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E-waste Management Using Microbial Biotechnology

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***Abstract* - Electronic waste is an alarming problem faced globally in today's constantly changing world of technological innovations. The major challenge is to create various innovative and cost-effective ways for decontaminating polluted environments so that they are safe for human habitation, consumption and functioning of various ecosystems that support life. To date, for the management of e-waste no sound eco-friendly technique is available. Hence, biological approach using microorganisms is currently being applied for recovering leached metals from contaminated soil, groundwater, surface water polluted by e-waste, removing toxicity and decontamination of these abiotic components polluted due to e-waste. There are different technologies used for management of e-waste using microorganisms which include microremediation, phytoremediation and vermiremediation. Microremediation involves the use of various microorganisms, phytoremediation the use of plants and symbiotic microorganisms, whereas vermiremediation involves the use of earthworms and necessary associated microbes for e-waste management. These technologies are becoming attractive alternatives as compared to the primitive disposal technologies because they are cost effective, work at ambient temperatures, do not have any major environmental impacts, generate minimum secondary waste and have an inherently aesthetic nature. This paper summarizes the status of e-waste and its harmful effects on life as well as environment and use of innovative microbial biotechnological approaches for handling of e-waste and metal recovery thereof.**

Keywords: Bioremediation, Microbial Biotechnology, E-waste management, Microremediation, Physical Recycling, Chemical Recycling.

I. INTRODUCTION

E-waste or electronic waste can be referred to as all electrical and electronic equipment (EEE) and their components that have not been in use by the users or are thrown away by the users. E-waste is also known as Waste Electrical and Electronic Equipment (WEEE), which comprises of electronic waste or e-scrap around different regions and under different circumstances in the world. The most important part in the term e-waste is "waste" which logically refers to the fact that the items have no further use and are rejected as useless to the owner.

E-waste is considered the fastest-growing waste stream in the world (UNEP et al. 2019) with 44.7 million tons of e-waste generated during the year 2016 which was equivalent to 4500 Eiffel Towers (Baldé, 2017). In 2018, an estimated 50 million tons of e-waste with annual value of $62.5 billion was reported thus the name 'tsunami of e-waste' was given by the UN (UNEP et al. 2019). It has been predicted that this surplus amount of e-waste would further go up to nearly 53 million metric tons by 2021 (Baldé, 2017).

There can be numerous sources of E-waste. Almost every used electronic items such as mobiles, cameras, televisions, radios, fax machines, printers, batteries, digital calculators, clocks, monitors, keyboards, fridges, air-conditioners, irons, heaters etc. are considered as e-waste. The disposal of these hazardous e-waste items in an improper way generally contributes to environmental pollution and also has severe impacts on life (Samajdar 2018). Toxic components such as zinc and lead, and flame retardants such as chromium and barium are usually an integral component in computers and most electronic items, which if released in the environment, cause extreme damage to the blood, kidneys and the CNS and PNS in case of humans. Burning of e-waste results in release of toxic chemicals in the air ultimately damaging the ozone in the atmosphere which is the biggest environmental impact of e-waste. This would result in various airborne diseases such as asthma, choking etc. and increase the toxicity of air, making it unfit for consumption. E-waste often gets dumped in the landfills which results in release of various toxins, which leach from landfills and mix with groundwater system. This contamination of soil will result in the loss of vegetation and affects life on both land and sea. Also, people living around various e-waste disposal sites exhibit substantial digestive, neurological and respiratory problems (Lubell, 2018).

Since the sources of e-waste are voluminous and each and every source has its own form of toxicity and negative influence on environment and life making it necessary to manage e-waste properly. There are many practices currently being followed to reduce the quantity of e-waste. For instance, incineration, open burning, pyrometallurgical processing,

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landfilling etc. to name a few. Some of these practices are not economically viable, cost effective and still some others are hazardous to life. Today biotechnology is playing a big role in many aspects of life and it has been demonstrated that microbial biotechnology through bioremediation can be very effective in the management of e-waste. Microbial biotechnology or bioremediation involves the use of microorganisms and their products for industrial or clinical relevance. Under this field of work most of the contaminated media including subsurface material like e-waste, soil, water etc. are treated by altering various environmental conditions to stimulate the growth of micro-organisms for destroying the targeted pollutants and obtaining important products out of this contaminated media. Bioremediation technologies like microremediation, phytoremediation, vermiremediation etc. are eco-friendly in nature, thus creating exciting possibilities for e-waste management. Microremediation is used for treatment of e-waste using microorganisms to eliminate or convert contaminants from hazardous state to less hazardous or non-hazardous form through microbial action (Narayanasamy et al., 2017).

Phytoremediation uses living plants to clean biological components such as air, water and soil that are contaminated with hazardous contaminants. It uses plants and microorganisms symbiotically, with proper soil and agronomic means to contain or make the toxic environmental contaminants non-hazardous or less hazardous in nature. Vermiremediation is an expanding technology that uses earthworms to remediate contaminated media normally present in soil. Earthworms are the major component in vermiremediation. It is also known that they have the ability to accumulate heavy metals from soils which can be used for e-waste management. All these technologies and their use in managing e-waste forms ground for discussion subsequently in this paper.

