Archives of Microbiology (2022) 204:478
https://doi.org/10.1007/s00203-022-03087-2

MINI REVIEW

Novel strategies and advancement in reducing heavy metals from the contaminated environment

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Received: 14 April 2022 / Accepted: 20 June 2022 / Published online: 13 July 2022

Abstract
The most contemporary ecological issues are the dumping of unprocessed factories' effluent. As a result, there is an increasing demand for creative, practical, environmentally acceptable, and inexpensive methodologies to remediate inorganic metals (Hg, Cr, Pb, and Cd) liquidated into the atmosphere, protecting ecosystems. Latest innovations in biological metals have driven natural treatment as a viable substitute for traditional approaches in this area. To eliminate pesticide remains from soil/water sites, technologies such as oxidation, burning, adsorption, and microbial degradation have been established. Bioremediation is a more cost-effective and ecologically responsible means of removing heavy metals than conventional alternatives. As a result, microorganisms have emerged as a necessary component of methyl breakdown and detoxification via metabolic reactions and hereditary characteristics. The utmost operative variant for confiscating substantial metals commencing contaminated soil was *A. niger*, which had a maximum bioaccumulation efficiency of 98% (Cd) and 43% (Cr). Biosensor bacteria are both environmentally sustainable and cost-effective. As a result, microbes have a range of metal absorption processes that allow them to have higher metal biosorption capabilities. Additionally, the biosorption potential of bacterium, fungus, biofilm, and algae, inherently handled microorganisms that immobilized microbial cells for the elimination of heavy metals, was reviewed in this study. Furthermore, we discuss some of the challenges and opportunities associated with producing effective heavy metal removal techniques, such as those that employ different types of nanoparticles.

Keywords Toxic chemicals · Bioremediation · Heavy metals · Environmental pollutants · Biosorbents

Introduction

Heavy metals are constantly polluting the soil environment today due to fast industrialization, mining, and other technical breakthroughs (Zamora-Ledezma et al. 2021). As a result, heavy metal contamination has become a significant concern and topic of discussion worldwide (Azimi et al. 2017). Substantial metal contamination in the situation has developed a severe problem for ecosystem-living beings (Chowdhury et al. 2016). Metal toxicity is a serious environmental issue, bioaccumulation, and nonbiodegradability in natural surroundings (Yijing and Jue 2019). Bioremediation converts toxic heavy metals into less dangerous conditions utilizing bacteria or catalysts (Crini et al. 2019). The approach is ecologically benign and cost-effective in ecological regeneration (Kumar et al. 2019). Practical implementation of microorganisms with specific proteolytic capabilities and associated metabolites, such as enzymatic reactions and biosurfactants, is a unique way to improve and augment their restoration effectiveness (Ojuederie and Babalola 2017). The resurrection of solid-state conductors as electron givers or acceptors for microbial progression has been accompanied by innovative potentials, principal to microbial-electrochemical technologies (METs) (Cabral Pinto et al. 2019). As a counteractive approach, genetically engineered microbes consumption has also been approved (He et al. 2018).

Communicated by Erko Stackebrandt.

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Genetic engineering and biochemical alteration can transform the cell membrane components, increasing adsorption properties selected for specific metal particles (Hegazi 2013). As a result, the objective of this paper is to go through prior research on the hazardous effects of various microorganisms and their metabolites, such as biosurfactants, to improve heavy metal restoration. Cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn), arsenic (As), mercury (Hg), chromium (Cr), silver (Ag), platinum (Pt), and iron (Fe), group elements are contaminants and metalloids with a molecular intensity more than 4.1 g/cm^3 (Bansod et al. 2017). Such poisonous metallic elements are discharged into the water regularly from a wide range of natural and artificial processes. The typical quantities of Mn, Cr, Co, Fe, As, Ni, and Cd observed in water bodies in numerous locations worldwide are substantially over the permitted limit for drinking purposes (Bodzek 2015; Gautam et al. 2014). Because heavy metals are not compostable, they are disposed to bio accrue, which means that their proportion in living organisms increases with time. They are also enduring, and due to bioaccumulation, they can damage a variety of creatures explicitly or implicitly. Many heavy metal ions are poisonous or cancerous (Gusain et al. 2019). They can cause organ damage in the lungs, kidneys, liver, prostate, esophagus, gastrointestinal, skin, and neurodegenerative illnesses and diseases, including Alzheimer's and Parkinson's disease, even at extremely low concentrations (Haldar and Ghosh 2020).

Metals can also impact aquatic creatures by massing numerous body parts and instigating oxidative impairment, endocrine disturbance, and immunologic suppression (Iram et al. 2013). Toxic chemical effects and their possible environmental consequences need the advancement of technology to eliminate contaminants from the environment (Khan et al. 2019). Microorganisms can break down, detoxify, and even accumulate toxic chemical and inorganic substances. Natural, agronomic, manufacturing solid left-over, domestic waste, distinctive foundations, and supplementary causes of substantial metals can all originate in the atmosphere (Singh et al. 2011a). Taking out, electrolysis, metallurgical processing, and counting the usage of insecticides and manures in farming have all polluted large parts of the planet (Varol and Sünbül 2018; Zhang et al. 2011). Toxic chemical pollution is a serious ecological issue that affects crop yield and food quality due to the overuse of farming inputs such as fertilizers, pesticides, and mulch, which has resulted in heavy metal contamination of soils (Medfu Tarekegn et al. 2020). New treatment technologies can effectively remove heavy metal ions from the soil, water bodies, and wastewater (Ahirwar et al. 2016). Various bacteria have been offered as practical and cost-effective maximum removal options in soil and water (Zhang et al. 2011). We also go through the methods for detecting these contaminants and the variables that impact their elimination.

The removal of these heavy metals from the contaminated environment by natural and human interventions, and their conversion to life-supporting healthy niches, has been a top priority (Vardhan et al. 2019). To eliminate these harmful metals from both the human body and the environment, an appropriate method is required. Sequentially, combinatorial methods employing physicochemical and biological techniques are used to get the optimum outcomes throughout the heavy metal treatment cycle (Khalid et al. 2017).

Diggings and burial of the soil in a lethal waste location for $1,000,000 per acre, on average, is a recent technology for the crackdown on dangerous metal-contaminated topsoil. The lowest calculated fee for cleaning or removing contaminants from places containing dangerous and radioactive metals in the United States is $300 billion. The difficulty level is higher in other countries, particularly when radionuclides are contaminated on a bigger scale, such as in the Chornobyl nuclear reactor areas. This metals phytoremediation process is cost-effective and desirable to invest in. As a result, this approach is also known as "green" technology since it uses metal-accumulating flora to separate and remove harmful metals, including radionuclides, from the soil and water. Phytoremediation has evolved into a popular issue and a scholarly interest, and it has been the subject of numerous recent reviews (Verma et al. 2021).

Chemical precipitation, ion exchange, membrane filtration, floatation, coagulation–flocculation, and electrochemical methods (such as electrodeposition, electrolocation, and electrocoagulation) are all common ways of removing heavy metals from wastewater (Fu and Wang 2011). On the other hand, these approaches have the drawbacks of high operating and maintenance costs and secondary contamination from hazardous sludge production. Furthermore, most of these approaches are prohibitively costly and/or useless at extremely low heavy metal concentrations, particularly below 100 mg/L (Birungi and Chirwa 2015; Jaafari and Yaghmaeian 2019).

Bioremediation of heavy metals employing diverse microorganisms such as bacteria, microalgae, yeasts, and fungus has been widely used as an alternative to traditional treatments due to its environmental friendliness and cost-efficiency at low heavy metals concentrations. Microalgae, which have remarkable biological traits such as high photosynthetic efficiency and a simple structure, can grow effectively in harsh environmental circumstances such as heavy metals, high salinity, nutritional stress, and extreme temperature, among all microorganisms. As a result of its high binding affinity, the number of binding sites, and vast surface area, microalgae are increasingly being used in the phytoremediation of harmful heavy metals (Cameron et al.

