REVIEW

Microbial cell factories in the remediation of e-wastes: an insight

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Abstract

Electronic waste, also known as e-waste, is the discarded or by-products of electronic appliances, constituting a major percentage of the total solid waste produced globally. Such e-waste is mostly composed of plastics, various heavy metals, azo dyes, and xenobiotic components, which are mostly non-biodegradable or less degradable in nature. As a result, they increase environmental toxicity, preventing the growth of crops and causing health issues for humans and other animals. On the other hand, recycling e-waste may also lead to the consumption of heavy metals through water or the inhalation of polluted air after combustion, which may cause various health issues such as asthma, nerve, respiratory, kidney, liver disease, and even cancer. Hence, microbial degradation of e-waste has become a new trend in managing such solid wastes. However, their mode of action is somewhat less explored. Microbes degrade various components of e-waste through a number of mechanisms such as bioleaching, biosorption, biotransformation, bioaccumulation, and biomineralization. Some microorganisms release enzymes such as reductases, laccases, esterases, carboxylesterases, catalases, and dioxygenases for the bioconversion of various components of e-waste into their less toxic forms. This review provides insight into the role of microbes in the conversion of various components of e-wastes such as polyaromatic hydrocarbons (PAHs), azo dyes, and heavy metals and their mode of action.

Keywords E-waste, Bioremediation, Heavy metal, Xenobiotics, Microbial enzymes

Introduction

With the global demand for electronic goods on the rise, effective management of electronic waste (e-waste) has emerged as a pivotal issue within the realm of solid waste management (Ghulam et al., 2023). This concern extends across developed, transitioning, and emerging nations, forming an intricate web of interconnected challenges [159]. The shipment of thousands of electronic products across borders is vital for global trade, yet once their usage lifecycle terminates, they transform into hazardous waste consisting of harmful substances such as toxic chemicals, heavy metals, and non-biodegradable plastics. This transformation results in pollution and the onset of severe health ailments [159]. E-waste is a complex mixture of metals and heavy metals, all of which are deadly and represent significant threats to the environment and its ecosystems [99]. Lead, mercury, cadmium, nickel, copper, zinc, and other metallic compounds typically found in electrical gadgets are considered hazardous [40]. Furthermore, e-waste disposal adds an array of plastic components to the environment, including polyethylene terephthalate esters, polystyrene, polyvinyl chloride, and polypropylene as well as ceramics, printed circuit boards, plywood, and a variety of other materials [119]. Organic substances found in e-waste include polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), polybrominated dibenzo-p-dioxins (PBDDs),

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dechlorane plus (DP), and polychlorinated biphenyls (PCBs), which are also toxic to the environment [137].

Directly or indirectly, there is no doubt that electronic waste pollutes the environment and its natural resources such as soil, air, water, or land surfaces (Raj et al., 2023). These wastes are dangerous to the health of both plants and animals, as they are mainly carcinogenic, consisting of heavy metals, acids, and non-biodegradable polymers [116]. Because of their ability to biomagnify the food chain, appropriate management from collection through disposal is necessary [9]. Around 75% of this waste remains within homes, offices, or industries, destined to become discarded materials. The non-recyclable waste undergoes processes such as dismantling, shredding, and even burning, releasing significant volumes of toxic smoke laden with heavy carcinogenic compounds. These emissions contribute to health deterioration, leading to skin and respiratory issues [33].

Microbes, in particular, have shown exceptional effectiveness in dealing with environmental contaminants. Both fungi and cyanogenic microbes are categorized as organotrophs [35]. Fungi are responsible for producing organic acids, while cyanobacteria produce hydrogen cyanide when organic carbon is present [65]. This interaction of organic acids and hydrogen cyanide aids the bioleaching process [161]. Improving the employment of microorganisms as bioremediation agents is critical for furthering the cause of a sustainable environment (Akinsemolu et al., 2018). This review places special emphasis on the role of various microbes in the remediation of the major biodegradable components present in e-waste such as heavy metals, PAHs, and azo dye,their mode of action; and the challenges associated with the process. Additionally, it provides a brief snapshot of the role of various microbial enzymes in the conversion of e-waste components.

Major sources and the components of e-waste

Currently, e-waste stands as the fastest-growing waste source, experiencing an exponential increase in volume [99]. Globally, millions of metric tonnes of e-waste are generated annually, with an expected yearly rise of 4–5% [173]. This remarkable expansion can be attributed to several critical factors, including urbanization, industrialization, and our dependence on electronic and electrical components [12]. Both domestic consumption and foreign export have contributed to the demand surge for a wide array of electronic products [89]. Notably, within the Indian industry landscape, the electronics sector has emerged as one of the fastest-growing segments [140].

E-waste encompasses a spectrum of over 1000 different materials, with composition varying based on the manufacturer, equipment type, and age [117]. Comprising approximately 38% ferrous metals, 16.5% non-ferrous metals, and 26% plastics, e-waste predominantly contains iron and steel constituting over 50% of the ferrous metal fraction, followed by various other elements (Moyen Massa et al., 2023). Metals are commonly found in e-waste in elemental form or as alloys of various elements [170]. In an era of increasing innovation, modern gadgets boast an astounding variety of up to 60 components, thereby complicating these devices [171]. With heightened complexity comes an upsurge in the number of metals with luminous, conductive, and alloying capabilities [171].

A multitude of metals can be found in varied combinations and concentrations in diverse electrical and electronic devices [168]. Precise quantities of elements are requisite for manufacturing components like printed circuit boards (PCBs), which are ubiquitous in laptops, personal computers, mobile phones, and similar devices. These components may encompass hazardous elements such as chromium, zinc, lead, nickel, and copper, whether in elemental state or alloyed form [78]. Electrical steels are widely employed in electronics due to their low iron loss and maximum magnetization capacity (Hayakawa et al., 2020). Display technologies like cathode ray tubes (CRTs), liquid crystal displays (LCDs), and light-emitting diodes (LEDs) are prevalent in TV monitors owing to their availability and high resolution (Ciftci et al., 2017) as well as their permanent magnetism (Bloodworth et al., 2014). Rechargeable batteries (lithium-ion/lithium polymer), extensively utilized in laptops and mobile phones, incorporate elements such as lithium oxides, lithium cobalt oxides, and rare earth metals such as lanthanum (La) [5, 103]. Additionally, heavy metals such as lead, mercury, cadmium, barium, beryllium, chromium, lithium, nickel, zinc sulfide, selenium, yttrium, and europium (rare earth elements) and arsenic constitute essential parts of electrical components [99]. Furthermore, halogenated substances such as CFCs, polychlorinated biphenyls (PCBs, polybrominated diphenyl ethers (PBDEs, polybrominated biphenyls (PBBs, brominated flame retardants (BFRs are also present in some electronic appliances such as ACs and refrigerators (Harrad et al., 2012; Birnbaum et al., 2004).

Environment and health effects

In recent years, concerns regarding the presence and distribution of organic contaminants, including heavy metals, within the environment have intensified [32]. Any method of garbage disposal, whether in landfills or bodies of water, has serious effects on both human health and the ecosystem [157]. Various hazardous electrical components and their health consequences are depicted in Table 1. Most e-waste contains heavy metals such as Pb,