II. PRIMITIVE E-WASTE MANAGEMENT TECHNIQUES

Efficient handling of electronic and electrical rubbish is the most important challenge in today's era for profitable material recovery and environment sustainability. Recycling and managing e-waste are an important subject not only for the treatment of this hazardous waste but also for the recovery of the valuable metals (Guo et al., 2007). However, the process of recycling is complex because of its heterogeneity as it comprises of various organic materials, metals and glass fibers (Table 1). Hence, this section elaborates various traditional and modern techniques as shown in Figure 1 for recovering valuable metallic and non-metallic fractions from e-waste.

Table 1: Occurrence of metals in e-waste (Bastiaan et al., 2010)

E-waste	Metal presence (percent)				Metal present (ppm)			
	Pb	Ni	Al	Fe	Cu	Pd	Au	Ag
PWB	2	2	7	12	16	-	0.04	-
TVS	0.2	0.04	1.2	-	4	27	27	27
TBS	1	0.3	10	28	10	10	17	280
PBS	1.5	1	5	7	20	110	250	1000
PCB	3	29	2	7	12	16	-	0.04
CS	0.1	0.05	5	4	3	5	50	260
PAS	0.14	0.03	1	23	21	4	10	150
DPS	0.3	0.05	2	62	5	4	15	115
MPS	0.3	0.1	1	5	13	210	350	1340
PCS	6.3	0.85	14	20	7	3	16	189

PWB= Printed wiring board; PCB= Printed circuit boards; PBS= PC board scrap; TBS= TV board scrap; MPS= Mobile phone scrap; PAS= Portable audio scrap; DPS= DVD player scrap; CS= Calculator scrap; TVS= TV scrap; PCS= PC scrap

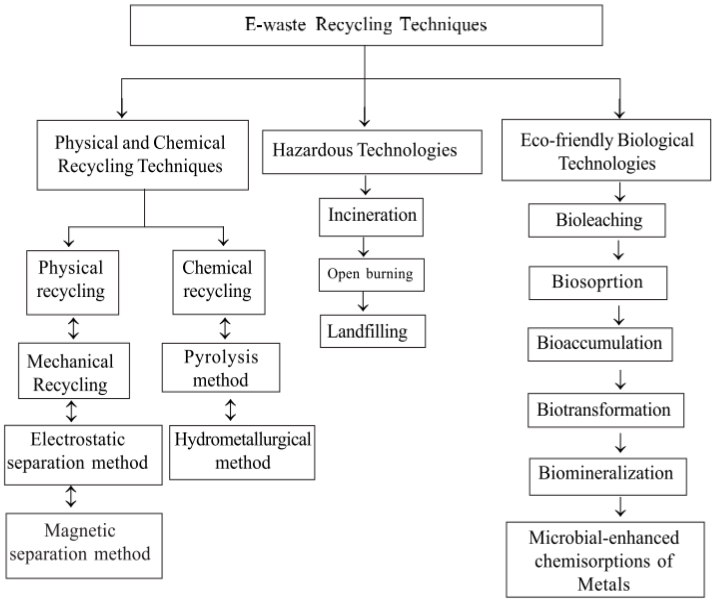

Figure 1: Overview of recycling techniques (Narayanasamy et al., 2017)

2.1 Chemical Recycling Techniques

2.1.1 Pyrolysis Method

Pyrolysis is a chemical method used for recycling various synthetic polymers as well as the polymers mixed with glass fibers. Pyrolysis of these polymers produces gases and oils which can be further utilized as fuel or chemical feedstock (Guo et al., 2008). Printed Circuit Boards (PCBs) are an integral component of majority of e-waste produced. They are heated to a particular temperature which melts down the solder that is used to bind the electrical parts to the circuit board. After pyrolysis process, blackish metal residue is left (Mankhand et al., 2012). This metal residue on leaching produces good amount of copper.

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2.1.2 Hydrometallurgical Method

Hydrometallurgical process is the most favored technique for the recycling of metallic fractions from e-waste (Bernardes et al., 1997). In this process, valuable metal constituting components of e-waste are directly dissolved in leaching solutions such as alkaline and acidic solutions. Then using electro refining processing desired metals are obtained (Bernardes et al., 1997; Kinoshita, 2003). Most commonly used leaching solutions are aqua regia, nitric acid and cyanide solutions (Kinoshita, 2003). Apart from this electrochemical processing is also done for metal recovery, in case there is presence of metallic substrates (Li & Shrivastava, 2004).

2.2 Physical Recycling Techniques

2.2.1 Mechanical Recycling

Mechanical recycling is a physical recycling method. Under this technique, the disassembled samples from e-waste are first broken and cut into specific sized pieces. These pieces are then subjected to a milling process which results in production of fine pulverized powder. This powder is then added to eddy current separators where separation of metals by their eddy current characteristics is achieved (Zhang & Forssberg, 1999). Finally, these samples undergo density separation process (Zhang & Forssberg, 1997). Depending upon the density and particle size, process of stratification is done for metal recovery (Rohwerder et al., 2003).