2018). Furthermore, biosorbents can be made from both living and non-living microalgal biomass.

Bioremediation of heavy metals using microalgae has the advantages of a robust and simple process, lack of toxicity constraint, rapid growth rate compared to higher plants, and formation of value-added products such as biofuels and fertilizers, in addition to outstanding removal capacity and being environmentally friendly (Abinandan et al. 2019; Balaji et al. 2016). Furthermore, heavy metal-induced oxidative stress increases the lipid content of microalgae (Upadhyay et al. 2016). In addition, microalgae may be used to recover valuable metal ions such as thallium, silver, and gold.

Heavy metal removal using biofilm

Numerous studies have been available on the consumption of biofilm communities to eliminate heavy metals. Biofilm is an operative bioremediation technology that also assists as a biological preservative. Even at toxic concentrations, biofilms show excellent tolerance for hazardous inorganic elements, as shown in Table 1. Metal subtraction efficiency fluctuated from 93–96% for biofilm cells and 5.1–12% for planktonic cells, according to research on *Rhodotorula mucilaginosa*. Exopolymeric constituents present in biofilms that comprise compounds with surfactant or emulsifier qualities might be used to bioremediate through bio sorbent or different exopolymeric substances in biofilms that comprehend particles with surfactant or emulsifier assets (Kuhad et al. 2004).

Microalgae and their potential in metal remediation

Heavy metal removal with great adsorption capacities has been done with these biosorbents (Abbas et al. 2014). Adsorption or acclimatization of algae biomass addicted to cells is employed for bioremediation of substantial metal adulterated wastewater. Phytoremediation employs several forms of algae and cyanobacteria to eradicate or worsen toxicants to remediate thick metals (Chabukdhara et al. 2017). On their surfaces, algae have molecules such as phosphate, hydroxyl, amide, and carboxyl, whose function is to attach metals (Abbas et al. 2014). In addition to having a higher HM restoration effectiveness, microalgae also allow facile HM retrieval. Biomass of live algal involves fewer nutrients and environmental factors, but deceased microalgae do not; additionally, they might extract HMs from multi-metal mixtures (Kumar et al. 2015). Furthermore, unlike microorganisms, they are suited for aerobic and anaerobic environments and do not require immobilization. Describe how microalgae may effectively sequester HMs and the transgenic procedures utilized to improve microalgae's HM adsorption effectiveness, such as using luminous HM immunosensors produced with recombinant Chlamydomonas. Microalgal sensitivities for polyvalent metals aid in determining their potential applicability in the treatment of wastewater containing dissolved metallic ions; Scenedesmus and Chlorella are the microalgae of choice for metal removal (Varshney et al. 2015).

Table 1 Sources, properties, and antithetical effects of heavy metals

Heavy metals	Sources	Extreme conc. level in H_2O (ug L^{-1})			Toxicity		Antithetical effects	Reference
		WHO	FAO	USA	Daily intake (mg/24 h)	Lethal dose (mg kg^{-1} bw)		
Lead (Pb)	Insect killer, manures, petrol, coal	10	5000	15	0.025–0.052	94–158	Effects on the nervous system and kidney mental illness cancer	Qadri, et al. (2020)
Cadmium (Cd)	Fuel, artificial chemicals, metal hypersensitive and plating industries	3	10	5	0.018–0.052	4.4–6.2	Effects on kidney, liver, reproductive body parts, cancer	Vardhan et al. (2019)
Mercury (Hg)	Electric, plastic, paper industries and renewable sources	6	–	2	0.03	5.1–10.0	Damage to kidney, brain, and reproductive organs	Joseph et al. (2019)
Zinc (Zn)	Mining, electroplating industrial left-over and coal incineration	–	2000	–	15–20	16.1–25.3	Skin irritation, fever, nausea, anemia and aching	Vareda et al. (2019)

However, expand on the significance of coastal microscopic and macroalgal species as biosorbents for metal absorption (Mg, K, Fe, Ca, Co, Sr, Mn, Cu, V, Ni, As, Zn, Mo, Cd, Pb, Al, and Se). *Chlorella miniata, Chlorella salina, Cyclotellacryptica, Chlorococcum* spp.*, Chlorella sorokiniana, Lyngbyataylorii, Phaeodactylumtricornutum, Scenedesmus abundance, Porphyridiumpurpureum, Chlamydomonas reinhardtii C and Scenedesmusquadricauda, Scenes. Vulgaris,* Perales–Vela, et al. also noted *P. tricornutum's* and *Chlorella, Scenedesmus,* ability to remove Cu, Cd, and U (Gupta and Diwan 2017). Like eukaryotic photosynthetic organisms, microalgae synthesize peptides highly capable of binding heavy metals. These peptide molecules attach to the HMs, generating organometallic compounds that are then placed within storage space to allow for proper management of the cytoplasmic concentration of heavy metal ions, neutralizing the HMs' potentially harmful action (Kang et al. 2016).

Cadmium elimination investigations often include Cd^2 experiments with pH 4.1 to 8.2. Cd is absorbed effectively by *Scenedesmus* spp., *Plantothidium platensis, Chlorella* spp., and *Tetraselmis* spp. *Plantothidium lanceolatum*. More focus has been placed on its hexavalent form, with *Chlorella* and *Spirulina* spp. as good competitors (Gupta et al. 2016). Among the many investigations on chromium remediation utilizing life, thermally treated, deceased, and acid-treated types of microalgae, live *Spirulina* spp. showed outstanding chromium absorption (341 mg/g). Most copper elimination investigations mainly concentrate on Cu2, with *C. Vulgaris* as the most commonly utilized species in different forms (live, non-living, immobilized, and free), and pH 4.1–7.1 as the pH range investigated. Live *Spirulina* spp., on the other hand, was successful in removing copper effectively (390 mg/g) (Goswami 2021). In addition, several microalgae have been used to study the trivalent forms of ferrous metal. Furthermore, in Hg2, *C. reinhardtii* and *C. Vulgaris* demonstrated their potential value in the pH range of 4.1–7.6. *C. reinhardtii* that had been immobilized showed exceptional removal abilities (107 mg/g). Correspondingly, nickel and zinc were investigated in their chelating forms in pH ranges of 4.6–7.6 and 5.1–7.6 (Lutzu et al. 2021).

Microbial genetic engineering

Numerous microbial-derived spontaneous biosorbents have already been found to have effective biosorption properties (Frederick et al. 2013). These biosorbents efficiently removed toxic chemicals at a variety of pH levels, temperatures, and solution conditions (Ibuot et al. 2017). For example, *E. coli* ArsR (ELP153AR) (Kostal et al. 2004) is used to object As(III), and *Saccharomyces cerevisiae* (CP2 HP3) is used to mark Zn^{2+} and Cd^{2+} in hereditarily contrived bacteria for heavy metal remediation (Vinopal et al. 2007). To detoxify As-contaminated locations, *Corynebacterium glutamicum* was genetically engineered to regulate the expression of the ars operons (ars1 and ars2), as shown in Fig. 1 (Mateos et al. 2017).

