Prasenjit Debbarma
Saurabh Kumar
Deep Chandra Suyal
Ravindra Soni *Editors*

# Microbial Technology for Sustainable E-waste Management

Springer

Microbial Technology for Sustainable E-waste Management

Prasenjit Debbarma · Saurabh Kumar ·
Deep Chandra Suyal · Ravindra Soni
Editors

# Microbial Technology for Sustainable E-waste Management

Springer

*Editors*
Prasenjit Debbarma
Department of Botany
Iswar Chandra Vidyasagar College
Tripura University
Belonia, Tripura, India

Deep Chandra Suyal
Department of Microbiology
Akal College of Basic Sciences
Eternal University
Baru Sahib, Himachal Pradesh, India

Saurabh Kumar
ICAR-Research Complex for Eastern Region
Patna, Bihar, India

Ravindra Soni
Department of Agricultural Microbiology
College of Agriculture
Indira Gandhi Krishi Vishwavidyalaya
Raipur, Chhattisgarh, India

ISBN 978-3-031-25677-6 ISBN 978-3-031-25678-3 (eBook)
https://doi.org/10.1007/978-3-031-25678-3



This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Preface

Tremendous technological advancement and a sharp rise in the use of electronic gadgets and items around the globe make e-waste a burning issue. The burden of multifaceted e-waste collection and its proper management is becoming a daunting task to the digital society. Conventional management strategies have a serious setback in terms of security, and safety to the environment as well as human health is a concern. Therefore, the world needs eco-friendly, cost-effective, and sustainable approaches to address this issue on an urgent basis. To this end, microbial technology is a promising tool to curve this burden in a sustainable manner as we have already known about the bioremediation potential of diverse microbes towards xenobiotics polymers and heavy metals over the past few decades.

The present book documents the latest innovations and technological advancements in the field of bioremediation of e-waste, especially for its assessment and roles of diverse microbes for its sustainable management. It comprises 21 chapters, starting with the current e-waste scenario, challenges, and associated opportunities. It is followed by the role of microorganisms in the bioremediation of hazardous materials as well as precious and other heavy metals associated with e-waste. Further, the bioremediation process and its various strategies are also being discussed. Further, the recent advancements in bacteria-, algae-, and fungi-mediated e-waste management are also covered in the book. The role of genetically modified microorganisms in bioremediation is also covered. Besides these, the role of biotechnological approaches for the valorization of precious metals from e-waste is included at the end that must be explored in future. Conclusively, this book, besides discussing challenges and opportunities, reveals the microbe–metal interactions and strategies for e-waste remediation in a different ecosystem.


| | |
|---|---|
| Belonia, India | Prasenjit Debbarma |
| Patna, India | Saurabh Kumar |
| Baru Sahib, India | Deep Chandra Suyal |
| Raipur, India | Ravindra Soni |

# Contents

# Chapter 1
# Current Scenario on Conventional and Modern Approaches Towards Eco-friendly Electronic Waste Management

**Ponnusamy Karthika, G. K. Dinesh, Velusamy Sathya, Sangilidurai Karthika, Murugaiyan Sinduja, Sangilidurai Kiruthiga, Sudha Kannojiya, P. Sakthi Priya, Shiv Prasad, and Ravindra Soni**

**Abstract** In the leap of electronic vehicle era, an enormous amount of electronic trash is produced due to the growing usage of electrical and electronic devices (e-waste), which is one of the ever-increasing urgent issues, especially in developing nations. Many e-wastes are buried, burned outdoors, or discharged into surface water bodies in these nations since there is no infrastructure to handle them properly. Many

The original version of this chapter was revised: Co-authors "Sudha Kannojiya and Shiv Prasad" affiliation has been updated. The correction to this chapter is available at https://doi.org/10.1007/978-3-031-25678-3_22

P. Karthika
Department of Microbiology, Chaudhary Charan Singh Haryana Agricultural University, Hisar 125004, India

G. K. Dinesh (✉) · S. Kannojiya · S. Prasad
Division of Environment Science, ICAR-Indian Agricultural Research Institute (IARI), New Delhi 110012, India
e-mail: gkdineshiari@gmail.com

V. Sathya
Tamil Nadu Pollution Control Board, Chennai 600032, India

S. Karthika
Tamil Nadu Agricultural University, Coimbatore 641003, India

M. Sinduja
National Agro Foundation, Chennai 600113, India

S. Kiruthiga
Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore 560012, India

P. Sakthi Priya
Department of Plant Pathology, Central Agricultural University, East Khasi Hills, Meghalaya 793104, India

R. Soni
Department of Agricultural Microbiology, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh 492012, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_1

developing countries currently use inefficient and highly polluting recycling techniques. Several harmful compounds of e-wastes are detrimental to the environment and endanger human health if disposal processes are not carefully handled. Design for environment cleaner production, extended producer responsibility, standards and labelling, product stewardship, recycling, and remanufacturing are some strategies many nations take to cope with the e-waste stream. This chapter discusses an overview of traditional (landfills and dumps, recycling, thermo-chemical treatment, pyrometallurgical treatment, bio-sorption, bioleaching, bioremediation methods, phytoremediation) and modern techniques (life cycle assessment (LCA), material flow analysis (MFA), and multi-criteria analysis (MCA)) in e-waste management that contribute to the eco-friendly, sustainable management of e-waste.