Table 1 Hazardous electrical components and their health consequences

Sl. no	Types of pollutants	Electrical components	Health consequences	Reference
1	Lead	Printed circuits boards, light bulbs, cathode ray tube, television and monitors, glass panels, computer gaskets, etc	Damage of brain development, blood system, kidney damage	Raj et al., 2023; [176]
2	Cadmium	Mobile phones, switches, springs, connectors, PCBs, infrared detectors, resistors in chips and semi-conductor chips, ink or toner photo-copying machines	Neural damage, flu-like symptoms if inhaled, can damage lungs and kidney. Also diseases like itai-itai, osteoporosis, and ostomalasis, reported in a study	[69],https://apps.who.int/iris/bitstream/handle/10665/329480/WHO-CED-PHE-EPE-19.4.3-eng.pdf
3	Hexavalent chromium	Untreated and galvanized steel plates from corrosion, data tapes, and floppy disks	Asthmatic bronchitis, nose irritation, respiratory tory cancer, perforated eardrums	https://www.arnolditkin.com/blog/plant-accidents/the-risks-of-hexavalent-chromium-exposure/
4	Mercury	Cold cathode fluorescent lamps, thermostat, relays and switches, PCB, sensors and monitors	Memory loss, neuromuscular effects, cognitive and motor dysfunction, CNS disorder, kidney toxicity	[98],Azevedo B. et al., 2012
5	Zinc	Cathode ray tubes, zinc air batteries for laptops, zinc carbon batteries, metal coatings, etc	Urine retention, nausea and vomiting, lethargy, kidney problems	https://environment.co/the-harmful-effects-of-e-waste-to-humans/
6	Lithium	Lithium batteries	Change in heart rhythm, muscle weakness, diarrhea and serious stomach issue, fatigue	[80]
7	Barium	Cathode ray tubes, fluorescent lamps, front panel	Muscle weakness, increased blood pressure, breathing difficulties, change in nerve reflexes	[133]
8	Beryllium	X-ray machines, motherboard, ceramic appliances	Skin diseases, lung cancer, kidney stones, night sweats	https://www.ccohs.ca/oshanswers/diseases/beryllium.pdf
9	Dioxin such as dibenzofurans and perfluoro-alkyls	Combustion by-product and fluoropolymers in electronic appliances	Severe skin lesions such as hyperpigmentation, drastic weight loss, altered liver function, depression of immune and endocrine systems	[9]
10	Chromium	Present in galvanized steel plates	Responsible for bronchitis	[156]
11	Aluminum	Transformers, condensers, PCBs	Deteriorating effects on reproductive system, immune system, nervous system; causes cancer	[64]
12	Ni, Cd	Mobile and computer PCBs, Ni–Cd batteries	Open burning causes severe health effects on inhalation; harmful towards pregnancy	Arshadi et al., 2015; [73, 74]
13	Zn-Mn	Spent Zn-Mn batteries	Cancerous	[146, 185]
14	Antimony	CRT	Inhalation might cause respiratory effects like inflammation of the lungs and chronic bronchitis	https://www.epa.gov/sites/default/files/2016-09/documents/antimony-compounds.pdf
15	Arsenic	Light-emitting diodes	Poisonous and harmful towards a prolong exposure	[64]
16	Tin, brominated dioxins	Chips and other gold-plated components in electronics	Inhalation is toxic to workers and nearby residents	[178]
17	Phosphors	Cathode ray tubes (CRT)	Toxic on inhalation	[169]

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Table 1 (continued)

Sl. no	Types of pollutants	Electrical components	Health consequences	Reference
18	Polybrominated biphenyl (PBB), polybrominated diphenyl ethers (PBDE)	Fire retardants for plastics	Acutely poisonous when burned and can causes long-term period injuries to health	[64]

Cd, Hg, Zn, and Li, which exhibit adverse health effects on the central nervous system, kidneys, blood, lungs, and skin, among others (Table 1). Additionally, components such as barium, beryllium, and dibenzofurans may cause various lung and skin diseases and even cancer (Table 1). The health effects of e-waste can result from direct exposure in recycling sites, consumption of heavy metals through water, or inhalation of polluted air after combustion [128]. This escalation of concern is largely due to substantial evidence indicating that a significant number of chemical groups have demonstrated carcinogenic properties in experimental animals, thereby posing a potential hazard to human health [129].

These chemicals are usually classified into three types:

- Primary contaminants include heavy metals and halogenated chemicals like lead, cadmium, barium, nickel, and zinc [38].
- Secondary contaminants, including by-products of incorrect recycling operations, contain chemicals such as dioxins, PAHs, and PHAHs [188].
- Tertiary contaminants include reagents used in hydro and pyrometallurgical processes [38].

The recycling process, such as chlorination, thermal treatment, adsorption, chemical extraction, membrane separation, and ion exchange, releases heavy metals that directly infiltrate the soil surface, posing a threat to the soil ecosystem [153]. Consequently, this waste can contaminate water sources, threatening marine life [16]. The biomagnification process can be triggered,for instance, cadmium pollution in groundwater systems that surpasses the normal threshold has a negative impact on aquatic species, triggering a biomagnification process [84]. Plants absorb and store heavy metals in their tissues when this water is used for irrigation, endangering both plant and human health if ingested [191]. A study conducted in Vietnam confirmed the presence of dioxins in e-waste recycling facilities as the outcome of open burning and storage practices, resulting in polluted land and rivers [81]. The concentration reported surpassed WHO guidelines [163]. For instance, heavy metal like cadmium inhalation can cause potential lung illness and kidney damage [40]. The overall effect of e-wastes on the environment is depicted in Fig. 1.

Three commercial forms of PBDEs (penta-, octa-, and deca-PBDEs) are banned in Europe, Canada, and America [68] due to their ability to biomagnify food chains, hence slowing brain development in animals and causing other health issues [66]. Birnbaum and Staskal [28] downplayed the use of brominated flame retardants in plastics used in numerous electronics, such as PBDE, octa-, deca-, and penta-PBDE. These substances possess the capability to induce significant health concerns, including the disruption of thyroid gland function. Additionally, heavy metals like mercury, often found in electronic components like fluorescent tubes, switches, and LED screens, exert negative effects on health, leading to sensory impairment, dermatitis, memory loss, etc. [18]. Polyvinyl chloride (PVC), widely used as an insulating material in electrical cables, has the propensity to bioaccumulate [167].

E-waste management practices

According to the United States Environmental Protection Agency (USEPA), the United States generates more garbage than many other countries, averaging an estimated 2.0 kg of municipal solid waste per person each day [174]. Notably, electronic waste has emerged as a significant issue in the United States [93]. Every year, over 3.2 million tons of electronic waste, including computers, displays, and TVs, find their way into US landfills [174]. This waste often gets incorrectly disposed of or repurposed without adequate consideration for environmental effects or worker health and safety [26]. Similarly, the European Commission has proposed updates to regulations governing electrical and electronic devices to enhance sustainability and mitigate environmental impacts. This initiative aims to reduce electronic waste by implementing various recommendations. These recommendations primarily focus on waste reduction, emphasizing the design of products to be more durable and repairable to extend their lifespan, encouraging reuse through takeback programs where customers can return old products for repair and resale, promoting recycling to recover and reuse valuable materials, and ensuring appropriate disposal of electronic equipment [61]. The amendment is designed to tackle the growing volume of waste in this category while acknowledging the environmental and health risks associated with improperly managed e-waste [61]. Efforts such as the Restriction of Hazardous Substances (RoHS) in Electrical and Electronic Equipment have been initiated in California, Norway, China, South Korea, and Japan. Additionally, many countries, including Australia, New Zealand, Thailand, Malaysia, and Brazil, are taking significant steps to restrict hazardous substances such as PAHs, PDBEs, and PCBs [41].