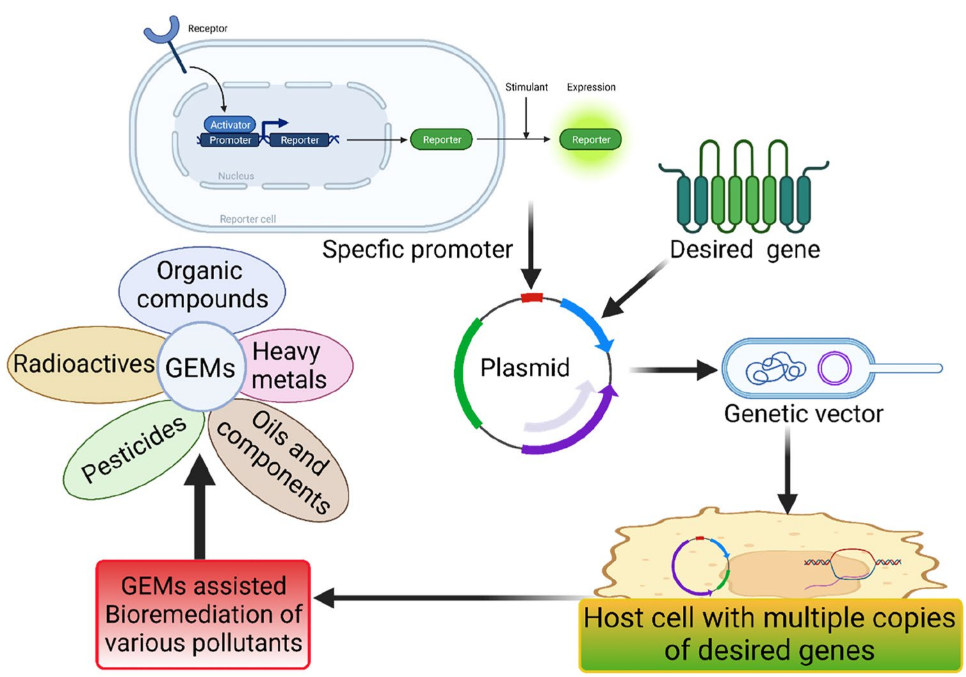

Fig. 1 Genetic engineering of microorganisms for bioremediation of different heavy metals. Created with biorender.com and extracted under premium membership

Stenotrophomonas sp. Br8 for uranium remediation

Metallic bioremediation from a new perspective *Stenotrophomonas* spp. is recognized for its ability to remediate many metals, including selenium, uranium, gold, chromium, arsenic, copper, nickel, zinc, and lead, through a variety of processes (Sánchez-Castro et al. 2021). (*Stenotrophomonas* sp. Br8) was previously identified as having a strong U abolition capability in a U nitrates solution supplemented with G2P at various metal deliberations. As a result, alginate matrices doped with microbial cells have remained studied extensively in recent years as influential biomonitoring representatives for metals like chromium, lead, cadmium, uranium, zinc, and copper at the same time (Sánchez-Castro et al. 2020). Furthermore, it has been demonstrated that cell-free alginate matrices generate equivalent results.

Heavy metal-ion import systems engineering

To enhance Gram-negative bacteria's utilization of heavy metals, recombinantly espoused inner membrane exporters belonging to three major transporter classes have been tested. Transporter classification database (TCDB): connections, supplementary carriers, and primary active transporters (Diep et al. 2018). The single-component -helical proteins Channels (TCDB 1. A) endorse passive diffusion of heavy metals through the inner membrane based on their concentration gradient. Since they are primarily energy-independent, they do not require proton-motive force or nucleoside triphosphates like GTP or ATP to move the substrates. Researchers have utilized pathways to promote As^{3+} and Hg absorption for bioaccumulation (Valls and Lorenzo 2002). Absorption of As^{3+} has been studied using the GlpF (homotetramer glycerol facilitators) from *Corynebacterium diphtheria, E. coli, Streptomyces coelicolor*, and the homologous Fps1 from *Saccharomyces cerevisiae*. The MerT/P transporter has been investigated in *Pseudomonas K-12* and *Serratiamarcescens, Pseudomonas K-62,* for Hg (Verma 2021).

Merv MerE, and MerC, are three additional transporters that can ingest Hg, and despite various topologies, it is hypothesized that they retain the exact uptake mechanism. Mer enzymes are members of the Mer superfamily (TCDB 1.A.72). Because tiny ion channels need no energy for absorption, they appear to be the optimum candidate for bioaccumulating heavy metals because they place a lower energetic load on the cell (Sauge-Merle et al. 2012). The efficiency of latent absorption, on the other hand, is a function of the target heavy metals diffusion coefficient. The GEM can no longer perform bioaccumulation after this differential approaches stability. But that has a little effect on the removal of HMs in general; it must be considered when developing microorganisms to treat highly concentrated heavy metals in wastewater effluents. Regulatory measures that require GEM bioaccumulation beyond equilibrium concentration (more Heavy Metal in the cell than in the environment) need an energy-dependent importation mechanism and storage system (Osman et al. 2018).

Porins (TCDB 1. B) are another significant carrier family that uses-barrels to build redistribution channels through the outer surface of Gram-negative bacteria. Schauer et al. discovered that the FrpB4 channel (UniProt O26042) is involved in Ni absorption using a gene knock-out technique from *Helicobacter pylori*. As a result, by enhanced expression of divalent cation-selective porins, it may be able to raise periplasmic heavy metal concentrations and hence improve the total absorption rate (Chiang et al. 2006). Creating porins with changing HM specificity may be feasible using the Pore Designer workflow.

Heavy metal-ion packing organizations' engineering

Determinations to enhance HM packing in bacteria have centered on developing intracellular metal-binding structures for HM absorption to reduce oxidative stress toxicity. Metal-binding proteins (MBPs) are most common, although catalysts that create polymers and peptides that can attach to HMs are also included.

Genetically encoded metal-binding proteins

MBPs with genetically predetermined binding sites have provided most of the ligands used in bioaccumulation investigations. MTs are widely present in archaea, prokaryotes, and eukaryotes. Furthermore, because their evolutionary ties are unknown, it has been proposed that they are a convergence of development byproducts. Low molecular mass, specific amino acid composition and spectroscopic properties suggestive of steel interactions are utilized to distinguish MTs since they do not have a shared universal progenitor (Balzano et al. 2020). Many MT studies focused on their capability to bind to Cd, zinc, and Cu; however, bioconcentration studies indicate that MTs may also attach to As^{3+}, Hg, Co, and Ni. Early on, investigations demonstrate that aggregation of highly expressed MTs lowers their functional storage capacity. Since then, MTs have been merged with several other soluble fusion partners, with the well-known glutathione-*S*-transferase and maltose-binding enzyme. Several bioaccumulation studies that utilize MTs as the storage mechanism, despite their effectiveness, fail to disclose a control in which just the fusing partner is generated (Yousefi et al. 2018). This is significant because it indicates how involved these fusion members are in HM storage.

Furthermore, bacteria establish a redox condition in the cytoplasm that prevents the production of cysteine residues in cytoplasmic proteins. A rise in demand for methionine and cysteine to manufacture other internal peptides caused by overexpression of these cysteine-rich MTs may disrupt this equilibrium and negatively influence growth. Histidine-rich MBPs are an option for cysteine-rich MTs. These molecules were recently identified as natural heavy metal storage devices that play an essential role in metal homeostasis in humans. Hpn (UniProt P0A0V6) from Helicobacter pylori, for instance, has been identified as an HM storage protein that can reversibly bind Ni. Streptomyces coelicolor A3's SCO4226 (UniProt Q9FCE4) has also been identified as a Ni storage protein (Diep et al. 2018).

Agricultural deposits

Agricultural residues are mainly composed of biopolymers, including hemicellulose, fiber, lignin, and stiffener, which have high adsorption capabilities and a wide range of valuable assemblies that simplify metal complexation (Zamora-Ledezma et al. 2021; Sud and G Kaurmp 2008). Furthermore, one of the most significant benefits of these biosorbents is that they can be easily manipulated to improve their adsorption capabilities and compliance with an industrialized measure (Castro et al. 2021). Compared to conventional remediation processes, these left-overs or decomposition products are also not as costly, are more proficient, and produce fewer biochemical or organic waste (Nguyen et al. 2013). The efficiency of these remnants is determined by factors such as heavy metal content, pH, adsorbent prescription, and temperature (Harris et al. 2019; Aksu and İşoğlu 2005).