**Keywords** E-wastes · Heavy metals · Remediation · E-wastes management · E-wastes recycling

## 1.1 Introduction

Electronic wastes (e-wastes) are the remnants of electrical or electronic equipment such as computers, mobile phones, TVs, fans, washers, and dryers that have been abandoned (Rautela et al. 2021). Approximately, 17.4% of the e-waste generated globally in 2019 was properly disposed or recycled. However, the fate of the remaining 82.6% may be disposed without sufficient treatment or recycling since it was not recorded. The development of e-waste worldwide is vital due to the enormous demand for electronic goods in contemporary society. Managing e-waste requires efficient techniques and management means because e-wastes possess of several hazardous components in the form of halogenated compounds like polychlorinated biphenyls (PCBs), tetrabromobisphenol A (TBBPA), polybrominated biphenyls (PBB), etc., and these toxic materials that are harmful to plants, microbes, and humans (Kaifie et al. 2020). The issue is made worse because the informal sector in developing nations manages heavy metals (HMs), such as As, Cr, Cd, Cu, and Hg, which must be treated carefully when deconstructing electronic garbage. Additionally, the e-waste management and treatment methods are inadequate and negatively affect human health directly and indirectly (Ganguly 2016; Garg and Adhana 2019).

Among the hazardous substances found in e-waste include lead, mercury, and brominated flame retardants, to name a few. After extended exposure during risky e-waste recycling methods, these substances cause harm to practically all significant biological systems, including the nerve and circulatory systems, brain development, skin issues, lung cancer, and heart, liver, and spleen damage. This is crucial in the unorganized sector since many unorganized e-waste workers do not adhere to preventative health and safety procedures (Garg and Adhana 2019).

Conventional methods for extracting metals from e-waste can either cause secondary contamination that requires additional treatment or be extremely expensive, whereas the biological technique is more environmentally benign

(Awasthi et al. 2019). Further compared to chemical and physical processes, the equipment required for bioremediation is cost-effective (per unit volume) and minimum (readily available). Furthermore, microbial bioremediation facilitates the complete breakdown of organic toxins into simpler compounds naturally, preventing the pollutants from spreading to other ecological systems (Mudila et al. 2021). Currently, e-wastes are primarily managed by landfills, incineration, and recycling. However, some modern advanced techniques, including management of e-wastes through microbial techniques, are in the developing stage. This chapter discusses the various eco-friendly traditional, current, and advanced techniques in electronic waste management in India and worldwide. It also reviews the harmful materials in e-waste and their possible effects on the environment and human health.

## 1.2 Significance of E-waste in the Current Scenario

E-waste is made up of both hazardous and non-hazardous materials. It qualifies as an "urban mine" since it has a variety of valuable, essential, and non-essential metals that, when recycled, can be used as secondary materials. However, they have negative consequences on health and the ecosystem. According to various studies, unregulated e-waste recycling has recently been linked to an increasing number of harmful health effects. These include undesirable birth results (Zhang et al. 2018), change in neural development (Vymazal 2007), unfavourable effects on learning (Brusseau et al. 2020), DNA damage (Alabi et al. 2012), unfavourable cardiovascular consequences (Cong et al. 2018), adverse respiratory effects (Nti et al. 2020), adverse immune system effects (Vymazal 2007), skin diseases (Seith et al. 2019; Decharat and Kiddee 2020), hearing loss (Xu et al. 2020), and cancer (Davis and Garb 2019). Due to the rising disposable of used and repaired electric and electronic devices, more urbanization and mobility, and further industrialization in other parts of the world, the amount of EEE is increasing. As a result, global EEE consumption weight rises by 2.5 million metric tonnes (Mt) annually on average (excluding solar panels). The top six countries producing the maximum e-waste are Japan, China, the USA, India, Russia, and Germany.

China has the highest amount of e-waste production, with 7.2 million metric tonnes produced, followed by the USA with 6.3 million metric tonnes. Asian continent generated the most electronic waste, followed by America, Europe, Africa, and Oceania, 11.7 Mt, 11.6 Mt, 1.9 Mt, and 0.6 Mt, respectively (Kumar et al. 2017). About 9 million tonnes of electronic trash are produced in the European Union each year and come from computers, televisions, and phones (Pahari and Dubey 2018). Approximately, 40 million metric tonnes of e-waste are produced annually globally, accounting for 5% of all solid wastes (Hazra et al. 2019). America generated 11.3 Mt of electronic garbage in 2016, with 7 Mt coming from North America, 3 Mt from South America, and 1.2 Mt from Central America. E-waste production varies significantly across industrialized and developing nations. In 2016, the wealthiest nations in the world generated an average of 19.6 kg per inhabitant (kg/inh), while the developing nations only produced 0.6 (kg/inh) (Baldé et al. 2017). More than 46 Mt of e-waste was produced worldwide in the year 2017. With an annual growth rate of 3–4%, the amount of e-waste is anticipated to increase to 52.2 Mt in 2021.

Approximately, 4.8 billion individuals, or 66% (67 countries) of the world's population, were protected by national law as of January 2017 in the case of e-waste management. Since 2014, when only 44% (61 nations) were covered, improvements have been made. In 2019, formal documented collection and recycling was 9.3 Mt, and 17.4% of the total amount of e-waste produced. Since 2014, it has increased by 1.8 Mt or generates Mt each year. By 2020, it was predicted that the amount of e-waste generated worldwide would increase to 51.8 million tonnes, according to estimate (Baldé et al. 2017).

