

Sustainable options for mitigation of major toxicants originating from electronic waste

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Electronic waste (e-waste) is an emerging source of toxic contaminants in the environment. It is considered to be hazardous as it is known to contain toxic metals, viz. Cr, Ni, Zn, Pb and Hg in huge amounts and organic pollutants, viz. polychlorinated biphenyls, polybrominated diphenyl ethers and tetrabromobisphenol-A. Rapid development and changes in lifestyle have resulted in a huge pile-up of e-waste and its continuous production further makes the situation troublesome. E-waste is usually processed informally for recovery of precious metals. During this process, a large amount of toxic metals, organic compounds and secondary organic pollutants such as polyaromatic hydrocarbons and dioxin enters into the environment. Disposal of raw or processed e-waste in landfills also results in contamination of soil and groundwater through leachate. Considering the present environmental condition along with toxic and persistence nature of pollutants originating from e-waste, their remediation using sustainable methods is highly desirable. This article provides an overview of different bioremediation options used and available for remediation of e-waste-related pollutants. Advantages and limitations of these methods along with their applicability in restoration of contaminated system are also highlighted.

Keywords: Bioremediation, electronic-waste, metals, microorganisms, organic pollutants.

EXTENSIVE use of electronic products in almost all walks of life has resulted in the build-up of huge piles of used and discarded electronic wastes (e-waste). This has now become the fastest growing hazardous waste stream in the world^{1,2}.

E-waste is highly heterogeneous and complex in nature and majorly comprises discarded or obsolete electrical or electronic equipment and their spare parts^{1,2}. From a chemical point of view also, it is equally heterogeneous as it generally contains 50% iron and steel, 21% plastics, 13% nonferrous metals and 16% other constituents like rubber, concrete and ceramics³. Safe disposal of e-waste is becoming a major environmental concern due to the presence of various toxic organic compounds and inor-

ganic components in the form of heavy metals. Generally it is disposed in landfills as such or after extraction of useful parts along with municipal solid waste; however, this improper disposal usually results in serious contamination of nearby environmental matrices like soil, aquatic systems and groundwater through leachate or infiltrate from these sites¹.

On the other hand, presence of some precious metals, viz. Fe, Al, Cu, Au and Ag in greater amounts makes e-waste a valuable resource of such metals. There are stringent regulations regarding processing and disposal of e-waste in many countries. In India, this is usually unscientific, unregulated and practised by marginalized workers without any safety concerns³. Recycling or processing of e-waste is usually done for metal recovery and/or extraction of other reuseable parts. During dismantling activities for the recovery of metals, other toxic, persistent pollutants, like polycyclic aromatic hydrocarbons (PAHs) and dioxin are also released in the environment. After recycling or recovery of useful products from e-waste, the wastes laden with toxic organics and other contaminants is usually dumped in the landfill sites.

Global e-waste production has been reported to increase from 39.8 million tonnes in 2013 to 41.8 million tonnes in 2014 (ref. 4). It is estimated that by 2018 the production will rise to around 50 mt if the current pace continues, which will further aggravate the problem associated with e-waste disposal^{4,5}. According to US-EPA estimates, only 15%–20% of total e-waste produced is recycled, while the remaining is usually disposed in landfills⁶.

There is rigorous legal framework for recycling and disposal of e-waste around the world. However, due to poor environmental law enforcement and inexpensive labour, e-waste from developed nations is also shipped to India for recycling⁷. Presently, annual e-waste generation in India is estimated to be 800,000 tonnes and this is expected to rise further in the coming years⁷. Because of flexible law enforcement, e-waste processing is done in an informal manner in open environment in India. This further strengthens the possibility of contamination of nearby areas with e-waste pollutants. Environmental risk assessment studies of areas nearby informal and uncontrolled e-waste processing site by various researchers have shown alarming levels of heavy metals and organic