2.2.2 Electrostatic Separation Method

In electrostatic separation method, the electric force which acts on charged or polarized materials is used for the broad separation of heterogenous materials (Shapiro M 2005). This technique has been applied for recycling of metals and plastics from various e-waste equipment (Luga et al., 2001). According to a study, this electrostatic separation method was used to recycle Cu, Al, Pb, Sn, Fe, some noble metals and plastic from scrapped PCBs (Zhang & Forssberg, 1998).

2.2.3 Magnetic Separation Method

Magnetic separators are widely being used for recovering various ferromagnetic metals from non-ferrous materials and other non- magnetic wastes (Hanafi et al., 2012). Since the valuable metals present in e-waste are metallic in nature this technique is widely used for separation of metallic and non-metallic components. However there also occurs the agglomeration of particles. This agglomeration allows the magnet to also pull the non-metal materials that are attached to the ferrous materials (Sohaili et al., 2012).

2.3 Hazardous Techniques

2.3.1 Incineration

Incineration is a method of treating and destroying e-waste by burning. However, due to different types of elements present in e-waste, there is a great challenge of generation and dispersion of harmful components. The gases that get released and the residue ash left on burning are highly toxic (Sasse, 1998). Various municipal solid waste (MSW) plants suggest that when flame-retardants are burnt, copper, present in PCBs and cables, continuously acts as a catalyst for dioxin formation which is hazardous. Also, PVC, which is normally present in e-waste in large quantities, becomes extremely reactive when incinerated and results in the production of these dioxins. Moreover, burning leads to the removal of various valuable components from e-waste which if had been sorted properly could be utilized productively (Shapiro, 2005).

2.3.2 Open Burning

Since open fires tend to burn at relatively low temperatures, they are being widely used. However, they tend to release more pollutants in the form of emissions as compared to incineration process. These emissions produced have the ability to trigger asthma attacks, respiratory disorders, coughing, chest pain, and eye irritation (Chen & Zhang, 2000). Moreover, due to continuous exposure to these emissions diseases such as emphysema and cancer could occur. Also, the residual particulate matter commonly known as fly ash is produced that is harmful if inhaled (Zhu et al., 2013). For instance, whenever PVC obtained from e-waste is burnt it emits hydrogen chloride, which on breathing directly reacts with moisture in the lungs and produces hydrochloric acid. This acid is corrosive in nature and leads to corrosion of the lung tissues, and several respiratory problems.

2.3.3 Landfilling

Landfilling technique is being widely used for e-waste removal. However, it is also known that all landfills tend to leach after some time (Luga et al., 2001). These leachates contain various metals and toxic substances produced from e-waste which ultimately contaminate soil and water. Old landfill sites expose a greater threat of emitting harmful emissions. Hg, Cd, Pb are the most toxic leachates. For instance, Hg will leach when certain electronic devices like various circuit breakers get destroyed (Yamawaki, 2003). Lead-containing glass such as the glass of cathode ray tubes from televisions and monitors results in leaching of lead. Plastic containing cadmium is landfilled, cadmium leaches into soil and groundwater (Rotter, 2002). Apart from leaching, vaporization is also a major concern. For instance, toxic compounds like mercury and its altered form like dimethylene

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mercury are released. Moreover, landfills are vulnerable to catch fire which ultimately release harmful fumes (Huang et al., 2007).

Several technologies including both physical, chemical and hazardous techniques discussed above fore-waste management are accepted and performed globally. However, these technologies are very expensive and lead to secondary pollution, which indirectly further leads to environmental degradation. Hence, the biological approach is applied for management of e-waste as it is environment-friendly in nature. Therefore, the next part of the present report discusses in detail the capabilities of biological approaches for recycling valuable metal recycling and removing toxicities of e-waste.

III. MICROREMEDIATION

Microremediation using microbes is a biotechnological approach for treatment of e-waste by eliminating and transforming the components of e-waste to least hazardous or non-harmful forms in environment using the metabolic activities of microorganisms. It is a creative technique towards the decontamination of e-waste by immobilizing metals and recovering them. Also, micro-remediation is preferable as it is less expensive and is more sustainable than other remediation alternatives (Agency, 2011).For microremediation to occur, microbial population having metabolic capacity for degrading the e-waste is a must. The metabolic activities used by microbes are highly specific in nature; hence environmental factors for degradation using microbes must be considered and regulated well as shown in Figure 2. Interaction between metals and microbes for metal extraction out of e-waste includes processes such as bioleaching, bioaccumulation, biotransformation, biomineralization and biosorption. Some examples on the use of micro-organisms for microremediation of e-waste are summarized in given Table 2.