Similarly, the European Commission has proposed updates to regulations governing electrical and electronic devices with the aim of promoting sustainability and reducing environmental impacts. These measures, which have been enacted to combat electronic waste, primarily focus on waste reduction by designing products to be more durable and repairable, thereby extending their lifespan. They also encourage reuse through takeback programs, recycling to recover valuable materials,
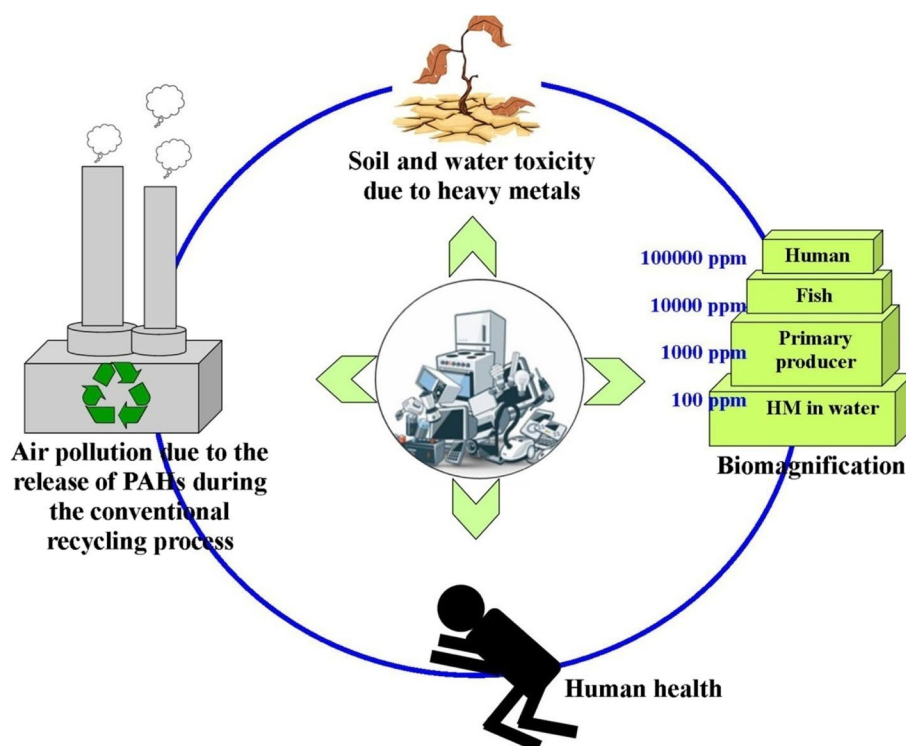
Fig. 1 The schematic diagram illustrates the comprehensive impact of e-waste on human health and the environment, including soil toxicity, biomagnification, air pollution, and other factors

and appropriate disposal of electronic equipment. This amendment aims to tackle the increasing volume of waste in this category while also addressing the environmental and health risks associated with improperly managed e-waste. Efforts such as the Restriction of Hazardous Substances (RoHS) in Electrical and Electronic Equipment have been initiated in California, Norway, China, South Korea, and Japan. Additionally, many countries, including Australia, New Zealand, Thailand, Malaysia, and Brazil, are taking significant steps to restrict hazardous substances such as PAHs, PDBEs, and PCBs. For example, Australia introduced the National Television and Computer Recycling Scheme (NTCRS) in 2011 to provide recycling services for TVs, computers, printers, and related equipment [53]. The Product Stewardship Act 2011 mandates producers and importers to responsibly handle the disposal of their goods, including electronic waste, after the product's lifespan. In New Zealand, extended producer responsibility (EPR) schemes for electronic items and the Waste Minimization Act 2008 provide a framework for electronic waste management and encourage waste reduction initiatives [172, 177]. Thailand has implemented the Hazardous Substance Act to regulate the production, import, export, and use of hazardous compounds found in electronic goods. The country also employs various e-waste management

measures, including collection and reusability of waste [165]. Malaysia has strengthened its regulatory framework for electronic waste management and hazardous substances. The Environmental Quality Act 1974 governs the production, storage, export, treatment, and disposal of dangerous wastes, including electronic waste. Similarly, Brazil has adopted the National Policy on Solid Waste (PNRS) and the National Solid Waste Plan (PNSR), which include measures for electronic waste management. Brazil actively participates in international agreements and alliances aimed at addressing the challenges posed by e-waste and hazardous substances [31].

In India, e-waste management operates in a comparable manner, wherein urban families engage in informal recycling activities like collecting, sorting, repairing, and disassembling outdated devices to secure employment opportunities (https://www.wastechindia.com/challenges-for-e-waste-management-in-india/). However, unlike in developed nations, there is no tradition in India of customers willingly giving unwanted devices to professional e-waste disposal centers (https://hindrise.org/resources/e-waste-management-in-india/). According to the National Research Development Corporation (NRDC), recyclable electronic items find their way to recycling facilities predominantly located in Asian and African countries [126]. For example, India, predominantly in

Delhi and Bengaluru [14], as well as Pakistan, notably in Karachi and Lahore [90], and China [186, 187] serve as major destinations. Other countries like Uganda, Peru, and Brazil also play a great role in generating massive amounts of e-waste [179].

Microbial degradation of e-waste

Biodegradation refers to the chemical breakdown of materials by living organisms, occurring either aerobically or anaerobically [164]. This process significantly impacts the breakdown of organic compounds [164]. Most of the microbes release biosurfactants to initiate the degradation process of PAHs. Biosurfactants are extracellular surfactants secreted by some microorganisms that accelerate the biodegradation process [29]. Biosurfactants are seen as promising options for bioremediation due to their ionic properties, low toxicity, strong emulsifying capabilities, multifunctionality, surface activity, and compatibility with the environment (Mishra et al., 2021). Additionally, biosurfactants exhibit a diverse range of chemical structures and a broad spectrum of metal selectivity and binding capacity, giving them a greater ability to remove contaminants (Mishra et al., 2021).

E-wastes are mostly composed of heavy metals (e.g., Ni, Cd, Al, Cu, Mn, Zn, Au, Zn, Fe, Ag, Pb, Hg, Cr, and Sn), polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs). Certain microbes have a diverse catabolic capacity that allows them to degrade, transform, or accumulate a wide range of compounds, including hydrocarbons such as oil, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), pharmaceuticals, pesticides, and metals (Table 2) [112]. A number of microorganisms such as *A. ferrooxidans, A. thiooxidans, S. thermosulfidooxidans, Pseudomonas putida, Pseudomonas aeruginosa, Pseudomonas fluorescens, Chromobacterium violaceum, A. fumigatus A. flavipes, A. japonicus A. tubingensis, A. versicolor, A. niger, Chromobacterium violaceum, B. megaterium, Penicillium simplicissimum, Saccharomyces cerevisiae, Leptospirillum ferriphilum, Alicyclobacillus sp., A. caldus,* and *Sulfobacillus* sp. are known to have the potential to absorb various heavy metals and other components such as PAHs and PCBs through a number of mechanisms (Arshadi et al 2015; Hong et al., 2014; Natarajan et al., 2014; Natarajan et al., 2015), [11, 36, 44, 94, 98, 145, 147, 154, 182]. Although heavy metals are not biodegradable, they could potentially be converted from one chemical state to another, making them less hazardous to the environment [63]. Microbes aid in the transformation of contaminants into end products such as carbon dioxide and water, as well as other intermediate metabolic chemicals, during mineralization. Similarly, immobilization is the process of converting chemicals into a state that makes them inaccessible in the environment [138]. *E. asburiae* and *B. cereus* have been found to have a function in immobilizing heavy metals that contribute to pollution [63]. Immobilization can be accomplished in situ or ex situ [138]. The ex situ method comprises transferring polluted soils from the pollution site to another place where a microbiological technique is used to immobilize the metal ions responsible for the contamination [15]. In contrast, the in situ technique entails treating pollution at its source [37].

A more effective approach to improving the efficacy of bioremediation processes in specific locations involves designing microbial methodologies that take into account factors such as regulatory mechanisms, microbial growth dynamics in contaminated areas, metabolic capabilities, and their responses to varying environmental conditions [8]. While exposure to certain organic solvents can lead to the disruption of cell membranes, microbes have developed defense mechanisms [83]. These include the formation of hydrophobic or solvent efflux pumps that serve as defensive barriers for the outer cell membrane [55, 83].

Among various modes of action of microbes, bioleaching, bioaccumulation, biotransformation, biosorption, biomineralization, reduction, and bio-oxidation are the key processes by which microbes contribute to bioremediation of e-waste. The detailed mechanisms involving microbes in e-waste degradation are discussed below.

Biodegradation of PAHs

A number of polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) are found in e-wastes. A diverge range of microbes have the potential to release biosurfactants which reduces the surface tension of these oily substances and converts them into smaller particles so that they can be absorbed by the cells for further metabolism [112]. Polyaromatic hydrocarbons (PAHs) are complex organic pollutants primarily produced through incomplete combustion processes [76]. These pollutants, released into the environment by both human activities and natural processes, disperse globally through air and water currents. They contaminate air, plants, and food, accumulating in organisms as they move up the food chain (Ghosal et al., 2017). Escalating levels of PAHs, notably from improper e-waste disposal, raise concerns about potential health risks such as cancer (Shengtao et al., 2022). Prolonged exposure to PAHs also increases the risk of asthma and cardiovascular diseases [72].