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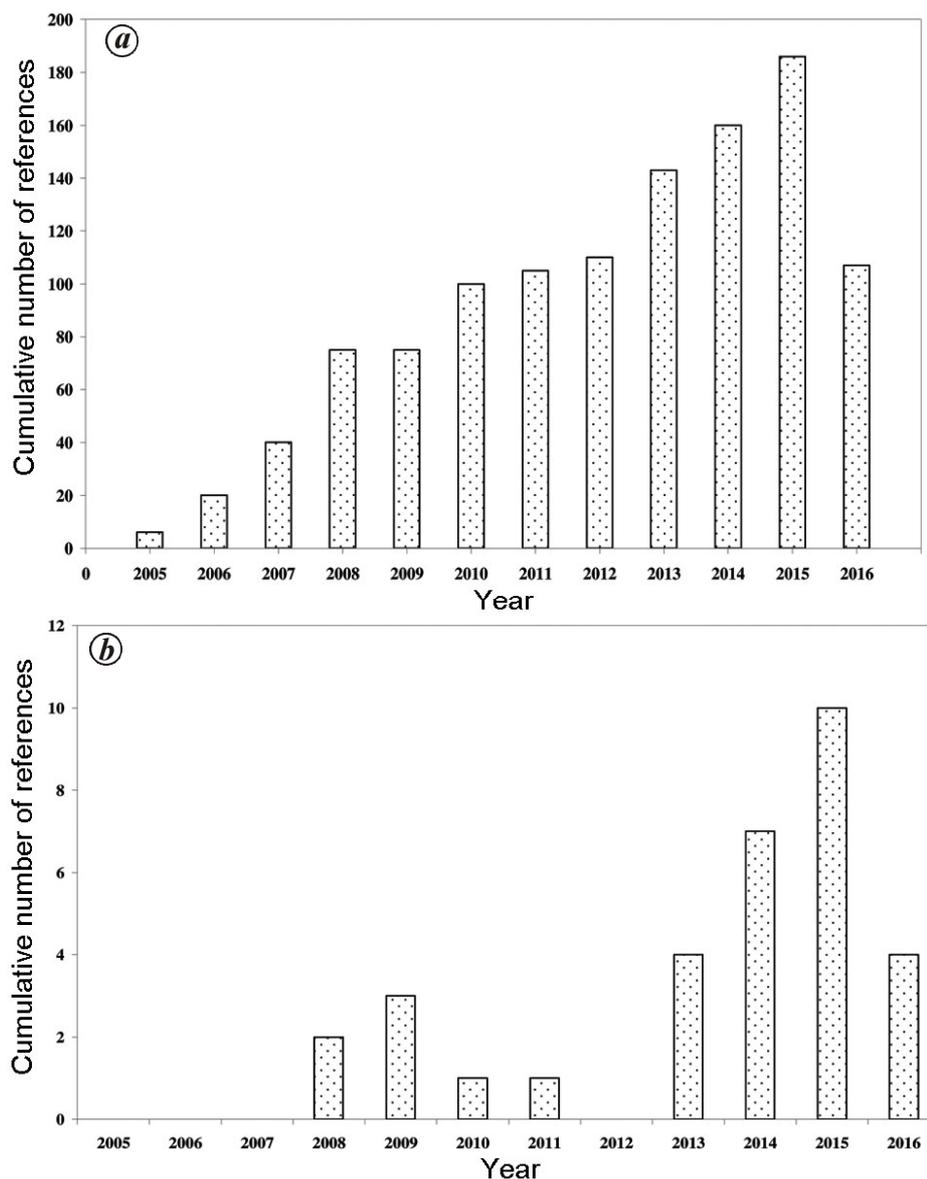


Figure 1. Cumulative number of references related to e-waste and its remediation. *a*, Keyword used: e-waste; *b*, Keyword used: e-waste, electronic waste, remediation. References were searched through keyword(s) using SciFinder® tool of Chemical Abstracts Service – a division of the American Chemical Society. Searched on 7 May 2016.

compounds in surface soil, vegetation and groundwater^{2,4,7}. Even elevated levels of these toxicants were also detected in blood samples of workers associated with e-waste recycling and also in nearby local residents⁸.