Table 2: Metal removal from e-waste using microorganisms (some studies based on biological approaches)

S. No.	Microorganisms	Reference
1.	*Acidithiobacillus ferrooxidans*	(Bajestani *et al.*, 2014)
2.	*Acidithiobacillus thiooxidans* and *Leptospirillum ferrooxidans*	(Beolchini *et al.*, 2012)
3.	*Acidophilic consortium, Acidithiobacillus* and *Gallionella*	(Zhou *et al.*, 2020)
4.	*Aspergillus niger*	(Brandl & Bosshard, 2001; Horeh *et al.*, 2018)
5.	*Penicillium simplicissimum*	(Brandl & Bosshard, 2001)
6.	*Leptospirillum ferrooxidan* and *At. thiooxidans*	(Bas *et al.*, 2013)
7.	*Bacillus megaterium*	(Arshadi *et al.*, 2019)
8.	*Chromobacterium violaceum, Pseudomonas fluorescens* and *Pseudomonas plecoglossicida*	(Brandl & Bosshard, 2001)
9.	*Pseudomonas putida*	(Işıldar *et al.*, 2016)
10.	*Sulfobacillus thermosulfidooxidans*	(Ilyas *et al.*, 2014)

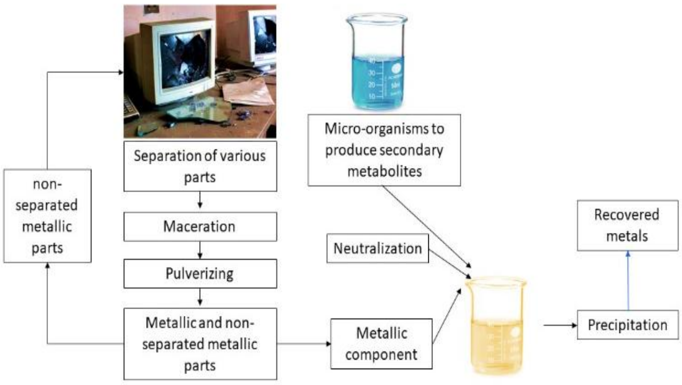

Figure 2: Demonstration of steps for the application of microbial metabolites for metal removal from e-waste (e.g., waste PCB)

3.1 Bioleaching

Bioleaching, also known as biomining, is defined as the extraction of metals using living organisms and this approach can be extended for recovery of valuable metals such as copper, lead, arsenic, lead, gold, silver etc. from e-waste. This approach is currently rising to be commercially exploitable methodology which can be used for recovery of metal present in e-waste and ores. Bioleaching processes are being used for enhancing the efficiency of exploitability of metals, where low-grade ores are normally treated using microorganisms for obtaining high value of metals, which is not exploitable by primitive methodologies i.e. physical and chemical (Agate, 1996). Since this process is successfully applied for leaching metals from ores (Olson & Brierley, 2003), yet the data about its utilization for extraction of metals from e-waste is still a little scanty. One-step bioleaching, two-step bioleaching and spent-medium leaching processes for metal-extraction from e-waste are discussed below in detail.

3.1.1 One-step bioleaching

In one-step bioleaching process, microbial culture is added directly in leaching system and it utilizes the substrate and rapidly leads to generation of protons as lixiviants. These generated lixiviants continue to react on various metals and their sulphides to get solubilized. As there are no substrates and energy sources available in case of e-waste, hence it becomes necessary to add proton (pyrite or sulphur, ferrous iron) in the leaching approach so that the organisms could generate required lixiviants. In this process, the microbial inoculum is mixed in the required leaching medium, with e-waste and this process continues for generation of proton lixiviant, which slowly leads to solubilization of metals.

A research-based study was conducted in 2016 by (Liu et al., 2016) in which one-step bioleaching for gold extraction from e-waste containing PCB's was studied in non-infected flasks containing YP media and 1 g/L MgSO4.7H2O at 15 g/L

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pulp density added with 1 mL of *Chromobacterium violaceum* microbial inoculum. The results indicated that when the pH was enhanced from eight to eleven in eight consecutive days, the gold leaching efficiency also drastically increased from 7.8% to 11% (Chi et al., 2011). However, *C. violaceum* had the capability of generating low concentration of cyanides while performing metabolic activities. It was noted that the presence of phosphates and cyanides in the medium favored copper dissolution from PCB's due to pH change, which was not useful for bioleaching of gold. Hence the concentration of cyanide produced by the microbial activity of *C. violaceum* was low and this favored bioleaching of copper in place of gold from the PCB's (Tran et al., 2011). Therefore, sometimes the presence of various highly toxic compounds generated during the process act as an inhibiting factor for microorganisms (Pradhan J 2012). Thus, activity as well as multiplication of microbial inoculum gets retarded. Such inhibition factors restrict this one-step process to operate at a lower pulp density. As mentioned in an article, mostly the processes work in the range of 1to 5% (w/v) e-waste to 10% (w/v) e-waste.(Liang et al., 2013). Adding lower pulp density resulted in lowered number of recovered metals in the sample media. Therefore, in this one-step process for bioleaching it is quite hard to maintain favorable environment, for growth of microbes as well as for metal retrieval. Hence, there are low metal extraction rates in this process which led to discovery of two-step bioleaching process.

3.1.2 Two-step bioleaching

In this process, during the first step the necessary microorganisms are cultured in their medium under particular average growth conditions. Then in the second step, when the maximum multiplication of microorganism and lixiviant concentration (proton and ferric) is attained then e-waste is subsequently added. This process actually minimizes the inhibition of microorganisms due to e-waste toxicity and provides an optimum environment for both the growth of microorganisms and metal solubilization. For more efficient metal extraction, direct growth of microorganisms along with e-waste is not advisable as toxicity gets produced acting as an inhibitor (Brandl & Bosshard, 2001). It is also observed to be more preferable because its outcomes allow faster and higher metal retrieval rates (Sand et al., 2001). Also, here we carry out the process at enhanced pulp density as compared to one-step bioleaching process. In the next step, bio-generated ferric or proton gets used in metal recovery process and it directly gets changed into ferrous state. This ferrous state is then shifted to the first step of the reaction, where it gets oxidized again to form ferric iron, which again serves as lixiviant for metal solubilization. Under the process of two-step bioleaching higher quantity of proton or ferric are required when e-waste is introduced, which will quickly react with e-waste mixture and corresponding metals to get dissolved at faster rate.