Microbial fuel cells

Microbial fuel cells (MFCs) are a potential technique that enables organic substances present in industrial effluents to generate power using biocatalysts like bacteria (Aksu and İşoğlu 2005). Microscopic organisms create protons and electrons on the anode cell in MFCs. The protons and electrons are transferred to the cathode cell via a porous membrane and electronic circuitry (aerobic). Due to its high redox potential, oxygen stops the circuits at the cathode and reduces to water (Vélez-Pérez et al. 2020). Heavy metal elimination utilizing MFCs enables the separation and recovery of toxic substances with a more significant redox potential than the electrode surface. MFCs have even been employed in rivers for in situ cleanups, with findings showing reductions of 88% Cu^{2+}, 96.9% Hg^{2+}, and 98.6% Ag^{1+} after 60 days of operation (Bagchi and Behera 2020). MFCs also improved the biodegradation of biological substances, produced electrical energy, and presented an alternate method for substantially attempting to resolve complex heavy metal pollution while recovering bioenergy (Wu et al. 2020).

Plant-mediated remediation of substantial metals

Phytoremediation is one widely utilized approach for removing metal contamination from communities or surroundings (Azubuike et al. 2016). To reduce the negative impact of pollution, it employs underdone or heritably reformed species of plants as shown in Fig. 2 (Delgado-González et al. 2021). To rectify polluted ecologies, plants are frequently merged by additional existing effects (fungi, bacteria, biofilms, algae, and plants), exterior procedures (physical, thermal, electrical and chemical), or inputs (soil amendments, macro–micronutrients, plant disorder, fertilizers, bio surfactants, nanocomposites, emulsifiers, sorbents, hydrogels, emollients, ceramic ware, muds, water, aeration) (Devi and Kumar 2020). Several new supplementary processes and procedures are being developed to optimize the effectiveness of this technology and address its existing shortcomings (Schück and Greger 2020). The architecture for heavy metal plant-mediated rehabilitation may be broken down into four stages. The four steps are primary concerns, procedures, state-of-the-art phytoremediation, and ultimate heavy metals disposal (Delgado-González et al. 2021). The root system, biomass over the surface, growth rate, pollutant sensitivity intended for the plant, adaptation to the surroundings and time necessary to lower the impurity absorption to a target level are all factors to consider when choosing a phytoremediator plant. The plant should also be disease and insect-resistant (Khan 2020).

Electro-fenton response progression

The EF approach remains among the highest widely used electrochemical progressive oxidation, and it is energy efficient for treating wastewater to improve the Fenton process (Zhu et al. 2021). Unlike the classic Fenton reaction, H_2O_2 produced by O_2 lessening at the cathode interacts swiftly with Fe^{2+} to produce Fe^{3+} and HO•, followed by Fe^{3+} creating Fe^{2+} at the cathode (An et al. 2019). At the same time, EF can create Fe^{2+} from Fe anode termination by interacting unswervingly with H_2O_2, as shown in Fig. 3. Electrodeposition, cathodic reduction, neutralization, and anodic oxidation may be involved in the catalytic reaction with the metal complex elimination method via EF. As a result, EF has a number of distinct advantages: (1) continuous production of H_2O_2 from O_2 lessening or Fe^{2+} from the iron terminal, lowering overhead expenses

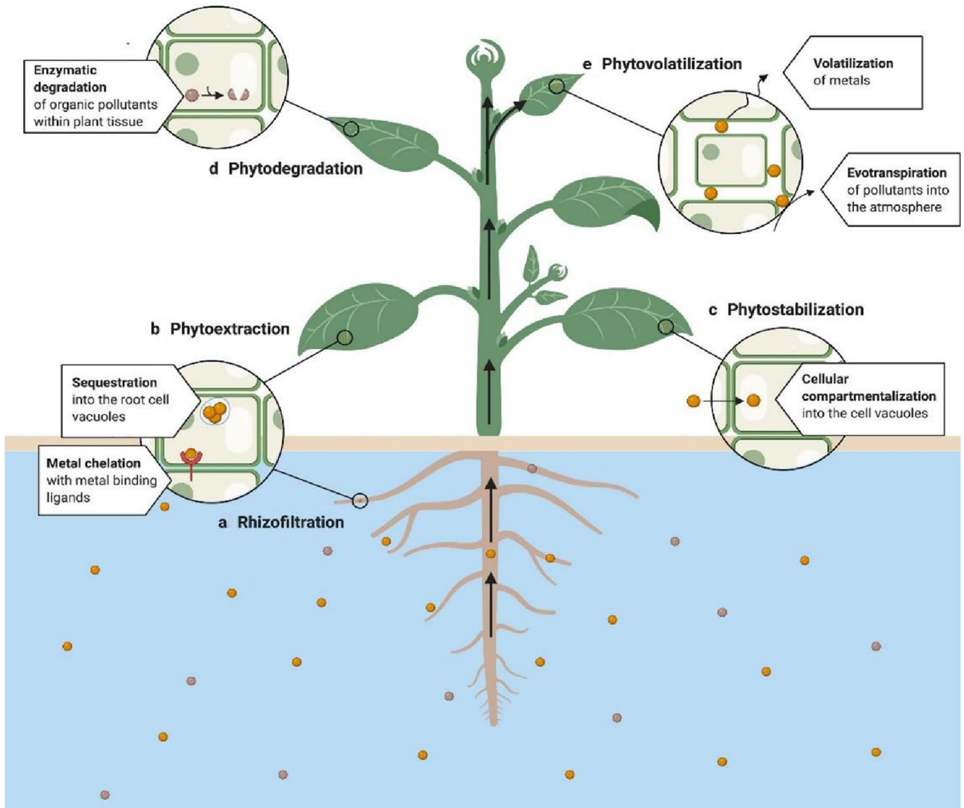

Fig. 2 Schematic illustration of different phytoremediation methods by plants. Reprinted from ref. (Delgado-González et al. 2021) with permission under the terms and conditions of the creative commons attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/)

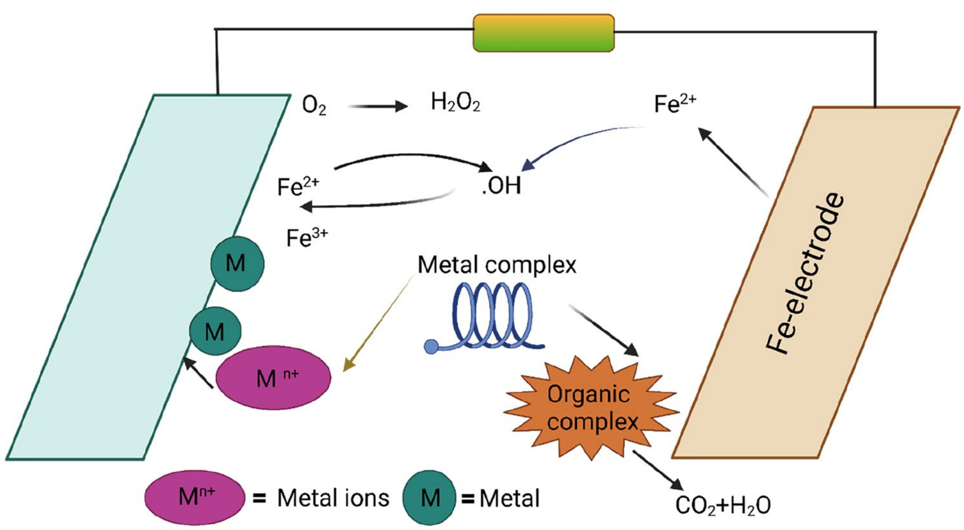

Fig. 3 Contrivance of the EF technique in heavy metal multiplexes exclusion. Created with biorender.com and extracted under premium membership

throughout the primary management; (2) avoidance of subordinate effluence; (3) extraordinary impurity exclusion measurements; and (4) the necessity to merely regulate voltage and existing even throughout the electrochemical reaction, enabling for automated systems (Burgos-Castillo et al. 2018; Zhou et al. 2020).