Keeping in view the various adverse effects of e-waste on health and environment, there is an urgent need for remediation of pollutants associated with e-waste using sustainable methods. Similarly, restoration of sites contaminated with e-waste pollutants especially near the e-waste recycling unit or landfill should also be done in a sustainable manner. The focus and interest in the field of e-waste toxicity and remediation research can be visualized through increasing number of research publications

in the last two years. Figure 1 shows cumulative number of references related to e-waste and its remediation in the last decade as searched through SciFinder® tool of Chemical Abstracts Service (CAS).

In the literature there are reviews on e-waste mostly covering management aspects, i.e. how to manage and regulate the hazardous waste using legal and policy framework along with risk assessment studies (Figure 1). To the best of our knowledge there are no reviews on different sustainable options to remediate the e-waste toxicants and sites contaminated with them. The present article thus is an attempt to fill this lacuna. A brief overview of different bioremediation methods to detoxify the

toxicants originating from e-waste disposal is provided in this article.

Toxic pollutants

E-waste is a complex mixture characterized by the presence of both organic and metal entities⁴. Organic compounds include persistent organic pollutants (POPs) in the form of PAHs, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA) and perfluorooctanoic acid (PFOA)⁴. Organic compounds PBDEs and TBBPA are generally used in electronic goods as fire retardants, whereas PCBs are used as insulators, lubricants and coolants². PAHs and dioxin are produced during combustion of e-wastes⁹.

The metal content in e-waste mainly consists of Cr, Ni, Zn, Pb and Hg in huge amounts. Besides, it is also laden with precious metals in the form of Au, Cu and Ag. These metals are usually present in printed circuit boards, cathode ray tubes (CRTs), semiconductor chips, coatings, and batteries of electronic items². As shown in Figure 2 *a*, metal content accounts for a major portion of e-waste

followed by plastics, CRTs and liquid crystal display (LCD) screens. Cu and Ni are present in abundance (Figure 2 *b*). Organic toxicants are present in smaller portions (14 mg kg^{-1}), usually mixed with plastics and other parts such as transformers and capacitors⁹.

Both types of pollutants are of special concern because of their toxicity and bioaccumulating nature. Persistent organic pollutants have high environmental persistence and stability along with lipophilic properties which ultimately results in their bio-magnification at higher trophic levels of the food chain. In addition, they are also known to possess hormone-disrupting, neurotoxic, mutagenic and carcinogenic properties^{8,10}. Similarly, heavy metals have high toxicity and mobility and thus can easily contaminate the nearby pristine environment. Toxicity of heavy metals is type-specific¹¹. Heavy metals cannot be degraded, though their toxicity can be minimized using different techniques like transformation to different oxidation states, precipitation and absorption/adsorption to different support systems^{11,12}.

The aforementioned pollutants present in e-waste are known to affect the ecological system through their detrimental effects on living beings, necessitating the development of suitable technologies for their remediation.

Bioremediation approaches for detoxification

As e-waste is known to possess mixed pollutants in the form of heavy metals and recalcitrant organic pollutants, its bioremediation approach becomes quite complicated¹³⁻¹⁵. Both pollutants are different in nature and there are different mechanisms of detoxification of these pollutants by microorganisms. The co-presence of toxicants in case of e-waste further enhances the toxicity to microbes and also affects the bioremediation of individual components^{14,15}. Hence, in order to use microorganisms for remediation of complex or co-contaminated system, they must possess tolerance and detoxification abilities towards different types of pollutants. These properties help them sustain and bioremediate in complex and mixed polluted systems like in the case of e-waste. Microbes possessing such novel properties can be either isolated from natural contaminated sources (soil contaminated with e-waste or leachate from e-waste landfill sites), or obtained through engineering processes. Such microbes, individually or as consortia, can be used for decontamination of e-waste.