According to a study, *C. violaceum* was in the first step cultured in LB media in the absence of ESM. In the second step, ESM was introduced into the media and maximum microbe density and cyanide concentration was achieved. The two-step bioleaching process was used to reduce the inhibitory effect caused due to cyanide production owing to toxicity of ESM. Results showed that at a high pulp density of about 0.5% w/v, *C. violaceum* demonstrated maximum possibility of bioleaching of gold of about 11.3% (Natarajan, 2015). Hence, this two-step bioleaching process is more suited for increasing the leaching efficiency of metals by microbes from electronic rubbish (Awasthi & Sood, 2008).

3.1.3 Spent-medium leaching

In this process, microorganisms are separated from the medium after maximum microbe density and cyanide production is achieved, and only microbe-free metabolites are used for spent medium leaching process. In a study conducted by(Natarajan, 2015), spent medium process showed higher metal extraction of both gold and copper as compared to in two-step bioleaching, at variable pulp concentrations. In spent medium process oxygen is used for gold complex formation in absence of microbes which is unlike in two-step bioleaching, where oxygen is consumed by the microbes. Maximum cyanide production occurred, however due to absence of microbes, cyanide was not consumed. So, this cyanide was used in gold leaching than in two-step bioleaching where cyanide acted as an inhibitor. Hence, spent medium leaching process gave an upper cut to two step bioleaching process as it increased the efficiency of metal extraction.

3.2 Biosorption

The technique of biosorption is defined as the concentration and attachment ability of contaminants or toxic metals from e-waste directly to the surface of cellular structure i.e. microorganisms, and it does not necessarily require active metabolism (Volesky, 1990). It is the ability of biological entities such as microorganisms for accumulation of metals (Mrvčić et al., 2012) and it is one of the best alternative for removal of toxic heavy metals from e-waste and aids towards the cause of environmental remediation. Biosorption is a physiochemical adsorption technique that employs various types of latent, dead or microbial inoculum to bind and concentrate heavy metals from very dilute aqueous solutions as an ion exchanger of biological origin normally does.

Biosorption is an advantageous process and does not need any type of nutrients. It is a single step method and does not have any dangers of harmful effects on cell growth. It

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allows optimal concentration of metal ions, and is independent from metabolism processes (Chojnacka, 2009). Also, biosorption does not require any energy. The number of contaminants a sorbent can remove from e-waste depends on the kinetic equilibrium and the composition of the chosen sorbent. Moreover, biosorption is preferable as it has a faster rate of occurrence and has the ability to produce higher concentrations. Since metals are attached to the surface of microbes, biosorption can be called as a reversible process (Velásquez, 2009)

Biosorption mechanism is understood through various techniques like acidic and basic properties of the functional groups, scanning electron microscope (SEM), Fourier transform infrared spectrometry (FTIR), energy dispersive X-ray (EDX), X-ray photoelectron spectroscopy (XPS) (Michalak, 2013). Process of biosorption is quite complex as it involves binding of sorbate and the biosorbent. Physical or chemical binding like chelation, reduction, precipitation, and complexation are the processes by which biosorbents involve the binding of various metal ions. Biosorbents contain various functional groups like sulfonate, amine, carbonyl, carboxyl, sulfhydryl, phenolic phosphodiester and phosphate groups that can attract and bind various metal ions with themselves from e-wastes. Bacteria and fungi are the commonly used biosorbents for e-waste management (Table 3).

According to a recent study, it was found that the PCBs obtained from e-waste had valuable metals such as Cu, Pb, Sb, Hg, and Cd. Biosorption process as shown in Figure 3 was applied to eliminate these metals using *Bacillus megateirum* microbe as dead biomass to remove copper from the PCB's. Also, the effect of contact time, adsorbent dose, pH, concentration and agitation speed were noted. It was found that 65% of copper was obtained by using 2 g of *Bacillus megateirum* at a contact time of 60 mins, at a pH of 5 and at an agitation speed of 150 rpm (Jayakumar, 2016).