Molecular mechanisms involved in the bioremediation process

Organisms can remove heavy metals through a variety of methods. In a genetically modified bacterium *Deinococcus* geothermal Hg reduction has been observed at high temperatures due to the production of the mer operon from *E. coli*, which codes for Hg^{2+} elimination (Brim et al. 2003). Genes (merG and merB) of *Cupriavidusmetallidurans* strain MSR33, regulating mercury degradation, were inserted into the pTP6 plasmid that also encodes for an organomercurial protein (MerB) and mercuric reductase (MerA) (Rojas et al. 2011). The pMR68 plasmid was used to modify a Pseudomonas strain using unique genes (*mer*), making it mercury tolerant. Biological decomposition of mercury (Hg) by bacteria (Klebsiella pneumonia M426) (H2S) occurs in two different ways, either by reducing mercury (II) to mercury (0) or by precipitating mercury as insoluble Hg due to thiol (Sone et al. 2013; Essa et al. 2002). By genetically engineering the tod and xyl operons of *Pseudomonas putida*, Deinococcusradiodurans (radiation-resistant bacteria) are capable of spontaneously lowering Cr (IV) to Cr (III) for full toluene (fuel hydrocarbon) breakdown. Metabolites from microbes, such as coenzymes and siderophores, played an essential role in the breakdown process (Brim et al. 2006; Penny et al. 2010).

Biotechnological intervention and engineering microbes in bioremediation processes

It has the benefit of allowing researchers to create microbial strains that can tolerate harsh settings and act as bioremediation in various environments. Genetic engineering has led to the creation of “biological immunosensors” that can swiftly and precisely monitor the level of pollution in hazardous places (Dixit et al. 2015). Heavy metal ratios like cadmium (Cd), mercury (Hg), nickel (Ni), arsenic (Ar), and copper (Cu), have been measured using a variety of biosensors. Bacteria expressing phytochelatin 20 on the cell surface, such as *E. coli* and *Moraxella* sp., have collected 26 times more Hg or Cd than wild-type isolates, as shown in Table 2. Nevertheless, maintaining the recombinant bacteria population in the soil in changing climatic circumstances and competition from native microbial pathogens is a crucial challenge for using these GEMs in harsh field situations (Divya and Deepak Kumar 2011).

Designer plant approach

Latest innovations in omics technologies, including proteomics, genomics, metabolomics, and transcriptomics, have aided in identifying features that optimize the advantages of field remediation methods (Aken et al. 2011). Treatment of metal tolerance, aggregation, and breakdown capacity of plants versus different inorganic contaminants can help to alleviate this issue. The bacterial genes involved in metal degradation may be inserted into plant tissues that use the modified crop technique, allowing metal breakdown inside the plant tissues (Mehwish et al. 2021). Compared to physical-based approaches, which are less sustainable and more dangerous to human fitness, the use of GE (genetically engineered) plant-based bioremediation for different HMs pollution is at the forefront due to its eco-friendliness and decreased health dangers (Singh 2011a). Various microbial genes can be used to detoxify and accumulate inorganic pollutants in the transgenic plant. Metal-detoxifying chelators like metallothioneins and phytochelatins can help plants withstand heavy metals by increasing their transportation, absorption, and storage. Furthermore, transgenic plants with the bacterial reductase enzyme can grow Se and Hg evaporation while collecting arsenic in plant shoots. Trees like willow, poplar, and Jatropha, which increase and provide a lot of biomasses, might be utilized for phytoremediation and energy generation (Rai 2018).

Engineering of rhizosphere

Engineered bioremediation options include adding growth stimulators to the rhizosphere to reduce substantial metals or adding nutrients to polluted soil to improve the growth of microorganisms and biosorption characteristics of microbes

Table 2 Genetically engineered bacteria for remediation of heavy metals

Genetically engineered bacteria	Heavy metals	Initial concentration (ppm)	Removal efficiency	Expressed gene	Reference
E. coli strain	As	0.05	100	Metalloregulatory protein ArsR	Kostal et al. (2004)
E. coli strain	Cd^{2+}	–	–	SpPCS	Kang et al. (2007)
Methylococcus capsulatus	Cr^{6+}	1.4–1000	100	CrR	Al Hasin et al. (2010)
P. putida strain	Cr	–	–	Chromate reductase (ChrR)	Murtaza and Dutt (2002)
E. coli strain	Hg	–	–	Organomurcurial lyase	Zhao et al. (2005)
E. coli JM109	Hg	7.4	96	Hg^{+} transporter	Kiyono and Pan-Hou (2006)
Pseudomonas K-62	Hg	–	–	Organomurcurial lyase	Ng, et al. (2009)

or bioengineered plants (Lovley 2003). Many modified microorganisms with heavy metal elimination capability were put in a definite rhizosphere to accomplish a definite purpose by expressing enhanced enzymes like uranyl reductase and electroplating (Dixit et al. 2015). Furthermore, bioengineered plants have been shown to generate chemicals that may aid in heavy metal rhizospheric transformation. Numerous studies have extensively used similar methods to use the rhizosphere ecology to repair heavy metal-contaminated soils (Sarma et al. 2019).

Biofiltration

Biofilters are porous transporter materials that remove columns of trapped microorganisms. It is a high-quality system for heavy metal decontamination and the elimination of sewage and air emissions (Singh et al. 2011b). In this process, single or numerous populations of microorganisms are produced and connected to an inert substrate, which can form biofilms. This design in bacteria ensures robustness in the treatment of heavy metals, including stubborn pollutants (Edwards and Kjellerup 2013). Microorganisms partitioned into complicated assemblies provide different mechanical properties, reducing heavy metal strain. This arrangement uses numerous mechanisms efficiently, including precipitation, redox reaction, biosorption, biosurfactants, volatilization, and bioaccumulation (Shukla, et al. 2017). However, because biofilm development for heavy metal treatment is a relatively new method, failure can happen due to nutritional limitations for high biomass density in the filter (Shukla et al. 2020).

Process of heavy metal remediation by microorganisms

The presence of heavy metals displaces essential components in biological molecules, interfering with their processes and altering the structure and function of enzymes, membrane carriers, and proteins, making them poisonous. Aside from producing supplementary toxic end-products, such procedures are typically expensive, even when successful. To eliminate toxic pollutants from the surroundings, it is essential to convert toxic heavy metals into non-hazardous forms using indigenous or genetically engineered microorganisms capable of degrading these heavy metals (Tak et al. 2013). This is a relatively efficient way to eliminate harmful pollutants and stabilize the ecosystem. Because they can tolerate metal toxicity in various ways, microscopic creatures are critical in the remediation of heavy-metal-contaminated ecosystems. The use of microorganisms to retain, deposit, or adjust the redox potential of certain heavy metals has attracted a great deal of interest. The following procedures are used in microbial bioremediation:

1. Toxic metals are sequestered by cell wall components or internal metal-binding proteins and peptides like phytochelatins and metallothioneins also compounds such as bacterial siderophores, which are primarily catecholase, however, fungi produce hydroxamate siderophores (Javaid et al. 2021).
2. Altering metabolic pathways to prevent metal absorption.
3. Enzymes convert metals to non-harmful forms.
4. Metal intracellular concentrations can be lowered via specific efflux mechanisms.