The following bioremediation methods have been reported to alleviate the toxicants present in e-waste.

Microbial remediation

Organic toxicants present in e-waste like PCBs and PBDEs are extremely toxic and recalcitrant in nature,

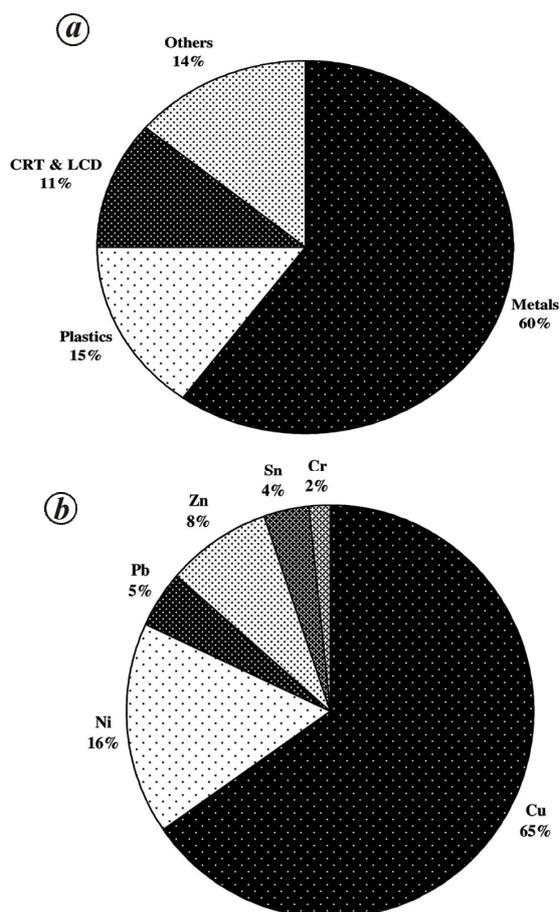


Figure 2. Typical composition of e-waste and its proportions. *a*, Total composition⁵⁹; *b*, major metal composition⁹.

Table 1. Microbial biodegradation of organic compounds present in e-waste

Microorganisms	Organic compound (initial concentration)	Medium/site	Culture conditions	% Removal	Reference
<i>Dehalobium chlorocoercia</i> DF1 <i>Burkholderia xenovorans</i> LB400	Polychlorinated biphenyls (8 mg kg ⁻¹)	PCB-contaminated sediment	Temperature 23°C; anaerobic treatment in the presence of lactate and zerovalent Fe	80% reduction after 120 days	16
<i>Pseudomonas aeruginosa</i>	Deca-bromodiphenyl ether (0.99 mg l ⁻¹)	Chlorine-free liquid medium containing glucose	pH: 7.5; temperature 30°C; agitation: 150 rpm	55% removal at 7 days	17
Soil microbes	Polychlorinated biphenyls (PCBs) and polychlorinated biphenyl ethers	E-waste contaminated soil	pH 7.0; temperature 25°C; lactate as nutrient source	29.5%–39.7% at 90 days	18
<i>Ochrobactrum</i> sp. T	Tetrabromobisphenol-A (3 mg l ⁻¹)	E-waste recycling site	pH: 7.0; temperature 35°C; inoculum: 25 ml of late log growth phase culture	91.8% at 72 h	46
Basidiomycetous fungi and laccase	Tetrabromobisphenol-A (1.0 mM)	Mineral salt media	–	100% removal within 4 days	47
<i>Bacillus cereus</i> JP12	Decabromodiphenyl ether (1.0 mg l ⁻¹)	Mineral salt media	pH 6.0; temperature 30°C; agitation: 150 rpm; inoculum: 0.6 (A _{600 nm})	88% removal after 12 days	48
<i>Comamonas</i> sp. JXS-2-02	Tetrabromobisphenol-A (0.5 mg l ⁻¹)	Mineral salt media	pH 7.0; temperature 30°C inoculum: 1% (v/v)	86% removal at 10 days	49
<i>Micrococcus luteus</i> (culture supernatant)	Biphenyl (1500 mg l ⁻¹)	Mineral salt media	pH 7.3; temperature 30°C agitation: 200 rpm; at 24 h 15% (v/v) of culture supernatant	100% removal	50
<i>Anabaena</i> PD-1	Polychlorinated biphenyls	Chlorine-free liquid medium	Temperature 25°C; illumination intensity: 2000 lux; 12 h : 12 h, light : dark ratio	84.4% removal after 25 days	51