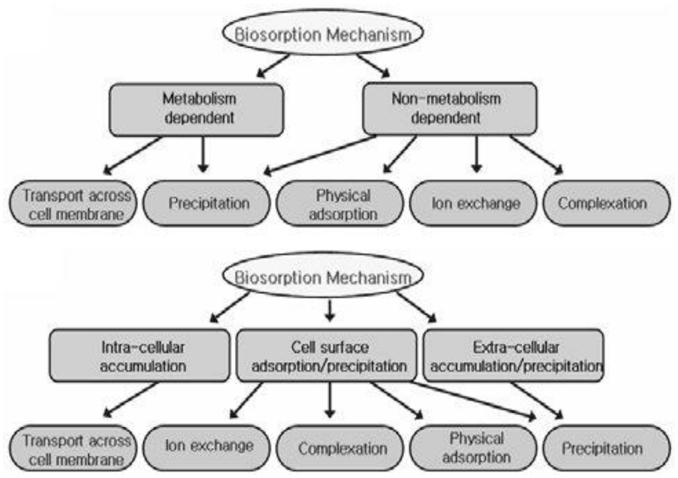

Figure 3: Biosorption mechanism for e-waste treatment

In another study the efficiency of metal removal of e-waste using microbial biomass in a number of reactor formats was studied (Butter et al., 1999). Also, the developments in various reactor formats include hollow-fiber crossflow microfiltration using *Pseudomonas aeruginosa* microbe used for the biosorption of Pb, Cu and Cd metals from waste. The efficiencies of removal using biosorption was Pb>Cu>Cd and at a concentration of 200 µM and flow rate of 350 ml h–1 satisfied the discharge regulation. Hence, Pb metal at maximum efficiency was removed the most using *Pseudomonas aeruginosa* as a biosorbent (Gadd, 2000).

Neodymium was removed from a leachate solution that was obtained from neodymium magnets present in waste electronic equipment and dried green microalgae (*Chlorella vulgaris*) was used as a biosorbent. Maximum neodymium uptake (q=157 mg/ g) was found at a pH of 5.0 using biosorbent dose of about 0.5 g/L. Hence, Chlorella vulgaris had a good potential as a biosorbent for obtaining neodymium out of leachate solution derived from neodymium magnets derived from e-waste. The use of this microbe as a biosorbent in the removal of Nd was successful (Kücüker et al., 2016). Several bacterial and fungal species were used in the biosorption of cadmium, chromium, lead and uranium from e-waste (Hu et al. 1996; Atkinson et al. 1998; Ahalya et al. 2003) (Table 4).

Table 3: Use of bacteria and fungi as biosorbents

Biosorbent type	Metal ion	Biosorption capacity/efficiency (mg/g or %)	Reference
A. Bacteria as biosorbents			
Bacillus cereus	Zn	66 mg/g[a*]	(Joo & Hassan, 2010)
Bacillus pumilus	Pb	28 mg/g[a*]	(Çolak *et al.*, 2011)
Trametes versicolor	Cu	140 mg/g[a*]	(Subbaiah *et al.*, 2011)
Lactobacillus delbruckii bulgaricus, streptococcus thermophilus	Fe (II), Zn (II)	100%, 90% a*	(Sofu & Sayilgan, 2015)
Bacillus coagulans	Cr	39 mg/g[a*]	(Vijayaraghavan, 2008)
Bacillus thuringiensis	Ni	15% a*	(Öztürk, 2007)
Bacillus thioparans	Cu, Pb	27, 210 mg/g[*]	(Rodríguez & Green-Ruiz, 2012)
E. coli	Ni	7.0 mg/g[b*]	(Quintelas *et al.*, 2009)
Pseudomonas putida	Zn	17 mg/g[a*]	(Green-Ruiz & Rodriguez, 2008)
B. Fungi as biosorbents			
Penicillium canescens	As, Hg, Cd, Pb	26, 54, 102, 213 mg/g[a*]	(Say & Yilmaz, 2003)
Penicillium chrysogenum	Ni	82 mg/g[a*]	(Haijia *et al.*, 2006)
Aspergillus niger	Cu	9 mg/g[b*]	(Dursun *et al.*, 2003)
Pencillium purpurogenum	As, Hg, Cd, Pb	35, 70, 110, 252 mg/g[a*]	(Say & Yilmaz, 2003)
Pencillium simpliccium	Cd, Zn, Pb	52, 65, 76 mg/g[a*]	(Fan *et al.*, 2008)
Saccharomyces cerevisiae	Pb, Ni, Cr	270, 46, 32 mg/g[a*]	(Özer, 2003)
Lentinus sajor	Cr	18 mg/g[a*]	(Arıca, 2005)

[a]biosorbent dry weight; [b]biosorbent wet weight; [*] biosorption experiments (batch) at laboratory scale

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Table 4: Biosorption of toxic metals from e-waste using microbes

Microorganism	Microbial Type	Toxic metals removed
1. *Myxococcus xanthus*	Bacteria	Uranium (U)
2. *Pseudomonas aeruginosa*	Bacteria	Uranium (U)
3. *Rhizopus arrhizus*	Fungus	Uranium (U)
4. *Bacillus sphaericus*	Bacteria	Chromium (Cr)
5. *Streptoverticillium cinnamoneum*	Bacteria	Lead (Pb)
6. *Saccharomyces cerevisiae*	Fungus	Cadmium (Cd)

3.3 Bioaccumulation

Bioaccumulation can be referred to as sorption or uptake of contaminants from e-waste by the micro-organism within itself. These contaminants get further transferred directly to a biomass cell which is present within the cellular structure and get concentrated there itself (Juwarkar, 2010; Prakash et al., 2012). Also, this process always requires active metabolism of microbes. For various organic contaminants, there occur various distinct chemical reactions in the cell cytoplasm for conversion of these contaminants to other compounds which are useful. However, the metals entering the cytoplasm of cells will not have any reaction but will eventually get deposited instead (Demirba 2001).

