall, and the sorption sites all affect

Table 3 Degradation of MPs by the microbial strains and analysis methods

Type of MPs	Microbial strains	Degradation rate/Weight loss	Degradation period	Characterization studies	References
PP/butylene-adipate-co-terephthalate	*Penicillium* sp. *Aspergillus* sp.	1.04%	30 d	FTIR, SEM	De Oliveira et al. (2020)
PP	*Lasiodiplodia theobromae*	-	90 d	FTIR, DSC, SEM	Anand et al. (2023)
PP	*P. azotoformans* & *B. flexus*	22.7%	365 d	FTIR	Aravinthan et al. (2016)
PE	*Bacillus gottheilii*	6.2%	40 d	FTIR, SEM	Auta et al. (2017)
PET		3.0%			
PP		3.6%			
PS		5.8%			
PE	*Enterobacter asburiae*	6.1 ± 0.3%	28 d	SEM, AFM, XPS, micro-ATR/FTIR	Yang et al. (2014)
PE	*Bacillus* sp. and *Paenibacillus* sp.	14.7%	60 d	FTIR, GC-MS, SEM, TGA	Park and Kim (2019)
PP, PE	*Lysinibacillus* sp.	9%	26 d	GC-MS, SEM	Jeon et al. (2021)
PE	*Bacillus cereus*	1.6%	40 d	FTIR, SEM	Auta et al. (2017)
PET		6.6%			
Polystyrene		7.4%			
LDPE	*Brevibacillus* sp. & *Aneurinibacillus* sp.	58.21 ± 2%	140 d	FTIR, SEM, AFM, EDS, GC-MS	Skariyachan et al. (2018)
HDPE		46.6 ± 3%			
PP		56.3 ± 2%			
PP and poly-L-lactide	*Bacillus cereus*, *Bacillus thuringiensis*, *Bacillus licheniformis*	-	182 d	FTIR, TGA	Jain et al. (2022)
PE pellets	*Zalerion maritimum*	-	28 d	FTIR-ATR, NMR	Paço et al. (2017)
LDPE	*Chelatococcus* sp. E1	44.5%	80 d	FTIR, NMS, Tensile strength, GC	Jeon and Kim (2013)
LDPE	*Enterobacter* sp. *Pseudomonas aeruginosa*	64.25 ± 2%	160 d	SEM, EDS, AFM, FTIR	Skariyachan et al. (2021)
LDPP		63.00 ± 2%			
PP	*Bacillus* sp. strain 27	4.0%	40 d	FTIR, SEM	Auta et al. (2018)
PP	*Sporosarcina globispora*	11%	40 d	Weight loss	Helen et al. (2017)
	Bacillus cereus	12%			
PE, PET	*Ideonella sakaiensis*	-	60 d	FTIR, SEM	Yoshida et al. (2016)
HDPE	*Aspergillus tubingensis*	9.34 ± 0.2%	30 d	Weight loss, FTIR, SEM	Devi et al. (2015)
LDPE	*Bacillus simplex* and *Bacillus* sp.	-	21 d	SEM	Lwanga et al. (2018)
LDPE	*Penicillium pinophilum*	-	943 d	XRD, SEM, FTIR	Yuan et al. (2020)
PS	*Agios Onoufrios*	0.19%	182 d	FTIR, SEM, GPC	Syranidou et al. (2017)

how stable the microbes-metal combination is. Degradation processes have different outcomes depending on the substrate and a variety of circumstances in the environment (Choudhury and Chatterjee 2022). Environmental factors such as temperature, pH, humic acids, and organic acids affect the transport, transformation, and bioavailability of HMs in bioremediation processes (Zhang et al. 2020b).

For environmental factors like pH, the adsorbent surface is more positively charged at higher hydrogen ion concentrations, which reduces the connection between the adsorbent and metal cation and raises the toxic effect of the substance (Soliman & Moustafa 2020). Factors like temperature, the adsorption of Heavy metals is greatly influenced by temperature. The rate of adsorbate diffusion across the exterior boundary layer increases as temperature rises. The increasing temperature makes the Heavy metals more soluble and increases their bioavailability (Priya et al. 2022). The initial concentration of the ion is one of the most important factors that also influence the bioremediation mechanism of microbes, as the initial concentration of metal ions increases. Biosorption subsequently increases, as the concentration of metal in the solution goes up, metal sorption primarily increases before becoming saturated after a specific concentration of metal (Sibi 2019).