According to UNEP, e-waste from computers, mobile phones, and old and outdated televisions might increase by five, eighteen, and two times by 2020 (Leung 2019). Global e-waste production has increased by 9.2 Mt since 2014, and by 2030, it is expected to reach 74.7 Mt, practically rising in just 16 years. As a result, it is not recycled correctly, which results in a loss of materials. According to estimates, 0.6 Mt of e-waste from EU nations is in trash cans (Rotter et al. 2016). A rough estimate of USD 57 billion in raw materials can be found in the global e-waste produced in 2019. The main contributors to its value are iron, copper, and gold. A raw material worth USD 10 billion is recovered from e-waste globally in an environmentally responsible manner with the current documented collection and recycling rate of 17.4% and 4 Mt of raw materials might be made available for recycling. The emissions from recycling secondary raw materials used in place of virgin materials resulted in a net reduction of 15 Mt of $CO_2$ due to recycling iron, aluminium, and copper. Worldwide electronic waste generation will leap from 6.40 Mt per year to 9 Mt per year by 2030 (Fig. 1.1). Global forecast on generation of e-wastes will be 75 million tonnes by 2030 and 111 million tonnes by 2050 (Table 1.1).

## 1.3 Data on Generation and Management in India and Globe

### *1.3.1 Data on Generation*

According to the Indian environmental regulatory authority of the Central Pollution Control Board (CPCB), the growing rate of this e-waste is much faster (Chaurasia 2014). During 2018–19, the e-waste generation was 7.71 lakh tonnes, while in 2019–20, it was 10.14 lakh tonnes, which is a 31% increase. Global e-waste generation and forecast by year is depicted in Fig. 1.1. India is third in e-waste generation after the USA and China (Borthakur 2020). In India, most e-waste is recycled informally, and less than 5% of e-waste volume is handled through the formal sector (Jiang et al. 2020). More than 3000 units are operating informally for e-waste recycling in and around India's big cities. Global e-waste generation continues to rise,

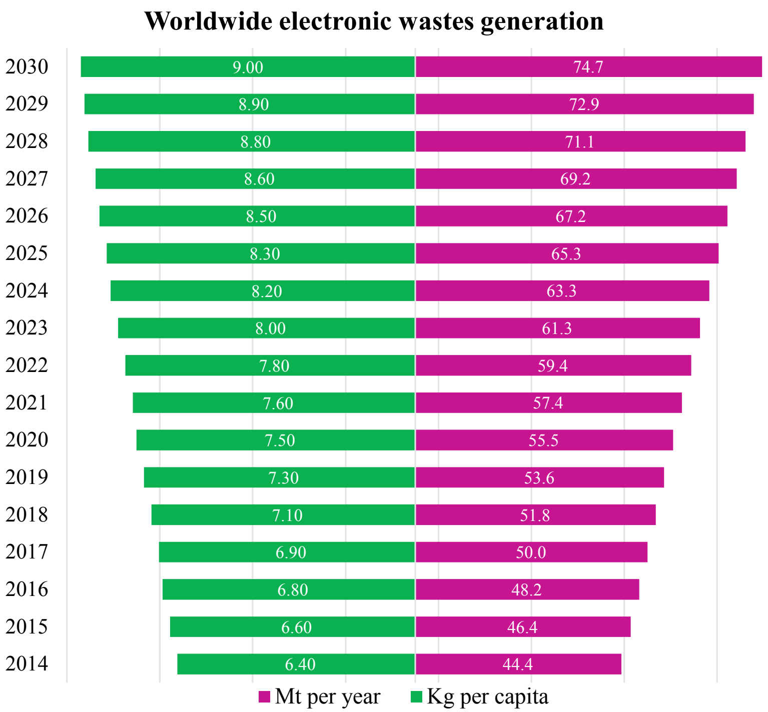



**Fig. 1.1** Global e-waste generation and forecast by year

**Table 1.1** Global patterns of e-waste generation and recycling

| S. No. | Name of the region | Amount of e-waste produced (Mt) | Quantity of e-waste collected for recycling (Mt) | Percentage of e-waste recycled (%) | References |
|---|---|---|---|---|---|
| 1. | Africa | 2.94 | 0.03 | 0.9 | Forti et al. (2020) |
| 2. | Asia | 24.9 | 2.9 | 11.7 | |
| 3. | Europe | 12 | 5.1 | 42.5 | |
| 4. | America | 13.1 | 1.2 | 9.4 | |
| 5. | Oceania | 0.7 | 0.06 | 8.8 | |

and only 17.4% of the world's 53.6 million metric tonnes (Mt) of waste were officially reported as appropriately recycled and managed in 2019 (Forti et al. 2020). In 2016, India dumped over 1.85 million tonnes of e-waste, accounting for approximately 12% of worldwide e-waste generation (Garg and Adhana 2019). The USA generated the highest e-waste of 11.7 million tonnes annually, followed by China with 6.1 million tonnes annually (Mishra 2020).