which makes it difficult for the most of microorganisms to grow in their presence. However, certain microorganisms with their unique tolerance mechanisms are able to grow and degrade or transform these toxicants into non-toxic forms. For instance, Payne *et al.*¹⁶ have reported 80% degradation of 8.0 mg kg⁻¹ PCB-contaminated sediment after 12 days of treatment using *Burkholderia xenovorans* LB400. Similarly, 55% removal of initial 0.99 mg l⁻¹ of decabromodiphenyl ether (DBDE) after 7 days of inoculation of *Pseudomonas aeruginosa* has been reported by Shi *et al.*¹⁷. Anaerobic transformation of PCBs and PBDEs using native dissimilatory metal reducing microbes (DMRMs) of the soil in the presence of lactate (electron donor) and Fe(II) have been studied by Song *et al.*¹⁸. DMRM performs oxidation of ferrous to ferric ions using lactate. Subsequently the ferric ions donate electrons to target contaminants for their reductive dehalogenation to easily metabolizable products. So the use of organic supplements or natural humic substances along with iron oxide in the presence of DMRM would also be beneficial for treatment of PCB- or PBDE-

contaminated soils¹⁸. Table 1 provides a list of such e-waste originated organic pollutant degrading microorganisms along with their culture conditions and extent of degradation.

Phytoremediation

This involves the use of vegetation/plant species to remediate pollutants from the contaminated soil or water. The plant species basically uptake, store or degrade the pollutants. Numerous plant species have been successfully applied for restoration of sites contaminated with diverse pollutants arising from e-waste¹⁹. Chen *et al.*²⁰ have tested the efficiency of four plant species, *Medicago sativa* (alfalfa), *Lolium perenne* (rye grass), *Festuca arundinacea* (tall fescue), and *Oryza sativa* (rice) for phytoremediation of PCB-contaminated soil from an e-waste disposal site. They have used various surfactants (cyclo-dextrin, Triton X-100) to increase the bioavailability of hydrophobic PCB. Rye grass in combination with 1%

(w/w) cyclodextrin was found to remove up to 38% of initial PCB. The authors²⁰ attributed the major role of rhizospheric microbial community in the removal of PCB from the soil rather than solely plant uptake. This is because plant uptake is merely 0.08% and major removal is due to microbial degradation around the rhizospheric zone. Around its rhizospheric zone, a plant secretes some specific chemical compounds which stimulate/accelerate the growth or migration of certain microbes responsible for degradation of PCBs.

Festuca arundinacea in combination with methylated cyclodextrin was found to remove 48% of PCB mostly from the rhizospheric zone of plants²¹. The potential of water hyacinth (*Eichhornia crassipes*) for phytoremediation of PCB containing landfill e-waste leachate has been studied by Omondi *et al.*²². In their study water hyacinth was observed to lower the initial PCB concentration of $15 \mu\text{g l}^{-1}$ to $0.42 \mu\text{g l}^{-1}$ over 15 days through uptake. Bioaccumulation/uptake of $0.179 \mu\text{g g}^{-1}$ was observed for initial $15 \mu\text{g l}^{-1}$ of PCB. Ye *et al.*²³ have tested the phytoremediation efficiency of vetiver grass for PBDEs/PCBs/PAHs and heavy metals (Pb and Ni) after washing of e-waste contaminated soil with tea saponin and peanut oil for extraction of contaminants. Soil washing using the above amendments resulted in 94.6%, 97.0%, 95.1%, 83.5% and 87.1% removal of PBDEs, PCBs, PAHs, Pb and Ni respectively. Further growth of vetiver grass on washed soil resulted in the removal of residual contaminants from the soil.