The dye's biodegradation mechanism is influenced by two factors that impact the deterioration of dyes. Environmental factors including pH, oxygen, agitation, and temperature, as well as nutritional factors like soluble salts, dye concentration, dye structure, carbon, and nitrogen additions, can all have an impact on bioremediation (Srivastava et al. 2022). The dye degradation is influenced by factors like (i) pH choosing a microbial species that can thrive at the wastewater pH or adjusting the waste pH to encourage dye-degrading bacteria to proliferate (Reyes et al. 2021). (ii) Oxygen and agitation are other influencing factors, where aerobic, anaerobic, and semi-anaerobic conditions are only a few of the parameters that diverse bacteria prefer. With oxygenation, that shaking appears to be beneficial. The activity of reducing enzymes may be increased in anaerobic environments. On the other hand, aerobic dye decomposition demands oxidative enzymes, which require oxygen (Pham et al. 2023). (iii) Extreme temperatures can kill or halt the growth of microbes. For a large variety of bacteria, it is widely acknowledged that the ideal temperature range for bacterial culture is between 30 and 40 °C. By doing this, color fading is accelerated. As the temperature rises, the degree of decolorization begins to slow down (Ikram et al. 2022).

Microplastics, all polymers that are used in plastic production do not dissolve in water, the one that tends to dissolve is transformed into acids, alcohol, and ketones (Bule Možar et al. 2023). The biodegradations of the plastics are identified by their chemical and physical properties. The factors that affect the microbes in the degradation of plastics are (i) the availability of functional groups increases hydrophobic properties. (ii) Compared to hard polymers, mild toughness polymers deteriorate more quickly. (iii) The structure's complication (iv) Molecular basis-based arrangement (v) Bond types, such as amide bonds and ester bonds, are easily breakable. Establishing a network of linkages. (vi) The weight of a molecule and polymer concentration. (vii) Morphological features: area size regions that are crystalline and amorphous (Wang et al. 2021b; Shams et al. 2020).

3.3 Engineered microbes/enzymes for bioremediation

The implication of microbial degradation and elimination of these contaminants include not only their genetic ability to degrade the pollutants but also the environmental factors involving temperature, pH level, nitrogen, and phosphorus availability (Pant et al. 2021). Metabolic engineering can address limitations in microbial bioremediation, including slow degradation, narrow substrate range, low efficiency, high cost, time consumption, and toxicity (Behera et al. 2019). Many pollutants are too large for natural metabolic pathways in microbes to break down. To generate desired compounds or enzymes involved in bioremediation, it is imperative to either establish novel pathways or restore pre-existing metabolic networks (Li et al. 2021). Figure 4 shows the genetically modified microbes for bioremediation, which was referred from Janssen and Stucki 2020.

Biodegradation uses two types of engineered microorganisms one is metabolic engineering; this method is employed to direct the metabolic pathways to enhance the synthesis of a certain metabolite utilizing a genetic engineering strategy by modifying the genetic system and its regulatory systems within a living cell (Behera et al. 2019). Biosynthetic pathways have been rebuilt via the metabolic engineering of microbes in recent days. For example, the *Pseudomonas putida* strain KT2440 for the aerobic breakdown of trichloro propane (TCP) was created through the application of metabolic engineering. By inserting three enzymes—epoxide hydrolase, haloalcohol dehalogenase, and haloalkane dehalogenase—from a different source, a synthetic pathway was rebuilt in *Pseudomonas putida* KT2440. These enzymes were necessary for the transformation of TCP into glycerol. As a result, the resulting strain could utilize TCP as the only source of carbon for growth (Gong et al. 2017). Furthermore, it is possible that the microorganisms employed in bioremediation were subjected to a particular kind of environmental stress, such as exposure to extremes in pH, temperature, ionic strength, solvent concentrations, or other