**Table 1.2** Current status and future forecasting of electronic wastes generation in India and worldwide

| Region | Current status | Future forecast | References |
|---|---|---|---|
| India | 366,705 tonnes/year | 50 million tonnes/year | Ahmed et al. (2014), Parajuly et al. (2019), Herat (2021) |
| Rest of the world | 53 million tonnes/year | 75 million tonnes by 2030, 111 million tonnes by 2050 | |

India has implied limits than China and holds fifth place in the production of electronic garbage. Computers and related accessories account for roughly one-third of e-waste, with others such telecom sector, medical equipment, and electric equipment contributing significantly to yearly e-waste output (Shittu et al. 2021). The industrial sectors contribute 75% of e-waste generation while the household sector contributes 16%. Mumbai tops the e-waste production in India, followed by other metropolitans such as New Delhi, Bangalore, and Chennai. India accounts for roughly 4% of all e-waste generated yearly (Mishra 2020). However, according to a survey by the Associated Chambers of Commerce and Industry of India (ASSOCHAM), only 1.5% of electronic waste produced in India gets recycled systematically. Globally, e-waste production is recorded as 57.4 million tonnes (Mt), while in India, the Central Pollution Control Board (CPCB) estimated that the production would reach 10 lakh tonnes in 2019–20, up from 7 lakh tonnes in 2017–18 (Awasthi et al. 2018a) which is a 31% increase. In contrast, since 2017–18, the capacity for dismantling e-waste has remained at 7.82 lakh tonnes. Among all the regions, Asia produces massive amounts (24.9 Mt) of e-waste (Table 1.1). The current status and future forecasting of electronic waste generation in India and worldwide were tabulated in Table 1.2.

### *1.3.2 E-waste Management in India*

In developing countries like India, methods presently followed for the management and disposal of E-waste potentially affect the environment and human health. The e-waste management scenario in India includes vital concerns such as identifying various stakeholders in the generation and management of e-waste (Sharma et al. 2020a). Since 2011, India has developed legal enforcements to handle e-waste, with requirements including only approved dismantlers and recyclers collecting e-waste. India passed the E-waste (Management) Rules in 2016, and Bhopal, Madhya Pradesh, the nation's first facility for managing e-waste gathered from residential and commercial units, has been established.

The emergence of new technologies and their subsequent upgrades in the various sectors like electrical, electronics, designing, marketing, etc., remarkably shortened the life expectancy of electronic appliances (Kiddee et al. 2013). However, more than 75% of e-waste in India remains untreated due to the indistinctness of the management options (Ramachandra and Saira-Varghese 2004). Generally, e-waste is mixed up with the domestic wastes in the household's disposal points, making it very difficult to segregate them (de Oliveira Neto et al. 2022). An unorganized sector does the majority of segregation with no proper facilities (MoEF (Ministry of Environment and Forests) 2010). Chatterjee (2012) reported that most e-waste, i.e. 95%, is recycled through the informal sector, whereas only 5% is processed through standard units. According to Greenpeace, in 2008, only 3% of e-waste produced in India is collected by authorized recyclers, while the remaining is sent to informal recyclers operated without proper facilities (Bhaskar and Turaga 2018). Gradually, the quantity of recycled e-waste increased to 9.79% during 2017–18. Later, the awareness was raised, and regulations were enforced effectively. As a result, it rose to 21.35% in 2018–19, and 22.7% of e-wastes was recycled during 2019–20 (Panchal et al. 2021). Even though various laws and rules are enforced, less than 25% of the e-waste produced is only recycled systematically. E-waste and solid garbage, according to scientists, are improperly dumped in land and surrounding waterbodies.

Developing countries like India have well-developed networks for e-waste collection, dismantling, and recycling processes but exist as unorganized sectors. They used to collect e-waste from rag pickers and dismantle the reusable components for resale purposes (Srivastava and Pathak 2020). The unorganized sectors are not receiving much attention regarding their stakeholders, social and economic implications, environmental effects, and the health of recycling employees and neighbouring communities (Shaikh et al. 2020). The nation's daily production of municipal solid garbage exceeds 1.6 million metric tonnes (Mt). Depending on population size, cities generate between 0.2 and 0.6 kg of trash per person every day. This is anticipated to increase at a pace of 1.33% annually. It is anticipated that by 2047, 260 million tonnes of trash will be produced annually. By 2047, the country will reportedly need more than 1400 $km^2$ of land, about equivalent to the area of Delhi, if e-waste disposal is not made more orderly and scientifically. India produces more than 8 million tonnes of hazardous garbage annually, of which 4.8 million tonnes (or 60%) are recyclable, and the remaining 3.2 million tonnes (or 40%) are not recyclable (Garg and Adhana 2019). In India, formal recyclers or institutional processing and recycling processes recycle about 1.5% of all the e-waste produced; the remaining 8% is deemed worthless and ends up in landfills (Jeyaraj 2021).

## 1.4 Types of E-waste

Almost all the waste generated by electronic equipment without the intent of reuse is considered e-waste. It is classified into various types according to the source generation and waste management practices. E-waste is divided into ten general categories such as primary household gadgets, little household gadgets, user gadgets, IT and telecommunication gadgets, electric and electronics apparatus, illumination gadgets, toys, leisure and sports gadgets, medical devices, automatic dispensers, monitoring and controlling equipment based on European Waste Electrical and Electronic Equipment Directive (EU Directive 2002). According to the global e-waste