Certain bacteria have been identified for their ability to degrade high molecular weight PAHs. Key bacterial genera involved in PAH degradation includes *Bacillus* sp., *Mycobacterium* sp., *Rhodococcus* sp., *Pseudomonas*

Table 2 Microorganisms involved in e-waste degradation

Sl. no	E-waste material	Source	Name of microbes	Reference
1	Ni, Cd	Mobile and computer PCBs, Ni–Cd batteries	*A. ferrooxidans*	Arshadi et al., 2015
2	Al, Cu, Mn, Zn	PCBs	*A. thiooxidans*	Hong et al.,2014
3	Cu, Al, Zn, Ni	PCBs	*S. thermosulfidooxidans*	[145]
4	Ni, Cd, Co, Zn	ZMBs & Ni–Cd batteries	Mixture of *A. fumigatus A. flavipes, A. japonicus A. tubingensis, A. versicolor, A. niger*	[98]
5	Au, Ag, Cu	Sim card, electronic scrap	*Chromobacterium violaceum*	[44], [124], [147]
6	Au, Cu	Computer and mobile PCBs	*B. megaterium*	Arshadi et al., 2015
7	Cu, Au	PCBs	*Pseudomonas putida*	Isildar et al., 2016
8	Cu, Ni	Cell phone PCBs	*Penicillium simplicissimum*	[11]
9	Pb, Hg, Ni	PCBs	*Saccharomyces cerevisiae*	[94]
10	Cu, Zn, Ni	Cell phone PCBs	*Leptospirillum ferriphilum*-dominated consortium	[154]
11	Zn, Ni, Cu	WPCBs	*Aspergillus niger*	[62]
12	Cu, Cr, Sn, Zn, Ni	PCBs	*L. ferriphilum*	[36]
13	Zn, Mn	Spent Zn-Mn batteries	*Alicyclobacillus sp., Sulfobacillus sp.*	[185]
14	Cu, Zn, Pb, Ni	PCBs	*A. ferrooxidans*	Priya et al., 2018
15	Au	Electronic scrap	*Chromobacterium violaceum, Pseudomonas aeruginosa*, and *Pseudomonas fluorescens*	[125]
16	Cu	PCBs	*Acinetobacter sp.* Cr B2	Jagannath et al., 2017
17	Zn, Cu, Al, Pb, Sn	PPCBs	*L. ferriphilum, A. caldus*	[182]
18	Au, Ag	Computer PCBs	*Pseudomonas balearica* SAE1	[99]
19	Ba, Pb, Ca, Si, Cd	CRTs	*Serratia plymuthica*	[131]
20	Au, Cu, Ni	Cell phone PCBs and computer gold finger motherboards	*Aspergillus niger*	Madrigal A. et al., 2015
21	Zn, Cu, Pb, Cd, Ni, Cr	PCBs	*A. thiooxidans, Bacillus subtilis* PCM 2021, and *Bacillus cereus* PCM 2019	[96]
22	Cu, Zn, Ni, Pb, V, Mo, Al, Co, Li	PCBs	*Aspergillus niger* and *Penicillium simplicissimum*	[51]
23	Cu, Al, Ni, Zn	Electronic scrap	*Aspergillus niger, Penicillium simplicissimum*	[30]
24	Cu	PCBs	*Acidithiobacillus sp., Gallionella sp., Leptospirillum sp., Redoxolysis sp.*	[184]
25	Cu	TV circuit boards	*A. ferrooxidans, Leptospirillum ferrooxidans, A. thiooxidans*	[22]
26	Au, Ag, Cu	Cell phone PCBs	*Pseudomonas chlororaphis*	Martinez D. et al., 2019
27	Cu, Zn, Al, Ni	PCBs	*Sulfobacillus thermosulfidooxidans* and *Thermoplasma acidophilum*	[88]
28	Ni, Cu, Al, Zn	Electronic scrap	*Sulfobacillus thermosulfidooxidans*	[87]
29	Au	Cell phone PCBs	*Pseudomonas putida* and *Bacillus megaterium*	[192]
30	Cu, Ni, Zn	Computer PCBs	*Aspergillus tubingensis*	Trivedi and Hait 2020
31	Hg, Pb	PCBs	*Frankia casuarinae*	[123]
32	Cu, Al, Zn	WPCBs	*Acidophilic consortium* (genera *Acidithiobacillus sp.*) and *Gallionella sp.*	[193]
33	Al, Cu, Ni, Zn	Electronic scrap	*S. thermosulfidooxidans*	[86]
34	Cu, Pb, Ni	Spent batteries	*Aspergillus nomius* JAMK1	[42]
35	Ag, Au, Cu	Mobile phone PCBs	*Aspergillus niger, Candida orthopsilosis, Sphingomonas sp.* consortium	Martinez et al., 2019
36	Cu, Al, Pb, Zn, Sn	Low-grade PCBs	*Purpureocillium lilacinum* and *Aspergillus niger*	[183]

sp., and *Achromobacter* sp. [76]. *Mycobacteria*, a type of actinomycetes, possess intrinsic resistance to adverse conditions and are particularly adept at decomposing heavy metals, polychloro derivatives of phenols, and various PAHs (Azadi et al., 2020). Bacteria typically degrade PAHs using enzymatic activities like oxygenases and peroxidases. Examples include AlkB from *Pseudomonas* sp., naphthalene monooxygenase from *P. putida*, and cytochrome P450 from yeast species such as *C. maltosa* and *C. tropicalis* [59], (Das et al., 2011). Various fungi, including basidiomycetes, deuteromycetes, and white-rot fungi, have also demonstrated PAH degradation capabilities [134]. Unlike bacteria, fungi utilize PAHs alongside other carbon sources, producing oxidized products including carbon dioxide (CO_2) [132]. White-rot fungi species such as *Phanerochaete chrysosporium* are particularly efficient at removing PAH chemicals due to their production of extracellular ligninolytic enzymes such as lignin peroxidase, manganese peroxidase (MnP), and laccase (Lac) [1, 100]. Despite the potential of bacteria and fungi in degrading PAHs, challenges exist. Some bacteria struggle to digest PAHs effectively, and simultaneous degradation of different PAH types is challenging due to factors like bioavailability and metabolic interactions [79]. Cometabolism, however, plays a crucial role in breaking down PAHs synergistically, making it easier for specific bacteria to degrade a wider range of PAHs, particularly those with high molecular weights [79]. Furthermore, a significant challenge hindering PAH bioremediation is the understanding of their dynamics in soil and marine ecosystems. Most emitted PAHs get trapped under coal tar and black-clayish carbon particles, significantly reducing their bioavailability [132]. Addressing these challenges requires further research and attention. The overall process of microbial degradation of PAH is depicted in Fig. 2.