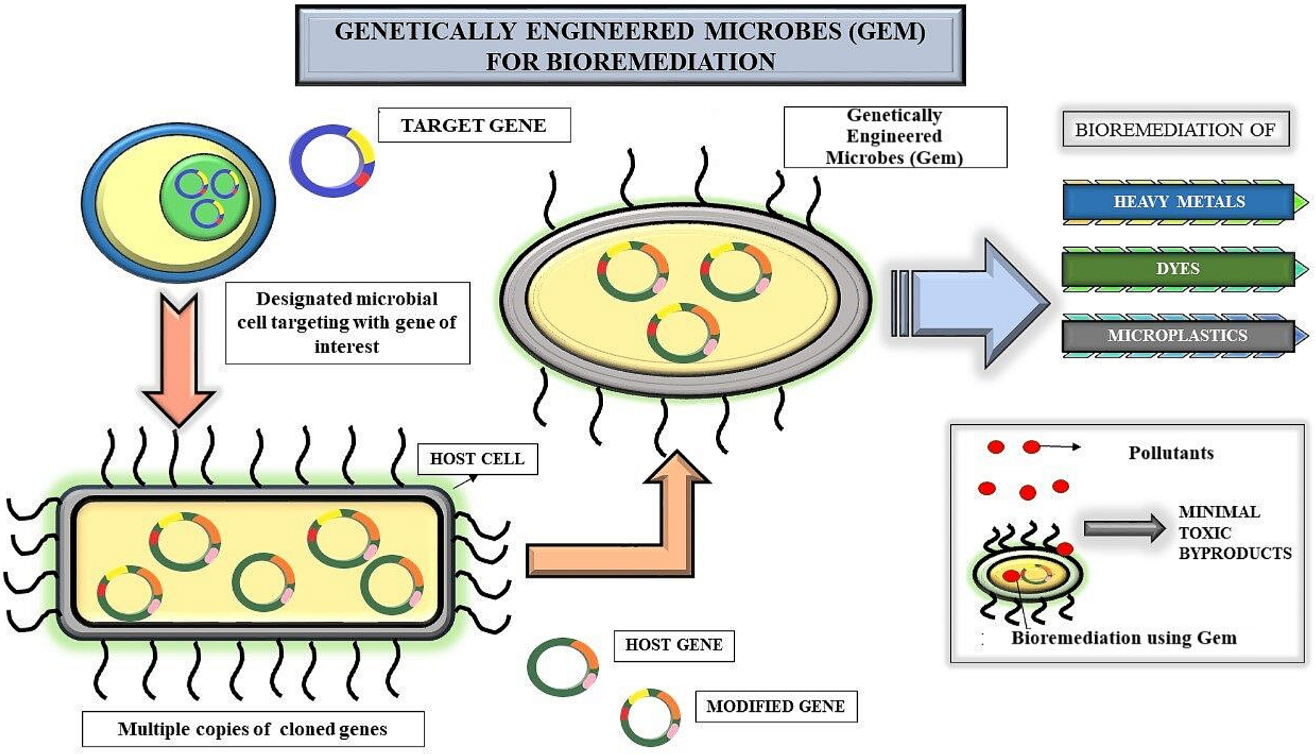

Fig. 4 Genetically modified microbes for bioremediation

environmental variables. The utilization of genetically modified microbes for the bioremediation of pollutants is shown in Table 4.

Another Metabolic engineering using recombinant DNA technology, which is the most often used method for creating a single bacterial stain with a combination of multiple breakdown pathways from other sources metabolic engineering using rDNA technology (Fasim et al. 2021). It offers specific benefits for successful in situ bioremediation to degrade the various pollutants at the target sites. Recombinant DNA (rDNA) technology alters the genetic structure of microorganisms to create strains that are resilient to the harmful effects of contaminants (Sharma et al. 2021). For instance, the Hg (II) resistance gene (merA) was transferred to the *E. coli* strain BL 308 from the naturally radiation-resistant bacterium *Deinococcus radiodurans*. The developed strains effectively converted radioactive mercury into its less hazardous equivalents and showed notable resistance. It is noted that several recombinant microbes have also been created using rDNA technology to effectively degrade contaminants (Sharma & Shukla 2022).

3.4 Immobilized microbes for bioremediation

Traditional methods of bioremediation use “free” bacterial cells; subsequently, in recent years, emphasis has shifted to the use of “immobilized” bacterial cells as a potential strategy because of its several advantages (Mehrotra et al. 2021). Immobilization procedures are divided into physical and chemical methods, several methods can be implemented to immobilize microorganisms on the carrier, the microbial cells are attached to the surface of the carriers by adsorption, trapping, covalent bond, and cross-linking of microbial cells (Woo et al. 2022; Rodrigues et al. 2019). Inorganic, natural organic, and composite carriers are the three distinct types to which the carrier materials for immobilizing various types of cells occur. Organic and inorganic carriers are eco-friendly, have minimum toxicity to the microbial colonies, have higher immobilizing density, and are easily modified according to their application (Gong et al. 2018; Thangaraj and Solomon 2019). Synthetic or composite carriers are made of both organic and inorganic carrier particles which are water-soluble and have a high number of pores. To achieve the intended bioremediation, the support matrix’s material must have adequate support and mass transfer characteristics (Jiang et al. 2022). Biosorption, biodegradation, and assimilation are the process that takes place in the elimination of pollutants by the microbes simultaneously. Where, in the process of assimilation the microbes take up non-usable nutrients like nitrogen, phosphorous, and carbon from the polluted environment and convert them as a source for their growth (Negi and Das 2023). Figure 5 elucidates