Bacteria produce siderophores, iron-chelating chemicals that promote movement while decreasing metal bioavailability and soil clearance. In the region of heavy metal removal, the mechanisms underlying the sorption process may be dependent on or distinct from the cell's metabolic activities (Gupta and Diwan 2017). Extracellular precipitation/accumulation, cell surface sorption/precipitation, and intracellular aggregation are all situations that might occur. Negatively charged functional groups present on the exterior of microbe membranes, including carboxylic groups, phosphorus, and hydroxyl, readily bind to heavy metal ions. Bacterial functional groups such as uronic acid of sulfate groups and carboxyl groups (RCOO) can also exchange ions. Gram-negative bacteria cell walls contain catalysts, lipopolysaccharides, glycoproteins, phospholipids, and lipoproteins (Selatnia et al. 2004). These cell wall elements are efficient sites for adsorption activities in bacteria, functioning as ligands for binding metal ions and ultimately removing them from contaminated environments. Bacteria are helpful biosorbents for polluted environment remediation because they can survive in controlled settings and endure high temperatures. As biosorbents, they effectively absorb heavy metals from dirty environments. Because of its ability to absorb toxic metals in contaminated effluents via the ion-exchange process, *Saccharomyces cerevisiae* yeast is also an efficient bioremediation reagent (Kang et al. 2016). Because algae produce a large amount of biomass, they have a high sorption ability when associated with additional microbial biosorbents. Halimoon and Mustapha found that algae had a 16–85% biosorption effectiveness compared to other microbial biosorbents. The use of ion-exchange methods accomplishes this. It was also shown that reactive groups on the surfaces of brown sea algae, such as sulfonate, carboxyl, sulfhydryl groups, and amino groups, readily repair heavy metals such as Pb, Ni, and Cd (Gupta et al. 2016).

Bacteria use heavy metals and critical nutrients as terminal electron acceptors, supplying them with the energy they need to detoxify metals via enzymatic progressions. Through biomagnification, bacterial cells may acquire heavy metal ions, both particulate and persistent, through their byproducts (Balcázar et al. 2015). To do this, exopolysaccharide (EPS) ion-exchange methods are utilized. It was also shown that reactive groups on the surfaces of brown sea algae, such as amino, carboxyl, sulfhydryl, and sulfonate groups, readily repair heavy metals. *Alcaligenes faecalis, Agrobacterium* spp*., Bacillus* spp*., Xanthomonas campestris, Leuconostoc, Zygomonas mobilis, Acetobacter xylinum and Pseudomonas* spp*.,* have all been discovered as EPS-producing bacteria (Selatnia et al. 2004; Roy 2020). The use of non-neutral, negatively charged EPS as a feasible biosorbent as the focus of attempts to achieve heavy metal cleaning by bacterial EPS must be prioritized. *Sphingomonas paucimobilis* (gellan), *Pseudomonas* aeruginosa alginate, hyaluronan (*Pasteurella multocida, Pseudomonas aeruginosa, Streptococci attenuated strains*), *Pseudomonas oleovorans* (galactopol), *Xanthomonas campestris* (xanthan), *Enterobacter A47* (galacto) (Gupta et al. 2016; Srivastava and Dwivedi 2015). The production of exopolysaccharides is connected to activities such as biofilm development, which is required for biomineralization and metal-ion biosorption (Kang et al. 2016).

Biofilms are communities of microbes wrapped in an extracellular milieu of exudates, polysaccharides, and detritus that a single bacterial strain may form. EPS (Exopolysaccharides) can be physiologically altered by carboxymethylation, acetylation, phosphorylation, methylation, and sulphonation, changing their biological activity and increasing their applicability (Jan et al. 2014). More EPS-producing bacteria should be considered for metal-ion chelation capabilities, as they may create a strong polysaccharide having anionic groups that aid in the removal of harmful metals from the environment (Wang and Chen 2009).

Role of PGPR in heavy metals removal

Identifying the mechanisms through which PGPR increases plant growth is acute for ensuring food stock and, consequently, enhancing food security. Because most rhizospheric bacteria are naturally resistant to external toxins, they are recycled in phytoremediation to remove organic and heavy metal pollution from food crops (Tariq et al. 2017). Rhizosperic bacteria increase the availability of nutrients in soils for plant development, produce Indole 3-acetic acid phytohormones, and protect plants from disease while also eliminating contaminants from the soil. This PGPR lives in the rhizosphere of the host plant, where it promotes plant growth and development through both direct and indirect means (Nehra and Choudhary 2015). Natural mechanisms include phosphate solubilization, 1-aminocyclopropane-1-carboxylate deaminase synthesis, and siderophore synthesis, which allow the plant to resist abiotic stress conditions by lowering ethylene rates and improving growth regulator hormone balance. In contrast, underlying mechanisms include the PGPR acting as biocontrol agents and detoxifying noxious substances such as heavy metals and pesticides. Among the ePGPR bacteria are *Pseudomonas, Micrococcus, Caulobacterium, Flavobacterium, Erwinia, Azospirillium, Chromobacterium, Serratia, Agrobacterium, and Azotobacterium* (Ahemad 2019). These PGPRs produce a wide range of chemicals that help plant growth in the face of abiotic stress.

Innovative molecular practices

Microbes are used in bioremediation because of their potential to break down environmental toxins via metabolic pathways linked to the organism's activity and development. Using the co-metabolism process, microorganisms can convert dangerous compounds present in contaminated settings to innocuous final products. Using indigenous microbes to clean up contaminated areas has not achieved many effective outcomes (Ghosal et al. 2016). Heavy metals such as mercury, for instance, cannot be removed from the environment by native microbes. On the other hand, recombinant DNA technology has a significant role in the bioremediation of heavy metal pollution since it improves the resolution process. With the discovery of restriction enzymes and DNA ligases in the 1970s, recombinant DNA technology made it feasible to modify the genome of live creatures. Bacteria' metabolism possibilities have been explored since then, and microbes have been bioengineered for particular reasons. The goal of genetic engineering for bioremediation is to make plants, microbes, and enzymes viable instruments for the breakdown of hazardous chemicals (Divya and Deepak Kumar 2011). Thanks to genetic engineering, heavy metals such as Cd, As, Fe, Cu, Ni, and Hg may now be removed from bacteria. On the other hand, the breakdown rate is determined by the enzymatic effectiveness of proteins present in the cells or those stimulated to a specific substrate.

Utilizing recombinant DNA technology, foreign genes from another creature of the same or other type are put into the genome of genetically engineered microorganisms. These modified microorganisms have been utilized to create competent strains for bioremediation of polluted environments, thanks to their improved capacity to break down a wide range of pollutants. The utilization of genetically modified *Pseudomonas putida* harboring the *merA*gene and *Escherichia coli* strain M109 to successfully remove Hg from polluted soils and sediments has been reported (Buermans and Dunnen 2014). Azad et al. provided a thorough overview of the application of genetically modified bacteria and plants in the bioremediation of heavy metal and other organic pollutant-contaminated environments. The majority of the strategies included identifying and inserting metal absorption genes into competent bacterial cells and plants. Hg resistance has also been obtained by inserting additional genes into Pseudomonas cells using the pMR68 plasmid. Specific genes in n-alkane-degrading bacteria, such as xylE, nidA, ndoB, are typically identified on plasmids and employed as indications for microbial biodegradation identification (Nostrand et al. 2012).

In the fight against harmful compounds in the environment, the use of GEMs to speed up the cleanup process is critical. Because the catabolic action to liberate GEM is mostly tied to the constancy of the recombinant plasmid injected into the bacterium, it is critical to preserve the sustainability of the microorganisms before using them for bioremediation. New metabolic pathways are created, allowing modified bacteria to transform hazardous heavy metals into less toxic or harmless versions, boosting bioremediation operations. The use of new vectors to implement new gene segments into a potential member, developing new methods for regulating gene expression, and using directed and random mutagenesis to increase the activity of biodegrading enzymes (Wu et al. 2021).