Bioleaching of metals

Bioleaching is the process whereby metals present in the waste electronic parts are mobilized using microorganisms. This ultimately results in recovery of metals and production of metal-free e-waste for safe disposal. Various metabolites, including organic and inorganic acids are produced during growth and metabolism of microorganisms which results in hydrolysis, complexation and chelation of metals from solid electronic waste²⁴. There are various studies in which the microbial process has been utilized for recovery of metals from e-waste. Table 2 provides a list of some metal-leaching microbes used for solubilization of metals present in e-waste along with their culture conditions and extent of leaching/removal.

Majority of microorganisms used for metal recovery belong to the acidophiles that thrive at acidic pH, e.g. *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* and their co-cultures have been used to solubilize 99.0%, 74.9% and 99.0% of Cu from printed wire boards (PWBs)—a component of e-waste²⁴. In another case, mixed culture of *Sulfobacillus thermosulfidooxidans* and an unidentified acidophilic culture (A1TSB) have been used for recovery of 81% Ni, 89% Cu, 79% Al and 83% Zn from e-scrap²⁵. Pant *et al.*³ and

Ilyas and Lee²⁶ have reviewed the use of diverse microorganisms in bioleaching and recovery of metals from e-waste.

Simultaneous bioremediation of POPs and heavy metals

As e-waste is known to possess both POPs and heavy metals as toxicants, their simultaneous remediation using microbes is reported to have a pronounced effect and remains in demand. However, in order to use microorganisms for such mixed waste, they must possess tolerance and detoxification abilities towards different types of pollutants. These properties help them sustain and perform efficiently in complex and mixed polluted systems. Generally microbes isolated from mixed waste environment work better, as they are pre-adapted to utilize diverse substances. Tang *et al.*²⁷ have reported simultaneous removal of Cr(VI) and 2,2,4,4-tetrabromodiphenyl ether (BDE-47) from e-waste using *P. aeruginosa*. A novel *Pseudomonas gessardii* LZ-E strain was also observed to co-remediate PAH (naphthalene) and Cr(VI) from a co-contaminated system²⁸. However, there are only few such examples available.

Use of zerovalent metallic particles

Zerovalent iron particles (ZVI) or nano particles (nZVI) have been used for detoxification of halogenated persistent organic pollutants, including trichloroethylene, chlorobenzenes, chlorophenols, PCBs and PBDEs²⁹⁻³¹ and range of heavy metals³²⁻³⁴. ZVI is a powerful and effective reducing agent and has been used for reductive dehalogenation of a number of recalcitrant halogenated pollutants^{30,35}. Use of ZVI or nZVI over other metallic particles has the advantage of being non-toxic and inexpensive compared to zerovalent metallic particles³⁶. Nano-scale ZVI is more effective than other metals because of its large surface area and high reactivity³⁵. Use of nZVI is now considered a novel approach for developing next generation environmental remediation technologies³⁷.

Excessive halogenation of organic pollutants makes them recalcitrant and toxic, because it is difficult for microorganisms to act on polyhalogenated pollutants³⁰. However, if the extent of halogenation is partially reduced, the resulting products are more amenable and easily metabolizable by the aerobic microorganisms. Hence sequential treatment of halogenated pollutants using nZVI followed by aerobic biodegradation of less toxic metabolites could be an efficient strategy for efficient remediation of POPs present in e-waste.