Table 4 Utilization of genetically modified microbes for the bioremediation of pollutants

Pollutants	Engineered microbes	Expression of modified genes/enzymes	Analysis methods	References
Pb (II)	*Pseudomonas aeruginosa* N6P6	bmtA	qRT-PCR, ESI-MS and SDS-PAGE	Kumari and Das (2019)
Cr (VI)	*Cellulosimicrobium* sp. (KX710177)	16 S rRNA gene	Energy Dispersive X-ray	Bharagava and Mishra (2018)
Hg (II)	*Vibrio parahaemolyticus (PG02)*	PG02	16 S rDNA gene sequencing analysis	Medfu Tarekegn et al. (2020)
3-Phenoxybenzoate	*Sphingobium wenxiniae* JZ-1	pbaA1A2BC/ 3-Phenoxybenzoate 1′,2′-dioxygenase	RT-PCR	Cheng et al. (2015)
Methyl parathion	*Pseudomonas pseudoalcaligenes*	ophc2/ Organophosphate	PyMOL	Liu et al. (2019)
Cd (II)	*Mesorhizobium huakuii*	Modified with genes encoding PCs	TrEMBL and Swiss-Prot	Porter et al. (2017)
Mercury	*Deinococcus radiodurans*	MerH	qRT-PCR	Pant et al. (2021)
Mn (II)	*Bacillus pumilus* CotA-laccase	Site-directed mutagenesis	. SDS-PAGE analysis	Luo et al. (2018)
Congo red dye	*Oudemansiella canarii*	Lacasse	Mass spectrometry	Iark et al. (2019)
Cr (VI)	*Bacillus amyloliquefaciens* ASK11	Cellulase	16 S rDNA sequencing	Aslam et al. (2019)
Remazol brilliant blue R dye	*Pleurotus pulmonarius* CCB-19	Lacasse and manganese peroxidase	RT-PCR	Saravanan et al. (2021)
Methylene blue dye				
Poly R478 dye				
Cd (II)	*Caulobacter crescentus* JS4022/p723–6 H	RsaA-6His fusion protein	SDS-PAGE analysis	Verma and Kuila (2019)
Anthraquinonic dyes and azo dyes	*Bacillus subtilis*	pMD18-T	PCR and SDS-PAGE	Bhandari et al. (2021)
Triphenylmethane dye	*B. vallismortis* fmb-103	pMD19-T-lac103	SDS-PAGE analysis	Sun et al. (2017)
Cu	*Kocuria* sp. CRB15	Cytochrome C oxidases	SEM and FTIR	Hansda et al. (2017)

the mechanism of immobilized microbes for the remediation of pollutants., which was referred from García et al., 2018.

In a pollutant-eliminating process called biosorption, the pollutants get attached to the surface of the carrier due to the complex structure and functional group of the carriers. This helps the microbes combine with the pollutants on the surface (Giese et al. 2020). Finally, the designated pollutants are degraded aerobically or anaerobically by the microbes through some biochemical reactions where the pollutants are converted into non-toxic components which is referred to as biodegradation (Folino et al. 2020). For example, a study where bacteria like *Bacillus drentensis* MG 21831T were immobilized on the outer surface of polysulfone, showed that pollutants like Pb (II) and Cu (II) were adsorbed to the surface and inner surface of the pore walls as plaque-type solid crystal form (Velkova et al. 2018). Fungal organism like *Trichoderma harzianium* was immobilized on calcium alginate-removed uranium (Kolhe et al. 2020).

Factors affecting bioremediation with immobilized microbial cells include mass transfer limitations, where protective encapsulation in hydrogel enhances tolerance to pollutants but slows the transfer of growth-promoting components like oxygen and nutrients. Another factor is the toxicity of pollutants, higher concentrations of toxic pollutants have an impact on both adsorption and the degradation of the pollutants (Mehrotra et al. 2021).