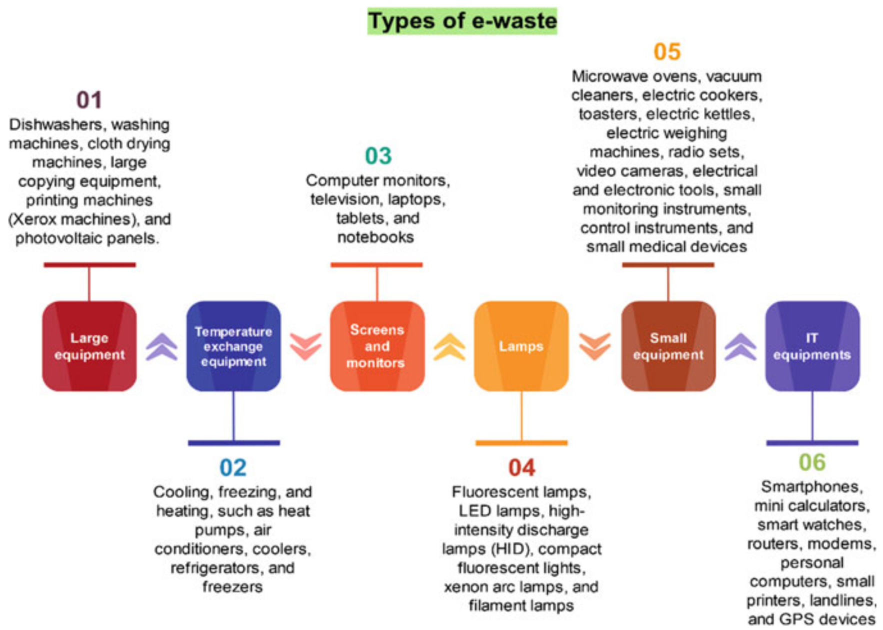



**Fig. 1.2** Classification of e-wastes

monitor (2020) report, electrical and electronic equipment are categorized into six based on their way of management, and there are 54 products included under six general categories according to their material composition, weight, and product life (Forti et al. 2020). The e-waste system does not have any batteries or vehicle-related electrical items. The e-waste categorization complies with the Waste Electrical and Electronic Equipment (WEEE) directive and the e-waste statistics report of the internationally recognized framework. The classification of e-waste is depicted in Fig. 1.2.

### *1.4.1 Large Equipment*

The equipment often used in households and offices includes dishwashers, washing machines, cloth drying machines, large copying equipment, printing machines (Xerox machines), and photovoltaic panels.

### 1.4.2 Temperature Exchange Equipment

The machines in this category are used for cooling, freezing, and heating, such as heat pumps, air conditioners, coolers, refrigerators, and freezers.

### 1.4.3 Screens and Monitors

Equipments like computer monitors, television, laptops, tablets, and notebooks are included in this category.

### 1.4.4 Lamps

This category includes fluorescent lamps, LED lamps, high-intensity discharge lamps (HID), compact fluorescent lights, xenon arc lamps, and filament lamps.

### 1.4.5 Small Equipment

This category includes equipment often used in the kitchen and other uses such as microwave ovens, vacuum cleaners, electric cookers, toasters, electric kettles, electric weighing machines, radio sets, video cameras, electrical and electronic tools, small monitoring instruments, control instruments, and small medical devices.

### 1.4.6 Small Information Technology and Telecommunication Equipment

The small IT and telecommunication category includes smartphones, mini calculators, smart watches, routers, modems, personal computers, small printers, landlines, and GPS devices.

Although the necessity and usage of electrical equipment in the current world are highly mandatory, waste production differs according to the per-capita purchasing capacity, directly reflecting use and e-waste generation. According to Forti et al. (2020), excluding photovoltaic panels, the e-waste generation was around 53.6 million metric tonnes in 2019, and per-capita generation was 7.3 kg. Therefore, it is estimated that e-waste generation will exceed 74 Mt in 2030. The e-waste quantity generated in 2019 comprised 17.4 Mt of small equipment, 13.1 Mt of large equipment, 10.8 Mt of temperature exchange equipment, 6.7 Mt of screens and monitors, 4.7 Mt of small IT and telecommunication equipment, and 0.9 Mt of lamps. Due to increasing consumption in lower-income countries, the weight base generation trend of e-waste primarily consists of temperature exchange equipment (7% annual average increase from 2014) followed by large equipment (> 5%) and small equipment and lamp (> 4%).

## 1.5 Traditional Approaches to E-waste Management

E-waste is a mixture of different product types, each requiring a distinct treatment method (Salhofer 2017). The primary pollutants from e-waste that are released into the air, water, land, and other ecosphere are polymers and VOCs, PCBs, PBDEs, or PAHs, rare earth metals, precious metals (Sn, Au, Cu, Li, Ag, Co, etc.), heavy metals (As, Hg, Cd, Pb, Cr, etc.), which account for 60% of electrical and electronics products, and heavy metals (As, Hg, Cd, Pb, Cr, etc.) (Mmereki et al. 2016; Mudila et al. 2019). Besides being a potential polluter, e-waste is a secondary source of rare metals (Awasthi et al. 2019). The five fundamental steps of the e-waste recycling process are collection, toxins removal, preprocessing, end processing, and disposal (Wang et al. 2012). After collection, the first step in separating harmful from functional components is disassembly or toxic removal. The components are broken during the preprocessing. End processing refers to the final processing of the products, such as re-melting steel scrap in steel mills (Kaya 2016; Nowakowski 2020). The remaining will be disposed of in soil as landfills, incineration, etc. (Vats and Singh 2014). Various e-waste management options are tabulated in Table 1.3.