An extensive study was conducted (Akintokun et al., 2017) in which he isolated the favored Zn, Cu and Pb tolerant microorganisms from soils that were contaminated due to leaching of heavy metals from e-waste and further assessed their metal accumulating capability.

Bacillus licheniformis, *B. polymyxa*, *Pseudomonas aeruginosa*, *Aspergillus niger* and *A. flavus* were artificially selected by him for conducting his bioaccumulation study, on the basis of their known tolerance to heavy metals. *Bacillus licheniformis* was one of the most efficient microbes used in the removal of copper (71.3%) and lead (70.1%). Pb accumulation obtained from *Aspergillus flavus* came out to be 65.76%. Zinc accumulation obtained from *Pseudomonas aeruginosa* and *Aspergillus niger* came out to be 74.1% and 78.3%, respectively. Many metals such as cadmium, chromium, lead and uranium from e-waste were bioaccumulated in microbes like *Aspergillus niger*, *Bacillus megaterium*, *Bacillus circulans*, *Micrococcus luteus*, etc. as shown in the given table (Narayanasamy et al., 2017) (Table 5).

Table 5: Bioaccumulation of toxic metals from e-waste (Demirba, 2001; Juwarkar, 2010; Malik, 2004; Srinath et al., 2017)

Microorganism	Microbial Type	Toxic metal removed
1. *Bacillus circulans*	Bacteria	Chromium (Cr)
2. *Bacillus megaterium*	Bacteria	Chromium (Cr)
3. *Aspergillus niger*	Fungus	Chromium (Cr) and lead (Pb)
4. *Monodictys pelagica*	Fungus	Chromium (Cr) and lead (Pb)
5. *Deinococcus radiodurans*	Bacteria	Uranium (U)
6. *Micrococcus luteus*	Bacteria	Uranium (U)

3.4 Biomineralization

Biomineralization is a general term given to the processes by which microbes form minerals and this can further be exploited to remove metals from e-waste solution acting as a detoxification process aiding to bio recovery as well. Under this process toxic metal ions generally generated by e-waste directly attach with free ions or ligands generated from the microorganisms due to metabolism, resulting in formation of precipitate of these metal ions leading to bio recovery (Achal et al., 2012). The common biominerals that are normally precipitated by microbes include oxides, phosphates, sulphides and oxalates present in e-waste, and these microbes can have special chemical properties such as high metal sorption capacities (Gadd & Xiangliang, 2016).

A study was conducted by (Taeichang, 2011) under which they proposed tetrabromobisphenol-A (TBBPA) debromination and biomineralization using a particular bacterial strain of *Ochrobactrum sp*. collected from e-waste recycling and management site. This bacterial strain exhibited maximal debromination activity occurring at a pH of 6.5, temperature of 35 °C, and rotation speed of about 200 rpm in Luria-Bertani medium. Highest debromination and mineralization activities were achieved using this microbe. Another study conducted by (Das, 2017) suggested gold recovery from electronic waste through different strategies which included (i)treatment of e-waste in order to remove competing metal ions, (ii) adapt the bacteria to high pH environment for its active working, (iii) bioleaching the gold from e-waste, and (iv) biomineralization to obtain the leached gold. Bioleached gold was finally mineralized and precipitated as gold nanoparticles using biomineralization technique using the bacterial strain of *Delftia acidovorans*. In a study scientists proposed that there are several bacterial and fungal species which are used in the bio-mineralization of cadmium, chromium, lead and uranium from e-waste (Achal et al., 2012; Benzerara et al., 2011; Tabak & Lens, 2005) (Table 6).

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Table 6: Biomineralization of e-waste (Achal et al., 2012; Benzerara et al., 2011; Tabak & Lens, 2005)

Microorganism	Microbial Type	Toxic metal removed
1. *Sporosarcina ginsengisoli*	Bacteria	Arsenic (As)
2. *Desulfotomaculum auripigmentum*	Bacteria	Arsenic (As)
3. *Aspergillus flavus*	Fungus	Lead (Pb)
4. *Bacillus fusiformis*	Bacteria	Lead (Pb)
5. *Cupriavidus metallidurans*	Bacteria	Cadmium (Cd)

3.5 Biotransformation

Biotransformation is a process in which there is alteration in the chemical form of a substance from one form to another by various kinds of reactions. In case of harmful metals generated from e-waste, by the addition or subtraction of electrons the oxidation state is changed, due to which change in the chemical properties is also observed (Narayanasamy et al., 2017). There are two methods for the biotransformation technique. Direct reduction using enzymes, under which harmful metal ions from e-waste were reduced by exchange of ions from the enzymes outside the cell structure. Indirect reduction using enzymes was done for immobilizing toxic metal ions from e-waste in subsurface environments by actions of metal-reducing microbes (Tabak & Lens, 2005). Some examples of metal reducing microbes are given in Table 7. Using a facultative anaerobic microbe named as *Shewanella sp*. HN-41 the transformation of heavy metals from soil polluted by e-waste was studied by Ayyasamy & Lee (2012) . Regular research was conducted to calculate the effect of glucose on the biotransformation of metals present in soil. Solubilization rates of various metals such as iron, chromium, arsenic, manganese, lead and aluminum ranged from 3 to 7664 mg per kg at different pH levels. The metal solubilization rate was low at pH of about 7. However, at acidic and basic pH it was found out to be quite high. These results assisted in understanding of metal bio-transformation processes for the amelioration of soils.