4 Recent developments – microbial bioremediation approaches

Finding new enzymes and subtypes with certain physicochemical properties would be an appealing approach to developing more successful and inexpensive tools for the elimination of polluting substances because the most crucial role is performed by enzymes in bioremediation processes (Chia et al. 2024). Numerous organic and inorganic pollutants, including Polycyclic Aromatic Hydrocarbons (PAHs), azo dyes, polymers, organocyanides, lead, chromium, and mercury, can be eliminated by enzymes. The bioremediation of contaminants has made use of numerous enzymes that have been extracted from various species (Ostovan et al. 2022). An entire cell, such as a bacterium, fungus, or algae, can be utilized in bioremediation instead of an isolated enzyme that is put into the contaminated region. Aeration, immunization, and nutrition must be provided continuously in a second manner. In addition, environmental circumstances should be favorable for microbes to exist, even though there may still be hazardous substances in the environment that inhibit microbial activity (Norzooi and Jarboe 2023). Using individual enzymes offers advantages over whole microbial cells, such as enhanced specificity, easier handling and storage, standardized activity, greater mobility, activity in high concentrations of hazardous substances, and biodegradability, reducing persistence and recalcitrance (Mousavi et al. 2021). A viable approach to

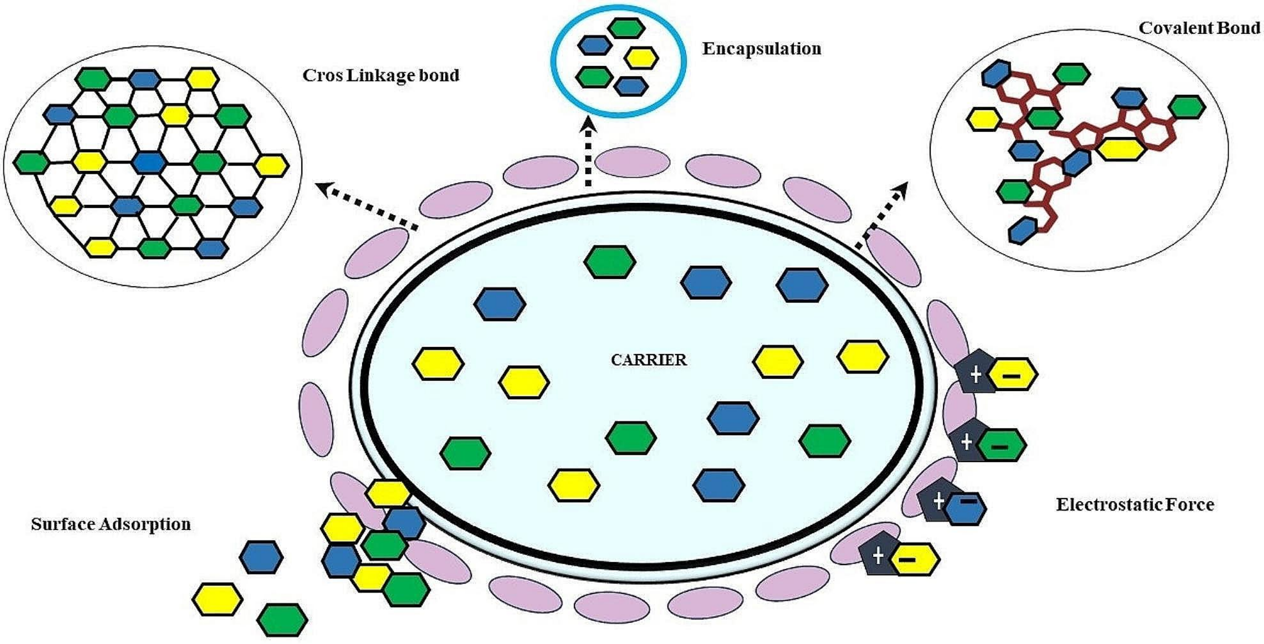

Fig. 5 Mechanism of immobilized microbes for the remediation of pollutants

discovering less costly and more efficient instruments for the remediation of contaminants would involve trying to identify novel enzymes and new subtypes with specified physicochemical properties.