Biodegradation of azo dye components of e-waste

When discussing e-waste, it is crucial to address the significant impact of azo dyes. Azo dyes are the most widely manufactured type of dye worldwide, accounting for approximately 80% of all dye production [149]. These dyes, produced through a straightforward process of diazotization and coupling, play a pivotal role in the dyeing and printing market [23]. Recently, there has been a rise in functional dyes tailored for high-tech applications, such as optoelectronics (e.g., photochromic materials, dye-sensitized solar cells, liquid crystal displays), electronic materials (e.g., organic semiconductors), and imaging technologies (e.g., electrophotography, thermal printing) [58]. Various electronic devices, including thermal transfer printers, lasers, nonlinear optical devices, and fuel cells, utilize these dyes [23]. Moreover, new azo-cyanine dyes with high molar absorptivity have been investigated for their potential as cyanine photosensitizers in the development of novel photodynamic therapy (PDT) agents [58]. However, there is growing concern
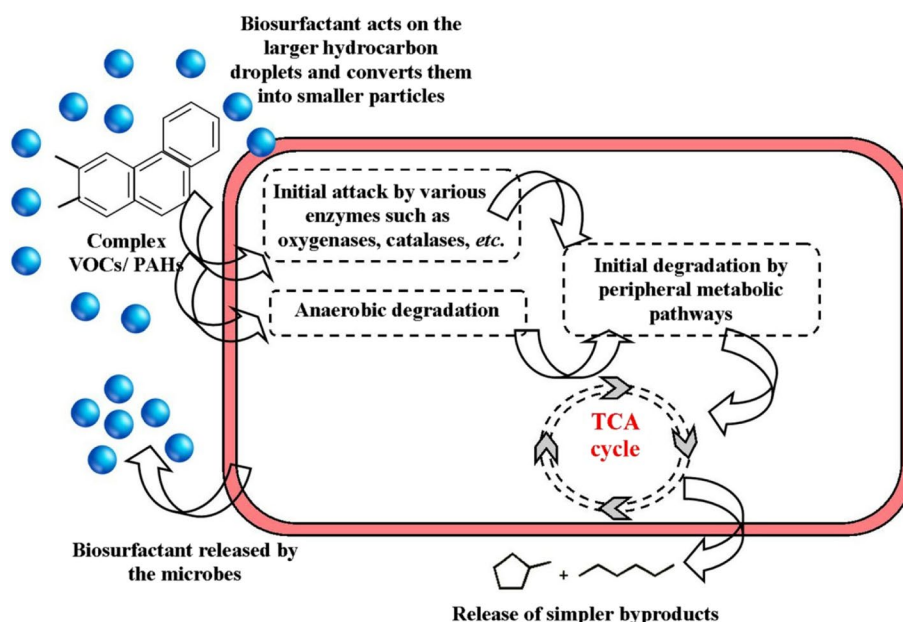

Fig. 2 The illustration demonstrates the initial degradation of PAHs and VOCs by microbial biosurfactants, followed by their internalization and subsequent breakdown by various microbial enzymes. This initial degradation occurs through peripheral metabolic pathways before the compounds enter the tricarboxylic acid (TCA) cycle, ultimately resulting in the release of simpler and less toxic byproducts

about the use of azo dyes in these sectors due to health risks and severe environmental consequences [111].

Many studies advocate for bioremediation approaches to address the remediation of azo dyes [149], (El-Rahim et al., 2021). Microorganisms, particularly bacteria, have garnered global attention for their ability to efficiently degrade a wide range of dyes under anaerobic or aerobic conditions [107]. For example, commonly used dyes like Congo Red in sectors such as printing have been effectively degraded by microorganisms; for instance, microbes like *Dichotomomyces cejpii* MRCH 1–2 and *Phoma tropica* showed a 95% degradation rate (Krishnamoorthy et al., 2017). However, the degradation pathways of azo dyes used in electronics and their specific environmental impact warrant further investigation, as there is limited literature exploring azo dyes in the electronics sector.

Bioleaching

Bioleaching involves the utilization of acidophilic microorganisms to aid in the solubilization of heavy metals that are solid inside a sediment matrix [150]. This method is particularly effective for contaminants such as iron or sulfur [24, 162]. Bioleaching processes may be of two types: "direct" and "indirect." Direct leaching involves electron transfer occurring directly from the metal sulfide to the cell connected to the mineral surface. Indirect leaching, on the other hand, occurs through the action of metal ions, such as iron (III) ions. These ions are produced by iron(II)-oxidizing bacteria, which can be free-floating or attached to the mineral surface. They function as metal sulfide-oxidizing agents [114]. In the realm of bioleaching, specific organisms are commonly employed for their metal extraction abilities [162]. Bacteria such as *Thiobacillus thiooxidans*, *T. ferrooxidans*, *Leptospirillum ferriphilum*, and *Acidithiobacillus ferrooxidans*, among others, as well as fungi such as *Aspergillus niger* and *Penicillium simplicissimum*, have found extensive usage in extracting metals from electronic waste materials (Brandl et al., 2000; [2]). Autotrophic bacteria (e.g., *Thiobacilli* sp. and *Sulfobacillus benefaciens*), heterotrophic bacteria (e.g., *Pseudomonas* sp. and *Bacillus* sp.), and heterotrophic fungi (e.g., *Aspergillus* sp. and *Penicillium* sp.) represent the three principal categories of microorganisms that play active roles in the bioleaching of metals [150]. These microorganisms possess the capability to extract metals from sulfide or iron-containing ores and mineral concentrates (Gokul et al., 2019).

Among them, the fungus *Aspergillus niger* stands out for its ability to produce organic acids such as citric, gluconic, oxalic, and malic acids (Biswal et al., 2023). These organic acids act as strong chelating agents in the bioleaching process, allowing metals to be recovered

from materials such as lithium-ion batteries (Biswal et al., 2023). Numerous studies have also demonstrated that *Aspergillus niger* generates gluconic acid, which can chelate and dissolve substantial amounts of different metals, including Li, Cu, Mn, Al, Ni, and Co (Horeh et al., 2018; Biswal et al., 2023). Furthermore, some research has found that *Aspergillus niger* may leach zinc oxide, while *Penicillium* sp. is often used in gold recovery bioleaching approaches (Trivedi et al., 2021; [148]). Metals such as Al, Zn, Cu, and Cd have been efficiently recovered from fly ash by *Aspergillus niger* (Annamalai et al., 2019).

Studies show that *Chromobacterium violaceum* is capable of detoxifying cyanide with the help of the beta-cyanoalanine synthase enzyme [13]. This species is potentially useful in the biological recovery of gold from e-waste. Additionally, it has been discovered that *Chromobacterium violaceum* can also participate in the leaching of gold and copper from waste mobile phone printed circuit boards (PCBs), showcasing its potential in metal recovery processes [2, 44]. On the other hand, *Pseudomonas fluorescens* is capable of catabolizing cyanide via the action of cyanide oxygenase. *P. fluorescens* proved to be more efficient in the bioleaching of gold compared to *C. violaceum*, even though it produces more cyanide than *C. violaceum* in the absence of electronic waste (Annamalai et al., 2019), [101]). An extensive literature survey shows *Thiobacillus ferrooxidans* as one of the most well-studied organisms for the microbial leaching of iron and sulfur with futuristic applications [130]. Despite bioleaching being a promising method with futuristic potential, it is time-consuming, yet eco-friendly in nature. Towards large-scale application, the slow rate of the process and metal toxicity towards microorganisms are significant setbacks [21]. Hence, there is a scope for further improvement in this method. A few contemporary research studies have demonstrated that the process of bioleaching may be improved by maintaining optimum pH, O_2, and CO_2 levels, temperature, and mineral substrate supply to favor the maximum growth of the microbes as well as by promoting the formation of bacterial biofilm for the process [67, 175].

Biosorption

The absorption and binding of ionized hazardous metals onto the cell surface is the basis of the biosorption process [155]. In the presence of ATP, metabolism-dependent biosorption occurs through processes such as chelation-a unique mechanism where ions and molecules attach to metal ions by forming two or more coordinate bonds between a polydentate ligand and a single central atom. Additionally, physical adsorption, a surface phenomenon, creates a film of the adsorbate on the surface of the adsorbent [155]. In the absence of ATP,

biosorption occurs through a variety of mechanisms such as adsorption, ion exchange, and covalent bonding. These mechanisms are governed by the chemiosmotic gradient potential [19]. Based on the cell metabolism requirement and the nature of metal contamination, biosorption pathways may be classified as metabolism-dependent or metabolism-independent [27]. Physicochemical interactions between functional groups on the cell surface of bacteria and metals occur through metabolism-independent pathways, involving chemical sorption, physical adsorption, and ion exchange [139]. Carbohydrates, lipids, and proteins in microbial cells consist of metal-absorbing groups such as phosphate, sulfate, amino, and carboxyl groups [3].

Because of their capacity to bond with e-waste in aqueous solutions, microbes are referred to as biosorbents [7]. It is critical to examine the microbial stability of biosorbents by analyzing their nature, including sorption kinetics, regeneration, maximal sorption capacity, and recovery of associated metals [95]. Dead biomass, live cells, or polymers derived from their metabolic processes are utilized as biosorbent materials in the biosorption of heavy metals (Fomina et al., 2014), [48],).