Bioleaching is a low-cost, environmentally friendly method for extracting metals from various minerals and waste products (Zeng et al. 2016a). Compared to traditional hydrometallurgy and pyro-metallurgy, which use many chemicals and produce much environmental pollution, bioleaching provides some advantages (Zeng et al. 2013). For example, some effective commercial bioleaching plants are currently in operation at the Morenci mine in the USA, which has a capacity of up to 230,000 tonnes per year (Panda et al. 2015). Additionally, it provides a broad overview of the bioleaching process and mechanism, opening the door to creating better and more effective industrial bioleaching operations.

## 1.6 Modern and Advanced Approaches in E-waste Management

The introduction of the waste electric and electronic equipment (WEEE) directive (Directive 2002/96/EC), which is anticipated to reduce the disposal of such waste and enhance environmental quality, has advanced the management of e-waste in

**Table 1.3** Different e-waste management strategies

| Methods | Process | References |
|---|---|---|
| *Physical method* | | |
| Landfills and dumps | Sanitary landfills are the most prevalent method of e-waste disposal. Pits are carved in soil, and impermeable coverings are constructed before burying to prohibit toxic chemicals from leaking<br>Controlled dumps are an alternate way for landfill disposal with a strategically designed load that does not involve cell planning | Li et al. (2009), Kiddee et al. (2013) |
| Recycling via mechanical approaches | The printed circuit boards are disassembled into powdered form and then subjected to eddy current separators for particle separation. The powdered samples are subsequently processed through a density separation technique | Zhang and Forssberg (1997, 1999), Copani et al. (2019) |
| | Individual metal separation in the liquid column may be noticed when density and particle sizes are factored in | Rohwerder et al. (2003) |
| Air classification | Depending on their relative weights, different components are separated. After confirming the parts' physical, electrical, and chemical characteristics, printed circuit boards were subsequently mechanically milled. Air classification was used to efficiently separate Cu and Al from the lighter parts of the e-waste | Laurmaa et al. (2011), Lanzerstorfer (2015) |
| Thermal treatment | Employing heat to process and degrade waste materials in a variety of ways | |
| | Open burning is the primary technique in thermal waste treatment with no emission control systems, causing particles to permeate the surroundings | Sepúlveda et al. (2010), Manhart et al. (2011), Gunarathne et al. (2020) |

(continued)

**Table 1.3** (continued)

| Methods | Process | References |
|---|---|---|
| | Incineration is one of the most frequent processes where e-waste is burned at extreme temperatures and is helpful as a source of energy and heat recovery. Also, e-waste volume is reduced significantly but produces various neurotoxins and carcinogens | Gunarathne et al. (2020), Secretariat (2011) |
| Thermo-chemical method | E-waste is treated at high temperatures with low oxygen using gasification and pyrolysis processes. Pyrolysis uses no oxygen to convert wastes into charcoal, fumes, and oils, whereas gasification uses less oxygen. As a result, the emissions are low compared to other thermal treatments | Shen et al. (2018), Gunarathne et al. (2020), Joo et al. (2021), Khaobang et al. (2022) |
| Pyrometallurgical treatment | Separation of the metals according to their chemical and metallurgical characteristics by high-temperature smelting in furnaces, incineration, combustion, and pyrolysis | Shuey and Taylor (2005) |
| *Chemical/hydrometallurgical methods* | | |
| Acid bath | Circuit boards are immersed in nitric, hydrochloric, or sulfuric acid solutions for a specified period to recover metal | Jha et al. (2011), Birloaga et al. (2014), Needhidasan et al. (2014), Jadhav and Hocheng (2015) |
| Chemical leaching using ligand | Leaching includes the complexometric interaction of ligands and metals. For this, a variety of chelating agents are employed | Pant et al. (2012) |
| Hydrometallurgical etching | Chemicals are employed in the process of hydrometallurgical etching to remove metals. To extract valuable metals, various chemicals are employed, notably $HCl$, $FeCl_3$, and $CuCl_2$ | Barbieri et al. (2010), Pant et al. (2012) |

(continued)

**Table 1.3** (continued)

| Methods | Process | References |
|---|---|---|
| *Biological methods for extracting metals* | | |
| Biosorption | The leaching and recovery of precious metals (palladium, gold, and platinum) from the liquid waste of PCBs is the primary application of the biosorption process | Ma et al. (2006), Brandl et al. (2008), Sheel and Pant (2018) |
| Bioleaching | Microbes change heavy metals that are not soluble into soluble forms that may be extracted | Patel and Kasture (2014) |
| *Bioremediation methods* | | |
| Bioaccumulation | Deposition of foreign pollutants in living organisms, which results in biomagnified. Microbes ingest contaminants through their importer complexes (lipid bilayers), which are then trapped by metal-binding sites (polyphosphates, peptides, etc.) | Diep et al. (2018) |
| Bioventing | To enable the safe microbial transformation of metals, etc., oxygen, nutrients, and moisture are allowed to circulate to unsaturated regions, increasing the activities of native bacteria | Philp and Atlas (2005) |
| Bioattenuation and bio-augmentation | Microbes are selected from the remediation site (those that grow well in the contaminated sites), cultured or genetically modified, and then returned to the remediation sites in bioaugmentation. In contrast, in bioattenuation, physical/natural phenomena and chemical reactions are used to promote the growth and activity of the microbes in the chosen polluted sites | Singh and Lin (2010), Chatterjee (2017), Mudila et al. (2021) |
| Biotransformation | Chemical conversion of one molecular structure to another changes their chemical characteristics and reduces their toxicity | Patel and Kasture (2014) |