Kim *et al.*³⁰ studied the efficiency of remediation of decabrominated diphenyl ether (deca-BDE) through sequential nano-biotreatment using nZVI and diphenyl

Table 2. Bioleaching of metals from e-waste

Microorganisms	E-waste (initial concentration)	Conditions	Extent of metal solubilization	Reference
<i>Acidithiobacillus thiooxidans</i>	Printed wire board (7.8 g l ⁻¹)	Mineral medium containing S and/or Fe ²⁺ ; pH: 2.5; agitation: 150 rpm; temperature: 28°C	74.9% solubilization of Cu	24
<i>Acidithiobacillus ferrooxidans</i>	Printed wire board (7.8 g l ⁻¹)	Mineral medium containing S and/or Fe ²⁺ ; pH: 2.5; agitation: 150 rpm; temperature: 28°C	99% solubilization of Cu	24
<i>A. thiooxidans</i> and <i>A. ferrooxidans</i>	Printed wire board (7.8 g l ⁻¹)	Mineral medium containing S and/or Fe ²⁺ ; pH: 2.5; agitation: 150 rpm; temperature: 28°C	99.9% solubilization of Cu	24
<i>Sulfobacillus thermosulfidooxidans</i>	Electronic scrap (10%)	Mineral medium having 2.5% S and 25% O ₂ + 0.03% CO ₂ enriched air; pH: 2.0; temperature: 45°C	91% Al, 95% Cu, 96% Zn, 94% Ni solubilization	26
<i>S. thermosulfidooxidans</i> and acidophilic heterotrophy (code A1TSB)	Electronic scrap (10 g l ⁻¹)	Mineral medium; pH: 2.0; temperature: 45°C; agitation: 180 rpm	81% Ni, 89% Cu, 79% Al, 83% Zn solubilization	27
<i>Aspergillus niger</i> and <i>Penicillium simplicissimum</i>	Electronic scrap (5–10 g l ⁻¹)	Mineral medium containing sulphur (1% w/v); pH: 2.5–2.7; temperature 30°C; agitation: 150 rpm	65% Cu and Sn >95% leaching of Al, Ni, Pb and Zn	52
Bacterial consortium	Printed circuit board (20 g l ⁻¹)	Mineral medium having 9 g l ⁻¹ Fe ²⁺ ; pH: 1.5	95% Cu bioleaching after 5 day	53
Mixed culture of acidophilic bacteria	Printed circuit board (12 g l ⁻¹)	Medium having 12 g l ⁻¹ Fe ²⁺ ; pH: 2.0; inoculum size:10%	96.8% Cu leaching at 45 h; 88.2% Al and 91.6% Zn at 98 h	54
<i>Chromobacterium violaceum</i>	Electronic waste (1% w/v)	LB medium; pH: 7.2; temperature: 30°C; agitation: 150 rpm	79% Cu, 69% Au, 46% Zn, 9% Fe, 7% Ag	55
<i>C. violaceum</i> and <i>Pseudomonas aeruginosa</i>	Electronic waste (1% w/v)	LB medium; pH: 7.2; temperature: 30°C; agitation: 150 rpm	83% Cu, 73% Au, 49% Zn, 13% Fe, 8% Ag	55
<i>C. violaceum</i> (mutated)	Electronic scrap (0.5%)	LB medium; pH: 9.5; temperature: 30°C; agitation: 170 rpm	22.5% Au recovery	56
<i>A. niger</i> MXPE6 and <i>A. niger</i> MX7	Printed circuit board (200 mg/15 ml)	Mineral medium containing glucose; pH: 4.4; temperature: 28°C	87% leaching of Au after 14 day	57
<i>S. thermosulfidooxidans</i>	Printed circuit board (10 g l ⁻¹)	Mineral medium containing Fe ²⁺ ; pH: 1.75; temperature: 50°C	99% leaching of Cu	58

degrading bacteria, *Sphingomonas* sp. Primary treatment with nZVI resulted in 67% reduction of initial deca-BDE to lower BDE within 20 days of treatment. The reaction mixture after nZVI treatment was further aerobically treated for four days using *Sphingomonas* sp. PH-07 for mineralization of lower BDE. Several researchers have demonstrated the use of nZVI for the treatment of differ-