Filamentous fungi with strong metal-absorbing capacity include *Aspergillus*, *Rhizopus*, *Mucor*, *Penicillium*, *Actinomycetes*, and *Streptomycetes* (Verma et al., 2019). Fungi can survive and detoxify metal ions by absorbing them in their mycelium and spores (Ayangbenro et al., 2017). *Aspergillus parasitica* and *Cephalosporium aphidicola* are even known to remediate Pb-polluted areas [6].

Microbes display varying biosorption capabilities due to their functional groups. Negatively charged functional groups, such as hydroxyl (OH^-), phosphate (PO_4^{3-}), and carboxyl (CO^-), bind to metal ions strongly [47, 55]. Ion exchange can also be facilitated by bacterial functional groups such as carboxyl (COO^-) and sulfate (SO_4^{2-}) groups of uronic acid [47]. Gram-positive bacterial cell walls, which contain alanine, glutamic acid, meso-diaminopimelic acid, and teichoic acid, and gram-negative bacteria's cell walls, which contain lipoproteins, glycoproteins, lipopolysaccharides, phospholipids, and enzymes, act as ligands for actively binding metal ions (Ayangbenro et al., 2017).

Yeasts are also considered attractive biosorbents due to the presence of polysaccharides in their cell wall. *Candida tropicalis*, *Saccharomyces cerevisiae*, and *Streptomyces longwoodensis* show potential for heavy metal adsorption, including cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), and lead (Pb) [47]. The yeast strain *Saccharomyces cerevisiae*, commonly referred to as baker's yeast, has demonstrated convenience in retaining metal ions such

as cobalt and copper [151]. Yeasts such as *S. cerevisiae* can also serve as bioremediation agents via processes such as ion exchange [106]. Bacteria and fungi are attractive biosorbents for e-waste remediation due to their capacity to grow in a variety of environmental conditions.

Algae have a remarkable biosorption capacity making them highly efficient compared to other microbes due to their substantial biomass [9, 50]. This biosorption method acts through an ion exchange mechanism. Brown marine algae (e.g., *Fucus vesiculosus*), with functional groups like COO^-, SO_3^-, SH, and NH_2, effectively remediate metals such as cadmium, nickel, and lead (Mustapha et al., 2015).

Biosorption is widely used as a biological tool for the accumulation of heavy metals, which are hazardous to the environment, through physico-chemical pathways of uptake due to its suitability with different environmental conditions (Errasquin et al., 2003). However, its effectiveness is dependent on the biosorbent materials used and the associated costs [151].

Biotransformation

Biotransformation, in the context of e-waste remediation, refers to the chemical alteration of metals by microbes or changes in their oxidative state caused by electron addition or removal by microbial agents, playing an important role in transforming chemical pollutants into more environmentally friendly compounds (Karigar et al., 2011; Das et al., 2012).

Various fungi, including *Allescheriella* sp., *Botryosphaeria rhodina*, *Klebsiella oxytoca*, *Phlebia* sp., and *Stachybotrys* sp., have demonstrated high metal binding capability [49]. Additionally, gram-positive bacteria strains, such as *Cellulosimicrobium* sp., have shown tolerance against xenobiotics and heavy metals such as Cd, Hg, Cr, and Pb (Bhaiti et al., 2019). In a study conducted by Thatoi and his team in 2014, a strain of bacteria known as *Bacillus* sp. SFC 500 was documented to reduce chromium into its less toxic form through biotransformation. Furthermore, research has shown the efficacy of fungi, such as *Rhodobacter sphaeroides*, in eradicating hydrophobic toxic metals like zinc and cadmium from the soil [135].

Metal biotransformation can be categorized as direct or indirect (Balfourier et al., 2023). Direct biotransformation, also known as enzymatic biotransformation, utilizes microbial enzymes to change oxidation states, resulting in the reduction of harsh multivalent metals [160]. In contrast, metal-reducing microbes immobilize metals in sedimentary and subsurface settings, stabilizing multivalent hazardous metals (Tabak et al., 2005).

Bioaccumulation

Bioaccumulation harnesses microbial capacity to absorb toxic metals and store them within their cellular vacuoles through a detoxification mechanism and an active process [85]. It requires energy for metal absorption and detoxification within the vacuoles (Errasquin et al., 2003). As a result, metals are taken from the environment and sequestered inside living cells, resulting in remediation (Das et al. 2012). Plants and microorganisms are efficient in eliminating metals through accumulation when used for bioremediation of metal-contaminated environments [54]. When paired with techniques such as phytodegradation, this approach delivers improved heavy metal removal [127]. Metals are incorporated into living biomass through bioaccumulation [45].

Tolerance to metals such as arsenic (As), mercury (Hg), cobalt (Co), iron (Fe), and chromium (Cr) was tested in several native strains of *Bacillus sphaericus*, along with the assessment of bioaccumulation in live biomass, where it was shown that both living and dead cells showed immense capacity of metal bioaccumulation (Velásquez et al., 2009).

Gram-positive bacteria such as *Tsukamurella paurometabola*, and Gram-negative bacteria, *Pseudomonas aeruginosa*, have been used in cadmium (Cd) and zinc (Zn) bioaccumulation [127]. The study has also looked at lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) removal by *S. cerevisiae*, *Pseudomonas putida*, and *Fusarium flocciferum* [109, 127, 141]. Another study compared the bioaccumulation of copper (II), lead (II), and chromium (VI) by *Aspergillus niger*, where *A. niger* was shown to be extremely susceptible to all levels of chromium (VI) concentrations [57]. These findings suggest that *A. niger* could serve as an effective living biosorbent for the removal of heavy metal ions [57]. Bacteria such *Bacillus circulans*, *Bacillus megaterium*, and *Deinococcus radiodurans* and fungi such as *Aspergillus niger* and *Monodictys pelagica* are also reported to accumulate Cr, U, and Pb from electronic waste (Patel et al., 2014).

Recombinant *E. coli* has also been reported by researchers for their role in cadmium bioaccumulation by expressing metallothionein (MT) in the cytosol [105]. Another study highlighted a twofold increase in cadmium bioaccumulation with glutathione and synthesis of phytochelatin expressing MT (González et al., 2021).

This technology is largely dependent on the growth rate of the microorganisms used in this method and also on their ability to accumulate the heavy metal. Besides, the success rate in field trials is still far behind in comparison to in vitro findings. However, the cost effectiveness of this method cannot be ruled out.

Biomineralization

Biomineralization entails the microbial synthesis of specific inorganic substances using substrate molecules, benefiting the biological system (Kim et al., 2013). This process includes microorganisms accumulating anions or ligands, which then bind to hazardous metal contaminants and precipitate (Patel et al., 2014). It is a frequently employed method for treating e-waste components such as hazardous heavy metals and polymers via degradation or precipitation [190]. As a result, polluting metals transform into moderately stable forms, while organic molecules fracture into less hazardous and more stable states (Ayangberno et al., 2017).

There are two types of biomineralization, viz., biological induced mineralization (BIM) and biological controlled mineralization (BCM) [122]. In some situations, BIM causes mineral production inside cells or on cell surfaces [56]. On the other hand, BCM includes extracellular mineral production due to the metabolic capacities of microbes [4].

Metallophilic bacteria, *Cupriavidus metallidurans*, can aid in cellular detoxification hence proving to be a potential candidate in accumulating Au (III) [144]. Additionally, bacterial strains such as *Bacillus fusiformis* and *Sporosarcina ginsengisoli*, along with *Cupriavidus metallidurans*, are well known for their role in the biomineralization process, effectively eliminating heavy metals such as cadmium, arsenic, and lead [4]. Another study led by Achal (2012) demonstrated the excellent biomineralization capability of arsenic (As III) by *Sporosarcina ginsengisoli*.

Although the method of biomineralization has received much attention in recent days, limitations related to the efficiency of the microbes to be employed and the degree of contamination in the affected area are some of the factors which also play a major role in biomineralization.