(continued)

**Table 1.3** (continued)

| Methods | Process | References |
|---|---|---|
| Biostimulation | It encompasses adding desirable nutrients and controlling environmental factors in the pollutant-affected location to promote biomass | Chen et al. (2010), Mudila et al. (2021), Li et al. (2022) |
| Nano-remediation | Nanoscale-zero-valent iron particles are now being used for remediation and showing tremendous potential. Iron nanoparticles readily break and immobilize Cr(VI) and Pb(II) from aqueous solution, reducing Cr(VI) to Cr(III) and Pb(II) to Pb(0) while oxidizing Fe to goethite (R-FeOOH) | Ponder et al. (2000), Zhang (2003), Tratnyek and Johnson (2006), Karn et al. (2009), Karthika et al. (2019) |
| Phytoremediation | The potential of plants, whether native or genetically engineered, to be employed in environmental decontamination and e-waste remediation | Alkorta and Garbisu (2001), Campos et al. (2008), Sinduja et al. (2022a, b) |

industrialized countries (Directive 2003). The research includes the separation of components that could be recycled and the recovery of rare and precious electronic waste. It is also a systematic technique for defining numerous environmental effect categories, including carcinogens, climate change, ozone layer, ecotoxicity, acidification, eutrophication, and land usage, to enhance the environmental performance of products. Furthermore, Scharnhorst et al. (2005) investigated environmentally suitable EoL treatment options for mobile phone devices. Six EoL therapy scenarios were used to discover that reusing material reduces mobile phones' adverse environmental effects.

Furthermore, an EoL personal computer's actual recycling rate was researched, and its environmental impact was evaluated by Choi et al. (2006). There were two options for disposal: landfill or recycling, which were discussed above. And there are several tools for managing electronic waste followed by different countries. To manage e-waste, several tools such as (i) life cycle assessment (LCA), (ii) material flow analysis (MFA), (iii) multi-criteria analysis (MCA).

### *1.6.1 Life Cycle Assessment (LCA)*

E-waste disposal demonstrated that recycling is the most cost-effective method of disposal. Economic factors, perceived risk, and environmental effects were assessed using LCA (Li et al. 2019a). The researchers revealed that a computer desktop's optimal life cycle was 25% shorter than its optimized cost and its optimized value of its waste impacts on the environment and any perceived risk to the general population. Recycling, as opposed to landfilling or incineration, is the preferred method for managing e-waste, according to studies employing LCA in several nations. Therefore, LCA is frequently utilized for managing e-waste (Pokhrel et al. 2020). The outcomes demonstrated that, in comparison to incineration, the e-waste recycling system and take-back were undeniably advantageous from an environmental perspective (Liu et al. 2020). A software tool life cycle assessment is used to create electronic products that are less harmful to the environment, reduce e-waste issues, and manage electronic waste. Much research has been done on the LCA of electronic devices in terms of eco-design, product development, and environmental effect since 2015. A superior alternative product is one with an environmentally friendly design, which may also appeal to customers. To create eco-design items, such as printers (Pollock and Coulon 1996), desktop computers (Kim et al. 2001), heating and cooling units (Prek 2004), washing machines (Park et al. 2006), and toys (Muñoz et al. 2009), it is essential to evaluate the potential environmental implications and management of such E-waste.

### *1.6.2 Material Flow Analysis (MFA)*

MFA tools create effective e-waste management (Tutton et al. 2022). A technology called material flow analysis (MFA) is used to track the flow of materials (including e-waste) into recycling facilities, trash disposal locations, and material stockpiles through time and space (De Meester et al. 2019). It establishes connections between the material's sources, distribution channels, and end destinations. MFA is a tool for environmental and waste management decision-making (Paul and Helmut 2004). This involves considering how e-waste is generated and evaluating its effects on the environment, economy, and society. MFA and the assessment of economic values were utilized by Streicher-Porte et al. (2007) to conduct system analysis and recycling of personal computers in India. They discovered that the high value of these metals and the concentration of Au and Cu led to profitability for recyclers. The study combining MFA and economic evaluation can be a valuable technique when there is a lack of data and rapid economic growth (Arain et al. 2022).

### *1.6.3 Multi-criteria Analysis (MCA)*

Multi-criteria analysis (MCA) is a tool for making judgments considering problem qualitative and quantitative components while tackling complex multi-criteria problems (Garfi et al. 2009). Environmental challenges, such as e-waste management, have been given optional e-waste management options using MCA models (Gollakota et al. 2020). For instance, Hula et al. (2003) used MCA decision-making techniques to weigh the environmental benefits against the financial gains from the EoL processing of E-waste management (Islam et al. 2021a). The following steps were part of a six-step technique that looked at EoL scenarios, defined product models, created an EoL evaluation model for electronic waste, and formulated multi-objective challenges. They developed EoL strategy graphs for the e-waste of optimal EoL strategies that minimize environmental impacts and financial costs (Gautam et al. 2022). MCA was employed by Queiruga et al. (2008) to determine the ideal location for e-waste recycling facilities in Spain. Using the MCA technique, Rousis et al. (2008) examined the various methods for handling e-waste in Cyprus and followed modern e-waste management in different countries (Sharma et al. 2020a). The best alternative was to partially disassemble the product, send the recyclable parts to the local market, and dispose of the rest in landfills (Zanghelini et al. 2018). MCA is frequently used for managing solid and hazardous waste, even though it is not generally used for managing e-waste (Hatami-Marbini et al. 2013). MCA is valuable in conjunction with other tools for managing e-waste because it has been suggested for the societal reaction to e-waste management in many countries (Williams 2005).