ent types of hydrophobic chlorinated waste^{29,35,38}. During the treatment, nZVI gets attached to the contaminants adsorbed on soil particles and directly transfers electrons to the contaminants resulting in reductive dehalogenation of organic pollutants³⁶. Thus, prior supplementation of nZVI before aerobic microbial degradation results in enhanced removal of contaminants from the polluted

system. However, some limitations associated with nZVI, e.g. aggregation and formation of iron oxide or hydroxide on the surface of nZVI have shifted the focus to bimetallic nanoparticles^{37,39}. In this case, nZVI are loaded with another catalyst metal such as Pb or Ni for prevention of aggregation or increasing mobility and accelerating the reaction rate³⁷. Fang *et al.*³⁹ have observed 53-fold faster debromination rate of deca-BDE209 using Ni/Fe bimetallic nanoparticles compared to single nZVI. Xie *et al.*³⁷ used Ni/Fe bimetallic nanoparticles for treatment of the deca-BDE209 contaminated soil and observed 72% removal efficiency using 0.03 gg⁻¹ dosage of nanoparticles at an initial pH of 5.6.

Electrokinetic bioremediation

Site contaminated with e-waste pollutants could also be treated using electrokinetic treatment coupled with bioremediation^{40,41}. This involves development of low electric potential across two electrodes placed in the contaminated system. Application of electric potential induces transport of particles, ionic species and interstitial water towards the electrodes of the respective affinity^{42,43}. Then application of extraneous microbes or bioremediation using native microbes is performed. The bioremediation process thus becomes more efficient due to increased bioavailability of nutrients and pollutants (especially hydrophobic ones) to microbes. Thus application of electrokinetic treatment principally increases the mass transfer and bioaccessibility of contaminants for biodegradation⁴⁴.

Electrokinetic treatment coupled with bioremediation has been used for successful treatment of the waste system^{40,41,45}. Non-uniform pH, voltage and moisture gradients in the contaminated system are some of the limitations observed with electrokinetic treatment, which can affect the overall bioremediation performance⁴⁴. Application of low electric current has no overall effect on viability of native/added microbes during electrokinetic treatment; however, change in pH and moisture gradients may result in stressful environment for the microbes. Gill *et al.*⁴⁴ have reviewed all aspects of the electrokinetic treatment coupled with bioremediation, including factors, mechanisms and applications. They conclude that this technique has the potential to effectively enhance bioremediation in physically heterogeneous or low permeability system compared to other techniques.

Presently, the aforementioned technologies for remediation of e-waste related contaminants are in initial stages of development in relation to actual field-level application. These low-cost remediation technologies essentially use natural processes for removal of contaminants and are thus preferable over other physico-chemical methods of remediation. However, some limitations like lower bioavailability and transfer rate, co-presence of other pollutants/toxicants, lack of nutrients and diverse

environmental parameters drastically affect the remediation processes. Thus, sequential or combined treatment using physico-chemical methods followed by biological method could be beneficial in increasing the overall bioremediation efficiency of e-waste related pollutants.

Conclusion

Toxic contaminants present in e-waste need to be efficiently remediated from the contaminated system in order to minimize their effect on the environment and living beings. Biological methods have the potential to minimize the toxicity associated with e-waste contaminants in sustainable way. However, bioavailability of contaminants present in e-waste is a limiting factor in the use of biological methods. The efficiency of biological methods could be further increased, if they are used in combination with mild or comparatively safer physico-chemical methods. Considering this, surfactants, electrokinetic treatment or zevalent metallic nanoparticles could be used as pretreatment tool before actual application of biological methods. An effort needs to be undertaken to spread awareness regarding proper and safe recycling of e-waste. Comprehensive environment and health risk assessment studies are lacking in this regard.

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