Clustered Regularly Interspaced Palindromic Repeats (CRISPR)-Cas systems, TALEN, ZEN, nanotechnology, Field scale applications, Metagenomics, and metatranscriptomics are some recent developments in the field of microbial bioremediation. The CRISPR-Cas, TALEN, and ZEN systems help in editing the gene to improve the pollutant removal capacity by making them survive in extreme environments, whereas without culturing, microbial populations in the contaminated sites are studied through techniques called metagenomics and transcriptomics. This technique helps in assisting the identification of microbes and their bioremediation pathways. Identification of Novel nanoparticles is another removal technique. A study done by Zakaria et al. 2024 shows the growth of Flavobacterium (Bacteroidota), Pseudomonas C (Proteobacteria), and Proteiniclasticum (Firmicutes), through the metagenomic sequencing of the 16 s rRNA gene.

5 Challenges, and disadvantages of microbial bioremediation

In the Engineered microbes, there are several challenges even though this method has demonstrated remarkable potential in bioremediation. (Saini et al. 2020). Furthermore, genetically engineered synthetic microbial consortiums can occasionally encounter difficulties, especially when environmental conditions make it impossible for microorganisms to exist, ultimately leading to their mortality (Pant et al. 2021). The use of various computational tools and algorithms that help in logical direction and aid in understanding the potential behaviors and interactions of microbes in simulated situations in comparison to real circumstances is one way to address these issues. Some newer techniques, such as the immobilization of the selective consortia community utilizing micro-bead encapsulation, are carbon-metabolic (Antar et al. 2021). Complex operations, matrix stability, characteristics of polluted resources, presence of multiple contaminants, industrial-scale process design, substrate transfer constraints, accumulation of toxic products inhibiting microbial growth, and biofilm development pose challenges in this context (Sun et al. 2020; Ma et al. 2021). Despite these challenges, work is still being done in this area to clarify and develop these processes (Teng et al. 2020; Cheng et al. 2021).

6 Future scope and perspectives

Future studies on immobilization should continue investigating the development of appropriate substrates with low cost, stable physical and chemical characteristics, high porosity and surface area, and non-toxic properties for immobilizing bacteria. To avoid cell population density, which leads to excess biofilm formation and pore-clogging, future investigations might look into the proper ratios of microbial biomass and immobilizing substrate dosage (Li et al. 2022). To remove the overgrown and fully developed biofilms and prevent pore blockage, the flow rate through the bioreactor may need to be optimized. The immobilized cell-based treatment method might be more sustainable if value-added products are recovered concurrently with bioremediation procedures, such as recovering the metals during the biological treatment of wastewater that is metal-rich (Hegab et al. 2020). Where genetically engineered microbes currently, require effort to get through the drawbacks of these technologies, such as off-target effects, unexpected host genome changes, poor selection methods, etc. (Chu and Agapito 2022). Additionally, the combination of these cutting-edge methods may assist in the development of synthetic recombinant microbial communities that are more robust and have a multiplied biodegradation ability (Fernández et al. 2019), further research into these methods can be done to increase bioremediation's process effectiveness. At this point, it is critical to comprehend the approaches as a whole and their potential applications in a growing bioremediation strategy. This is important since it helps to develop strategies for effective bioremediation (Chu and Agapito 2022). However, these characteristics necessitate additional work on creating knowledge-based technologies and ensuring that researchers use them to their fullest potential.

7 Conclusion

Utilizing the ability of naturally existing microorganisms to break down, change, or immobilize pollutants, bioremediation attempts to mitigate their adverse environmental consequences. Bioremediation provides a flexible and effective approach to addressing pollution across varied ecosystems by utilizing the diverse metabolic capacities of these microbial populations. It has been demonstrated that beneficial microbial communities possess remarkable endurance and adaptability, enabling them to flourish in a variety of environmental conditions and efficiently break down or detoxify contaminants. This versatility, together with developments in genomics and molecular methods, makes it possible to choose and improve microbial consortia that are adapted to particular pollutants and habitats. Additionally, microbial-based bioremediation techniques are frequently sustainable and environmentally friendly. The optimization of bioremediation procedures for complicated pollutant mixes, assuring long-term efficacy, and scaling up laboratory discoveries to field applications are still difficulties. To progress in the area and deal with these issues, it is essential to do ongoing research, innovate, and collaborate across disciplines.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40974-024-00335-7.

Acknowledgements I am grateful to Saveetha Institute of Medical and Technical Sciences for their support and my co-scholars' immense help with this article.

Author contributions Pavithra Swaminaathan and P. Thamarai -wrote the main manuscript textA Saravanan, P. R. Yaashikaa and A S Vickram - Prepared figures, tables and reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Compliance with ethical standards This article does not contain any studies involving animals performed by any of the authors. This article does not contain any studies involving human participants performed by any of the authors.

Competing interests The authors declare no competing interests.

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