Microbial-based sensors generated utilizing genetic engineering are now being utilized to determine the level of contaminants swiftly and accurately in polluted locations. Biosensors were used by Dixit et al. to assess heavy metal values in polluted environments, including As, Ni, Cd, Hg, and Cu. Therefore, biosensors are confined in their use due to differences in reaction times, sensitivity, signal relaxation durations, detecting sensitivities, and stability (Sharma et al. 2021). Genetic engineering enhances the likelihood of obtaining effective pollutant-degrading microorganisms since they may have a more excellent capability for environmental cleanup than natural bacteria. Current genetics and omics tools, including proteomics, metabolomics, and genomic, have prompted researchers to research the degradation of organic pollutants by microbes, allowing them to understand better the physiological, demography, and chemistry of PAH-degrading organisms (Jiménez-Díaz et al. 2022). Using whole-genome sequencing, it is now feasible to examine the physiology of microorganisms involved in removing pollutants from the environment in great detail. The discovery of genes that code for bacterial inorganic transformation has cleared the door for applying molecular genetics to improve metal resistance. Transgenic plants with enhanced bioremediation properties can be created using gene technology. It also entails genetically modifying biochemical detoxifying pathways to allow such plants to digest contaminants and break down xenobiotics properly. Metal pollution may be efficiently remediated using genetically engineered endophytes and PGPR for soil pollutant degradation (Sarma et al. 2019). Overexpression of genes that determine antioxidant activity and enzymes involved in the biosynthesis of glutathione and other phytochelatins increases metal accumulation capacity and tolerance. Other genes and the merA genes must be investigated for their potential application in the heavy metal cleanup. Other culture-independent technologies have been defeated by DNA microarrays, a high-throughput tool that detects several regions in a specific experiment. The most often utilized technology for researching gene function is the GeoChip array. It affects a wide range of genes involved in N, C, P, and S biogeochemical processes and metal tolerance, breakdown, and pollution control (Fuller et al. 2021).

When introducing genetically designed bacteria into the ecosystem for biosorption, caution must be used since horizontal gene transfer between the created microorganisms and natural microbes in the environment is conceivable. Environmentalists are concerned about horizontal gene transfer from synthetic bacteria to native microbes. This is because germs may easily penetrate the surroundings and use plasmids to transmit resistance genes from one bacterium to another, allowing them to adapt to new ecological conditions. Before releasing such bacteria into polluted areas, the impacts on indigenous microbes in the ecosystem need to be researched (Chettri et al. 2022). However, for any microbial-based technology encircling the bioremediation process to be adopted, embedded recombinant strains of bacteria must be measured, and strategic initiatives to program cell death once the biocatalyst has completed its task or if genetically engineered genes are accidentally transferred. In this sense, lethal gene systems should be built such a horizontal gene transfer does not occur once modified bacteria have completed contaminated site cleaning.

Genetic manufacturing of microorganisms for improved bioremediation

The genetically engineered bacteria *Pseudomonas putida* (NRRLB-5473) and *Pseudomonas aeruginosa* (NRRLB-5472) were initially patented in the United States in 1981. These two strains were created in the early 1970s and had genes for breaking down poisonous compounds such as camphor, naphthalene, and salicylate (Chakrabarty 1986). Such variants are capable of degrading toxins. For the elimination of polychlorinated biphenyls, the PCB catabolic genetic factor found on the genetic material of *A. denitrificans* JB1, *R. eutropha* A5, and *Achromobacter* sp. LBS1C1 was transplanted to the heavy metal tolerant strain *R. eutropha* CH34 by spontaneous transference, as shown in Table 3 (Valls et al. 2000). As a result, biosafety regulatory bodies such as the UNEP (United Nations Environment Program) and the EPA (the United States Environmental Protection Agency), who supervise the regulation of genetically modified organisms and living modified

Table 3 Xenobiotics humiliating microorganisms

Microorganisms	Detrimental chemicals	Reference
Pseudomonas	PCBs, Benzene, Hydrocarbons	Vidali (2001) and Cybulski et al. (2003)
Bacillus species	Halogenated hydrocarbons, phenoxyacetates	Dean-Ross et al. (2002)
Rhodococcus species	Aromatics, hydrocarbons	Dean-Ross et al. (2002)
Atotobacter species	Branched hydrocarbon benzene, aromatics cycloparrafins	Dean-Ross et al. (2002)
Corynebacterium	Aromatics	Kapley et al. (1999)
Flavobacterium	Biphenyl, aromatics, naphthalene	Kapley et al. (1999)
Methanogens	Polycyclic aromatics, PCBs, biphenyl	Verma and Kuila (2019)
Methosinus	PCBs, formaldehyde	Verma and Kuila (2019)

species, have set stringent requirements (Sriprang et al. 2003). DNA segments were produced to collect Cd^{2+} and proclamation phytochelatins in the manifestation of a bacteroid-specific sponsor (the nif H gene). Heavy metal deterioration utilizing in herently modified microbes has intrigued attention, as demonstrated by the use of AE104 pEBZ141 (*Alcaligenes eutrophus*) for chromium deterioration from manufacturing effluents and the production of a chimeric photosynthesizing bacterium with the instant aneous countenance of the Hg transportation organization and metallothionein for Hg^{2+} deprivation commencing wastewater and heavy metal *Rhodopseudomonas palustri* (Verma and Kuila 2019).

Fungal dilapidation applications of aliphatic hydrocarbons and enzymes involved

The biodegradation processes of indigenous fungal and bacterial species are one of the key processes for removing hydrocarbon pollutants from the environment (Aydin et al. 2017). Typically, fungi degrade aerobically; yeasts primarily observe anaerobic disintegration, although filamentous fungi have also been shown. Fungus decomposes hydrocarbons that are the most common organic wastes, primarily under aerobic circumstances; in reality, fungi work via enzymes that oxidize hydrocarbons to produce H_2O and fewer hazardous remainders (Daccò et al. 2020). The substrate oxidation in microsomes facilitated by monooxygenases (EC:1.14.13.12) and CYP (cytochrome P450), including enzymes alkane-oxygenase, is required for the biosynthetic processes identified in fungi (Durairaj et al. 2015; Asemoloye et al. 2019).

- Methane monooxygenase-like enzymes in bacteria catabolize C1–C4 alkanes (Prenafeta-Boldú et al. 2018).
- Non-heme iron oxygenase catalysts catabolize C5–C16 alkane decomposition (Ryle and Hausinger 2002).
- The enzyme pathways that catabolize the breakdown of C17 and longer alkanes are mostly unexplored (Singh 2011b).

Possible microorganisms in lindane dreadful conditions

The bacterial humiliation of lindane and other xenobiotics is extensively described. Bacterial cells customize organic impurities as the sole basis of nitrogen and carbon. Presently, aninteger of lindane-degrading bacterial varieties has been separated, supplemented, and housetrained, including *Paracoccus, Achromobacter, Microbacterium*, *Rhodococcus*, *Burkholderia*, *Chromohalobacter*, *Staphylococcus*, *Kocuria*, *Streptomyces*, *Azotobacter*, *Arthrobacter, Sphingomonas*, *Pseudomonas*, *Xanthomonas*, *Klebsiella*, *Pseudoarthrobacter*, *Pleurotus*, *Actinobacteria and Fusarium* (Saravanan et al. 2020). According to reports, various microorganisms break down lindane at varying rates. Phragmiteskarka strain *Microbacterium* spp. P27 was isolated and identified as a rhizospheric bacteria that efficiently decomposed 83% lindane (51 mg L^{-1}) in two weeks while promoting plant development. White rot fungi's ligninolytic extracellular enzyme activity rapidly destroys lindane. Fungi biodegradation activity is influenced by conservational soil variables, as well as the existence of other microorganisms (Gangola et al. 2018).

Innovative technologies

The trapping of magnetic nanoparticles by epoxy cross-linking is one unique way of enzyme immobilization (Kumar and Pannu 2018). This method can boost the action of bacteria, fungus, or heterologous-expressed enzymes that degrade pollutants. Recent high-throughput approaches may be utilized to investigate crucial variants from the pesticides degrading microbial population, bridging the gap among lab cultures and comprehensive presentations (Gangola et al. 2018). Pesticide degradation was studied using omics-based methods (Bhatt 2018). Upcoming-generation sequence alignment advances have resulted in a massive number of microbiological information in the arrangement of nucleotide and protein series uploaded to numerous internet databases (PDB, NCBI, Uniprot, DDBJ, etc.) (Bhatt and Barh 2018). The data from the omics-based techniques may be utilized half to discover new inheritable factors and enzymes and molecular docking investigations. These datasets are also helpful for phylogenetic analysis and categorization of new lindane-degrading microorganisms (Sparks et al. 2019).