Enzymatic degradation of e-waste

As an environmentally friendly biotechnological technology, bioremediation employs biological agents such as plants, bacteria, and their enzymes to transform hazardous pollutants into less toxic or non-harmful chemicals via various metabolic pathways [17]. Scientists have discovered that numerous enzymes originating from microorganisms (bacteria and fungi) and plants play an important role in the bioremediation of pollutants [120]. The enzymatic actions of important enzymes, such as oxidoreductases, dioxygenases, and hydrolases have been extensively studied (Fig. 1) (Karigar et al., 2011). Microbial enzymes such as reductases, laccases, esterases, carboxylesterases, catalase, dismutases, and dioxygenases show their ability to convert various heavy metals and PAHs into their less toxic forms (Table 3), [60, 92, 120,

Table 3 Microbial enzymes involved in e-waste degradation

Sl. no	Name of the enzymes involved	Name of the microorganisms	Bioremediation potential	Reference(s)
1	Chromium reductase	*Pseudomonas sp.* MA14, *P. putida*, *Bacillus*, *Enterobacter sp.*, *Deinococcus sp.*, *Gluconacetobacter hansenii*	Reduces hexavalent chromium Cr (IV) to Cr (III)	Thatoi H. et al., 2014; [92]
2	Laccase	*Trametes versicolor*, *Raoultella planticola*, *Trametes pubescens*, white rot fungi (*Phanerochaete chrysosporium*)	PCBs (polychlorinated biphenyls), lead (Pb), nickel (Ni), epoxidation, cadmium (Cd)	Keum et al., 2004
3	Esterases, carboxyl esterases E2	*E. coli*, *Pseudomonas aeruginosa* PA1	*Phthalate* acid *esters* (PAEs), Mercury ion [Hg ($^{2+}$)]	[120, 189]
4	Catalase and superoxide dismutase	*Aspergillus spp.*, *E.coli*, *Streptococcus sp.*, *B. cepacia*, *Enterobacter cloacae* B1	Lead (Pb), cadmium (Cd), nickel (Ni)	[20]
5	Biphenyl dioxygenase and biphenyl 2,3-dioxygenase	*B. cepacia* LB400 and *Pseudomonas aeruginosa*, *Pseudomonas alcaliphila* JAB1	Degradation of PCBs	Erickson et al., 1992
6	Cupric reductase	*Streptomyces sp.*	*Reduction of copper (Cu)*	Saravanan et al., 2021
7	ChrR (quinone reductase)	*E. coli*, *Geobacter sp.*	Reduce Cr (VI) and uranyl [U (VI)] to Cr (III) and U (IV)	[60]
8	Biphenyl dioxygenase (bphC)	*Dehalococcoides* spp.	Efficiency towards PCBs, high chlorinated PCBs, and less chlorinated PCBs	Hasmi et al., 2016
9	Reductive dehalogenase	*Dehalococcoides mccartyi* (Dhc)	Tetrachloroethene (PCE)	[110]
10	Laccase, manganese peroxidase, versatile peroxidase, lignin peroxidase, dye decolorizing peroxidase, glyoxal oxidase	*P. chrysosporium*	Chlorophenols, PAHs, PCBs	[143]
11	Cytochrome P-450 monooxygenase	*A. cylindrospora*	Efficiency towards anthracene and fluoranthene	[71]
12	Monooxygenases	*Paecilomyces lilacinus*	Efficiency towards chlorinated biphenyl derivatives	[158]
13	Cytochrome P450 monooxygenases (P450s), epoxide hydrolases, glutathione S-transferases, NAD(P)H quinone oxidoreductases, and UDP-glucuronosyltransferases	*Aspergillus terreus* and *Cladosporium oxysporum*	Endosulfan	[108, 121]
14	Lignin peroxidase (LiP) and manganese-dependent peroxidase (MnP)	*Fusarium solani*	Anthracene (ANT) and benz[a] anthracene (BAA)	[180]
15	Cytochrome P450 monooxygenases (P450s), epoxide hydrolases, glutathione S-transferases, NAD(P)H quinone oxidoreductases, and UDP-glucuronosyltransferases	*Trichoderma species*	Petroleum hydrocarbons	[10, 108]

166] (Keum et al., 2004; Saravanan et al., 2021; Erickson et al., 1992;).

Microbial enzymatic pathways play an important role in many stages of bioremediation, interacting with hazardous contaminants and converting them to harmless substances [25]. Enzymes offer benefits such as substrate specificity, independence from microbial growth rates, uniformity, and simplicity of handling and storage, minimizing dependency on toxic chemicals [39].

Various enzymes exhibit diverse capabilities when it comes to degrading heavy metal pollutants from e-waste [120]. Enzymes such as Cytochrome p450, nitrilases, dihydrodiol dehydrogenase, esterases, amidases, laccases, proteases, MnP (manganese peroxidase), glucose oxidase, and glyoxal oxidase play an essential role in breaking down different classes of contaminants [25, 97, 142]. Natural enzymes are generally preferred due to their cost-effectiveness. However, emerging technologies such as genetic engineering, recombinant techniques, and nanotechnology offer promising opportunities to produce more efficient enzymes [120]. This is because these technologies can be tailored to change the amino acid sequences of enzymes to achieve specific pH, temperature tolerance, stress resistance, and other metabolic properties necessary for the bioremediation of heavy metals [25]. However, enzyme production can be enhanced by genetic engineering by transferring coding genes for expression [75]. It is also expected that under

natural conditions, recombinant enzymes would excel in pollutant breakdown [115].

The overall molecular mechanisms involved in bioleaching, bioaccumulation, biotransformation, biosorption, biomineralization, reduction, and bio-oxidation are depicted in Fig. 3.

Challenges associated with bioremediation

Despite technological breakthroughs and cost-effectiveness when compared to older processes such as incineration or landfilling, bioremediation confronts several challenges. Certain e-waste components, such as chlorinated organic chemicals and strongly aromatic hydrocarbons, resist bacterial decomposition (Viswakarma et al., 2020). The type and amount of contaminants, soil texture, geographical location, and adsorption by soil particles all have an impact on bioremediation effectiveness (Temitope et al., 2022). Bioremediation selectivity necessitates the use of particular microbial species, proper growth conditions, and enough food availability (Philip et al., 2005).

Microbial competition, post-inoculation decline, temperature, pH, oxygen levels, wetness, and other environmental conditions all have an impact on bioremediation [77, 104]. Pollutant solubility increases as temperature rises [136]. A lack of in-depth knowledge of physiology, microbial ecology, gene expression, and site-specific variables is also a barrier. Developing advanced bioremediation technologies suitable for complexly polluted sites with diverse toxic pollutants remains a challenge [46].