Table 7: Biotransformation of toxic metals from e-waste (Lovley & Coates, 1997)

Microorganism	Microbial Type	Toxic metal removed
1. *Anaeromyxobacter sp.*	Bacteria	Uranium (U)
2. *Clostridium sphenoides*	Bacteria	Uranium (U)
3. *Halomonas sp.*	Bacteria	Uranium (U)
4. *Serratia sp.*	Bacteria	Chromium (Cr)
5. *Fusarium oxysporum*	Fungus	Cadmium (Cd)
6. *Rhizopus oryzae*	Fungus	Cadmium (Cd)

IV. CHALLENGES AND FUTURE OUTLINE

Everyday more and more people continuously buy electronic gadgets based on use and throw manner. This increased demand has actually led to the generation of a torrential amount of e-waste. This new emerging area of bioremediation needs more focus and how techniques from these areas can aid microbial treatment of such wastes. There are many hurdles in using microbial biotechnological approaches for e-waste management which could be as follow:

1. The main limitation of microbial treatment is that these methods handle limited amount of e-waste and the microorganisms used in the technique fail to survive for a longer duration due to the hazardous effects of e-waste. Therefore, there is a dire need to concentrate on evolving new and better strains of these microbes, scaling up the current process and speed for e-waste treatment and management. Better strains or communities of microorganisms need to be identified using genetic engineering that can withstand higher concentrations and toxicity of metals from e-waste.
2. Usually, it is seen that the waste materials have heterogeneous mixtures and compositions. Also, e-waste is quite variable in regions of a country and differs from day-to-day, or from season-to-season depending on the behavior and use of the population. Hence, it is very difficult to find appropriate microorganisms that deal with this heterogenous, composition and texture. More research work needs to be focused on the utilization of communities of microbes. Different and new microorganisms having varying functional capabilities that are able to acclimatize to different geochemical and mineralogical situations of the e-waste mixture.
3. Numerous important genetic and metabolic molecular tools for genetic engineering of microbes for enhanced removal of environmental pollutants produced by e-waste have been reported and can be used for the enhancement of efficiency of micro-organisms for e-waste management. Genetic engineering allows the generation of new and improved strains of microbes quite easily and rapidly and also includes engineering of new strains with unique genes, metabolic pathway construction, and by changing the coding sequences of already present genes. However, ethical considerations need to be taken care of before releasing genetically modified organisms (GMOs) into the environment before using such novel strategies for e-waste management. The transfer of the engineered DNA and the stability of GMOs developed are important concerns regarding the effect of their release into the environment. In addition, it is useful to keep record of the genetically engineered DNA with which the GMO has been developed so as to

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record the probable escape of these genes and their likely transmission to other microorganisms.

4. The usage of microbial biotechnology should be confined to the respective social, economic and technical needs and situations of particular areas. For example, if in a particular local area, the situation does not have any defined space for bioleaching then microbial biotechnology approaches that are based on space-requirements bioleaching methods cannot be suitable for that particular area.
5. The microbe based biotechnological approach may not be financially and economically viable at all if the yield produced is not significantly higher as compared to physical and the chemical methods of e-waste handling.
6. Using genomics, proteomics, and metabolomics along with bioremediation would help humans to explore various solutions targeting specific contaminants in e-waste. Moreover, identification, phylogenetic studies as well as the comparison of gene and protein sequences in microbes could be done to remove and recover targeted contaminants from e-waste. These challenges suggest that there are still many paths to be tread in order to overcome the obstacles and apply microbial based biotechnological tools on a significantly higher scale for e-waste management. It is worth to put efforts into the advancement of these microbial technologies to bring the recovery of metals from e-waste sources to an eco-friendly and financially viable platform.

V. CONCLUSION

E-waste is considered the fastest-growing waste in the world. Since the sources of e-waste are voluminous and each and every source has its own form of toxicity and negative influence on life making it necessary to manage it properly. There are many practices currently being followed to reduce the quantity of e-waste. Some of these practices are not economically viable, cost effective and still some others are hazardous to life. Microbial biotechnology involving the use of microorganisms and their products creates exciting possibilities for e-waste management. Using biological techniques, the recovery efficiency can be increased as compared to non-biological thermal or physio-chemical methods that are currently in vogue. The application of microbes in electronic waste management is upcoming area and much needs to be done so that these techniques can efficiently overcome the drawbacks of non-biological methods. Although microbial techniques for e-waste management seem to be eco-friendly, nevertheless, existing lacunae in the studies need to be bridged. A more cohesive approach needs to be followed, bringing ancillary disciplines together. However, there are several opportunities as well as bottlenecks in applying microbial biotechnology strategies to e-waste management such as developing new and efficient strains of microbes, adaptation of microbes to heterogeneous composition of e-waste and use of genetic engineering to produce novel microorganisms with enhanced efficiency for e-waste remediation.

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