Physicochemical and biological properties of solarization and ozonation

Pesticide overuse in agriculture has necessitated the development of remediation technologies to decrease or remove pesticide concentration in soils (Alvarez et al. 2017). Solarization and ozonation are two non-chemical techniques that try to attain this goal. The longevity of insecticides in the soil\varies substantially reliant on the collaboration among the pesticide particle and the soil (Goi and Trapido 2004). Solarization can promote the decomposition of these chemicals in the soil by increasing temperature, moisture, solar irradiation, and the oxidizing power of ozone (Liang et al. 2019). Nevertheless yet, because certain chemicals, such as neonicotinoids, require UV frequencies to be destroyed, the breakdown driven by solar irradiance is often restricted (Ghahrchi and Rezaee 2020). Several investigations have shown that when soil organic matter is oxidized, H^+, salts, and other chemicals linked to the organic matter are liberated into the soil solution. Ozone may immediately target double bonds in soil molecules, resulting in highly reactive oxidizing agents. In this case, organic molecules' amine functional groups might react with ozone to produce NH^{4+} (Avalos et al. 2020).

Furthermore, in addition to creating NH^{4+} from nitrogen-rich composites in soil organic matter, NH^{4+} fabrication has been proposed as an antibiotic method used by specific bacteria (i.e., Streptomyces) (Haritash and Kaushik 2009). Because solarization is routinely used to reduce soilborne illnesses and ozone has a powerful antimicrobial influence, both techniques were predicted to significantly influence the soil microbial population in terms of biomass and composition (Mitsugi et al. 2014; Fuhrer et al. 2016). Solarization's early rise in soil temperature and relative humidity may have helped anaerobic and thermophilic microbial species while damaging those susceptible to such variables (Luo et al. 2019). Solarization, either alone or combined with ozonation (SOS and SOD), reduced bacterial biomass (Díaz-López et al. 2021). In contrast, the prevalence of other taxa, such as Aspergillus, which includes multiple diseases as well as potential pesticide degraders, increased in all treatments (S, SOS, and SOD) (Bressuire-Isoard et al. 2018; Bordjiba et al. 2001).

Nano-photocatalyst application in wastewater treatment

For the past two decades, advanced oxidation processes (AOPs) have gotten a lot of attention when it comes to the progress of treating wastewater. At the pilot size, several of the approaches, such as Fenton, cavitation, ozonation, and photocatalytic oxidation, have proved successful in breaking down stubborn organic pollutants (Donkadokula et al. 2020). In the wastewater treatment arena, a study has been undertaken on both homogeneous and heterogeneous AOPs. To promote AOPs, catalysts such as ZnO, TiO_2, UV/visible light, and different oxidants such as O_3, H_2O_2, and others are used. AOPs create OH • radicals upon reactivation and interact with organic polymers in the presence of dissolved O_2 in the suitable solvent (Chang et al. 2009; Dow et al. 2013). Among many other sectors, the coloring, printing, and papermaking plants contaminate the air significantly, owing to the extensive use of natural chemicals in operation. Since natural dyestuffs are present in water reservoirs, sunlight penetration and dispersion will be hampered.

Consequently, the proportion of toxic substances rises, posing a threat to aquatic life (Danwittayakul et al. 2015). Dynamic AOPs can be used to achieve absolute mineralization of organic colorants. Many investigations on various AOPs have demonstrated the effective degradation of dye impurities in the aqueous phase. The photocatalyst AOP has the potential to initiate complex chain reactions, as well as the formation of uncolored biological precursors, which can occasionally become hazardous. Much prior research has demonstrated that microsize catalysts were utilized in various AOPs to biodegrade complex compounds. Still, no application of nanomaterials in AOPs for wastewater treatment has indeed been recorded. Elamin and Elsanousi have reported using semiconductors such as CdS, TiO_2, WO_3, and ZnO as photocatalysts (Elamin and Elsanousi 2013). For example, ZnO is regarded as one of the best photocatalytic materials for the effective degradation of organic pollutants (Ali et al. 2010). Extensive studies have also indicated that ZnO is extremely photochemically responsive, cost-effective, and non-toxic, especially when it comes to the decomposition of organic pollutants compared to TiO_2 (Yoshida et al. 2003). Figure 4 portrays different waste-to-energy technologies and thermochemical and organic adaptations for municipal solid waste administration.

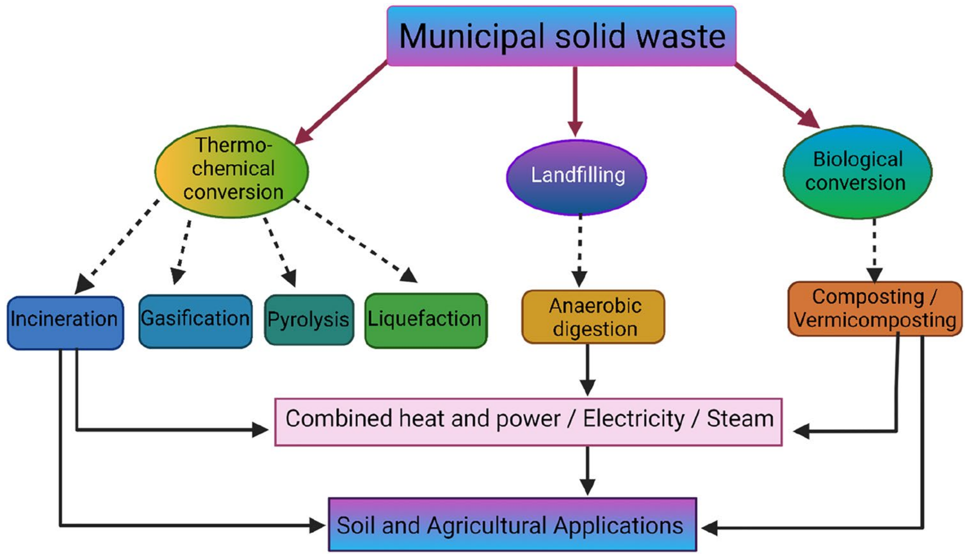

Fig. 4 Different waste-to-energy technologies and thermochemical and organic adaptations for municipal solid waste administration. Created with biorender.com and extracted under premium membership

Conclusion and outlook

Heavy metal contamination in recent decades has increased dramatically. Therefore, methods, regulations, technologies, and materials must be developed to address this issue without causing potentially devastating health and environmental effects. This study has shown that selecting the correct detection and measurement methodologies, treatment technologies, and operating parameters is critical for maximizing heavy metals removal efficiency and efficacy. Researchers and developers must develop quick, low-cost, and reliable methods to measure the concentration of heavy metals on the spot or in situ. In this manner, we can better understand heavy metal contamination issues in various ecosystems. Despite the numerous established heavy metal removal methods and technologies available today, it is essential to consider the environmental conditions in which they will be implemented, differentiating between appropriate for centralized and decentralized situations. The capital and knowledge requirements for installation, operation, and maintenance must be assessed. A range of materials have been examined; low-cost, easily disposed of materials and composites with nanostructures are particularly intriguing. To develop safe, innovative, environmentally friendly, efficient, and economical solutions, we review various approaches for removing heavy metals from polluted environments, including residues, natural and sophisticated materials, and enhanced detection and quantification methods.

Acknowledgements Consejo Nacional de Ciencia y Tecnología (CONACyT) Mexico is thankfully acknowledged for partially supporting this work under Sistema Nacional de Investigadores (SNI) program awarded to Hafiz M.N. Iqbal (CVU: 735340).

Author contributions QM, NH and MB conceptualized the review theme. QM, NH, MM, MB and HMNI wrote the main manuscript text. QM prepared the Tables. NH and HMNI prepared figures. All authors reviewed the manuscript.

Funding The authors have not disclosed any funding.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The author(s) declare no conflicting interests.

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