There is disarray regarding bioremediation acceptance criteria, and no widely accepted explanation or treatment technique exists (Sharma, 2021). Assessing bioremediation potential is complex, as the inhibition of microorganisms by toxic heavy metals depends on factors like metal ion concentration, redox potential, and environmental conditions [85]. The effectiveness of metal-microbe complex stabilization is dependent on parameters such as sorption sites and microorganism cell wall structure [85]. Overall, the efficiency of bioremediation is determined by the substrate subjected to treatment and the unique environmental circumstances at hand (Anekwe et al., 2022).
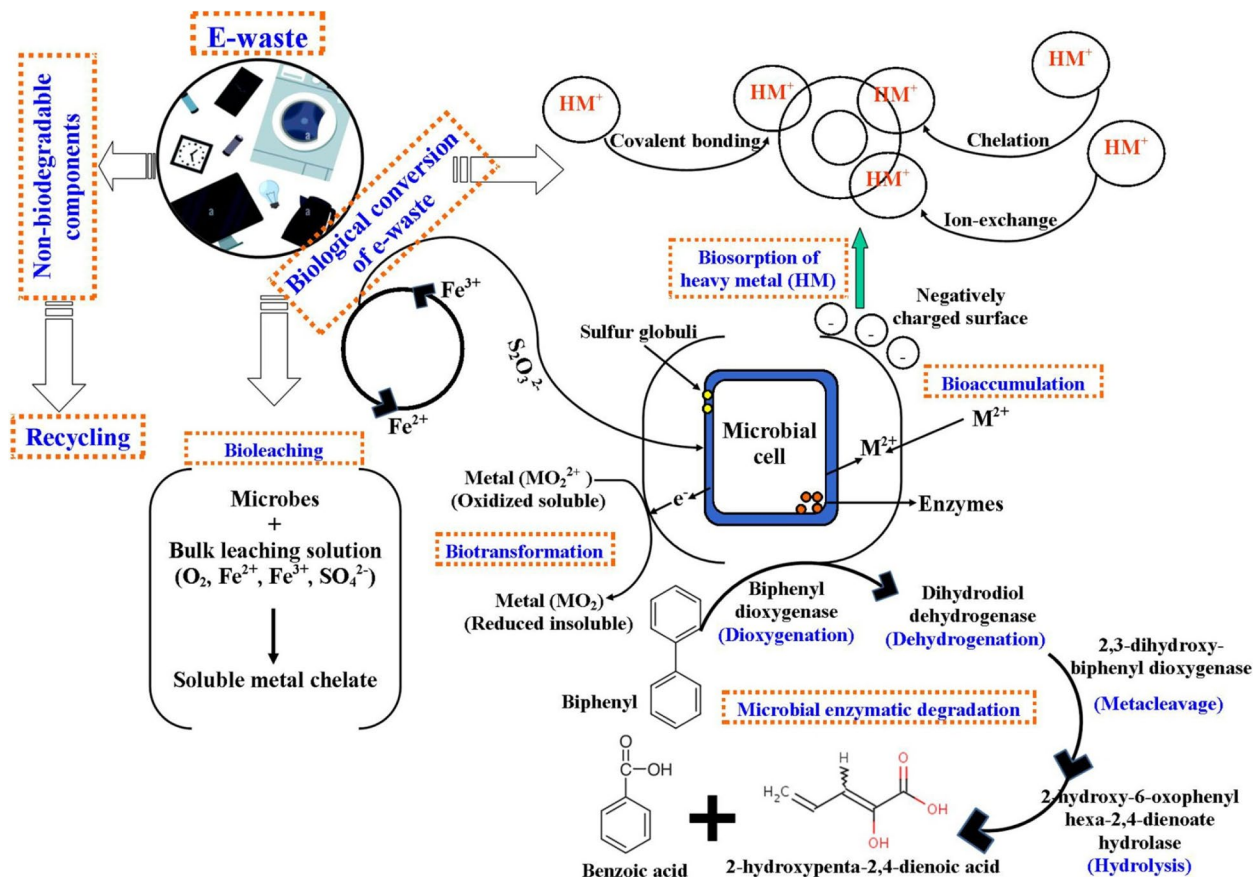

Fig. 3 Various modes of action of microbes involved in the biodegradation of e-waste

Potential roles of genetically modified organisms (GMOs) in degrading e-waste components

Genetic engineering presents promising opportunities for mitigating various heavy metals and pollutants, including polyaromatic hydrocarbons (PAHs), which are often challenging to address through conventional bioremediation methods (Verma et al., 2019). Genetically modified organisms (GMOs) offer significant advantages for bioremediation due to their environmentally friendly nature and reduced health risks compared to physiochemical methods, which are less eco-friendly and pose potential dangers to life [91].

For instance, *E. coli* JM109 modified with pCLG2 (M5) and pGPMT (M4) plasmids demonstrated enhanced absorption of Cd^{2+} due to the expression of the cadmium transport system and metallothionein (MT) in M4, effectively doubling the strain's original absorption capacity [52]. In another study, Huang et al. [82] utilized a genetically modified *Bacillus subtilis* strain 168 to methylate and volatilize arsenic (As) with the CmarsM gene from heat-resistant algae *Cyanidioschyzon merolae*, potentially aiding in the cleanup of As-contaminated compost. Li et al. [102] employed a novel approach, STAR, using CRISPR-ddAsCpf1 to enhance the electron transfer capacity of *Shewanella oneidensis* MR-1, leading to improved bioreduction of heavy metals like chromium.

Furthermore, certain enzymes can transform heavy metals (HMs) into less toxic forms. For example, when the mercury resistance gene merA from *Deinococcus radiodurans* is expressed in *E. coli* BL308, it enables the bacterium to tolerate higher concentrations of Hg (II) and convert it into less toxic Hg (0) [34]. Researchers have identified metal-binding peptides responsible for capturing heavy metals (HMs), such as cadB for cadmium (Cd) (II) and zinc (Zn) (II), pbrT and pbrD for lead (Pb) (II), and copM for copper (Cu) (II), while metallothioneins with cysteine and sulfhydryl groups are utilized for HM binding [70, 181].

In addition to heavy metals, genetically modified organisms have shown effectiveness in degrading polyaromatic hydrocarbons (PAHs). The breakdown of PAHs by genetically engineered microorganisms (GEMs) relies on specific enzymes such as dioxygenase, monooxygenase, hydroaldolase, and dehydrogenase [43]. Changes in degradation pathways and efficiency often depend on variations in enzymes encoded by functional genes [43]. These functional genes are frequently utilized to construct GEMs responsible for degrading PAHs. For example, Mohtashami et al. [118] inserted the laccase gene (poxa1b) from *Pleurotus ostreatus* into *E. coli* BL21, resulting in the oxidation of benzo[α]pyrene by 17%. They co-expressed pdoAB with plasmid pBRCD, achieving oxidation for phenanthrene, pyrene, anthracene, and benzo[α]pyrene, facilitated by electron transfer components from plasmid pBRCD. However, no literature shows successful field implementation of GMOs in degrading e-waste components from the best of our knowledge.

Future prospective

The importance of addressing the current pace and quantity of e-waste, as well as its environmental effects, cannot be overstated. The current scenario highlights that inadequately managed e-waste recycling processes result in the release of enduringly hazardous substances like PBDEs and PCDDs into the atmosphere, residual ash, airborne particles, soil, water, and the nearby environment. Furthermore, as shown by Miller et al. [113], these hazardous elements eventually make their way into both oceanic and terrestrial ecosystems, sparking a process of bioaccumulation and biomagnification.

As the accumulation of such hazardous chemicals continues to rise, the availability of extractable elements diminishes. Scientists have developed environmentally friendly appropriate methods for recycling and recovering toxic substances from waste to avert disastrous repercussions. These measures not only enhance human health but also have significant environmental effects, both now and in the future [152]. Additionally, the adoption of bioremediation methods has gained substantial traction for the purification of landfills and groundwater reservoirs [137].

Despite the array of techniques available for waste management, there persists a deficiency in their appropriate implementation, both in developed and developing countries, even within the framework of improvement (Ferronato et al., 2019). However, the pressing necessity for well-defined regulations, maintenance protocols, and comprehensive policies to monitor health and environmental issues stemming from toxic metals cannot be understated. This need is particularly relevant in the current context and remains a priority for the future.

Conclusions

The rapid increase in e-waste poses a significant challenge that requires immediate attention. This problem has global ramifications, impacting regions worldwide with a wide range of difficulties associated with e-waste disposal. Addressing this challenge is crucial as we strive for a sustainable future. As research progresses, new technologies are emerging to confront this impending disaster, each with its own advantages and disadvantages. However, the practicality of any advancement lies in its ability to serve humanity in a cleaner and more environmentally friendly manner. Microorganisms offer a promising solution to this issue through various mechanisms

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such as biosorption, bioleaching, biotransformation, bioaccumulation, and enzymatic pathways. It has been found that microorganisms can effectively remediate a wide range of e-waste, including hydrocarbons like polychlorinated biphenyls (PCBs), pharmaceuticals, oil, and polyaromatic hydrocarbons (PAHs), in an eco-friendly, reliable, and economically feasible manner. Furthermore, certain microbes have been observed to facilitate the leaching process, potentially opening up new avenues in metallurgy and metal extraction from ores. However, it is important to note that microbial degradation processes are often more time-consuming compared to physical and chemical methods. Nonetheless, there is significant potential for improving microbial degradation processes through modern biotechnological interventions in the future.

Authors' contributions
Farheen Sabina Alam and Sahiba Khan compiled all the data and drafted the initial manuscript. Debajit Borah edited the manuscript and supervised the study.

Availability of data and materials
No data associated with this manuscript.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors have given their consent for publishing this manuscript.

Competing interests
The authors declare no competing interests.

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