According to the polluter pays principle, extended producer responsibility (EPR) holds producers responsible for recovering products after use (OECD 2001; Widmer et al. 2005). In order to permit the return of goods for processing and recycling, the WEEE Act was established in 2004. In 1991, the EU designated e-waste as a priority waste stream. As a result, the WEEE Directive of the European Union established regulations based on EPR 2002/96/EC. The legislation defines producers' accountability for managing e-waste downstream and promotes environmentally sound end-of-life reuse, recycling, and recovery of e-waste (Directive 2003). The EU recognized e-waste as a priority waste stream in 1991, and the WEEE legislation was created in 2004 to allow for the return of products for processing and recycling. Regulations based on EPR were created by the European Union's WEEE Directive 2002/96/EC (Habib et al. 2022). The legislation defines producers' accountability for managing e-waste downstream and promotes environmentally sound end-of-life reuse, recycling, and recovery of e-waste (Directive 2003). It was the first to be in charge of a product's whole life cycle, from design to garbage, and it prompted import restrictions on all used electronic gadgets for charitable purposes as well as a provision to reduce the use of certain dangerous compounds in electronic devices (Ibanescu et al. 2018).

The key to effective e-waste management is eco-design of devices, proper e-waste collection, material recovery and recycling, proper e-waste disposal, prohibiting the export of used electronic devices to developing nations, and increasing consumer and manufacturer awareness of the adverse effects of e-waste pollution. Most industrialized nations currently employ this strategy regularly. In contrast, emerging countries and those in transition have not yet persuaded local communities to adopt such management techniques for E-waste (Maheswari et al. 2020). The next generation's education could be a step towards managing e-waste in industrial countries.

## 1.7 Environmental Damages and Problems

A complex mixture of pollutants could be released during the handling and processing of e-waste in several different environmental matrices. Depending on the procedures and protective measures, these discharges may be more or less substantial. According to the types, ages, and handling and processing of the e-waste, contaminants are emitted in highly heterogeneous combinations with various compositions.

A complicated assemblage of several hundred tiny parts, many of which contain hazardous chemicals, make up electronic products. Both the environment and human health are put under stress by these pollutants. The majority of lead, cadmium, mercury, polyvinyl chloride (PVC), brominated flame retardants (BFRs), chromium, beryllium, and other toxic materials are present in electronic device components. In addition, these e-wastes will have long-term environmental consequences if inappropriately disposed of incinerated/landfilled instead of recycled with residential waste, contaminating the soil, water, and air.

Direct and indirect exposures to contaminated soil, air, dust, and water near e-waste recycling facilities can come from improper e-waste recycling and unlawful disposal activities, which can then impact the biota zone. The processes that cause environmental biogeochemical fluxes include atmospheric deposition (dry/wet), leaching, adsorption–desorption, complexation (during which secondary products like heavy metal–organic matter aggregations can form), plant uptake, chemical/biological degradation, and volatilization (in air/soil).

### *1.7.1 Effect on Soil*

Acidification of the soil occurs when acids and sludge from melting computer chips are dumped on the ground. Landfills that are not adequately inspected may pose environmental risks. When plastics containing brominates or polymers that are flame retardant or contain cadmium are landfilled, polybrominated diphenyl ethers (PBDE) and cadmium may leak into the soil and groundwater. Improper e-waste disposal affects soil fertility since it includes few chemical and hazardous compounds that are not decomposable for a long time (Pant and Kumar 2018).

Large amounts of persistent organic pollutants (POPs), such as polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and dioxin, will be released into the environment during the processes of informal e-waste recycling or disposing of like uncontrolled dumping and combusting. Persistent organic pollutants (POPs) can quickly accumulate inside living things, move through soil food or water food cycles, and are generally stable in the natural environment (Shi et al. 2019). Typically, soils from the e-waste recycling zone unintentionally release PCBs, PAHs, and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) into the environment (Shi et al. 2019).

### 1.7.2 Effect on Air

E-waste incinerators have the potential to release hazardous gases and pollutants into the air, greatly contaminating it. The highly toxic consequences of open-air burning influence the local ecosystem, and more importantly, global air currents, depositing them in numerous locations worldwide. The burning of the PCB and other plastic components of electrical gadgets emits acutely poisonous gaseous dioxins and furans, endangering key ecosystem components (Wang et al. 2005; Awasthi et al. 2016). In regions with open flames, numerous e-waste pollutants dissipate into the air as dust or fume, dominating human exposure pathways through inhalation, ingestion, and skin absorption. Studies have also shown that halogenated flame retardants (HFRs) and polychlorinated biphenyls (PCBs) from e-waste recycling sites cause bioaccumulation in wildlife (Li et al. 2019b; Peng et al. 2019).

Severe consequences of air pollution by improper e-waste management include ozone layer damage and global warming (Gangwar et al. 2019; Rautela et al. 2021). Greenhouse gases are released when raw materials are extracted and purified from e-waste. Chlorofluorocarbons (CFCs) are greenhouse gases that raise the earth's temperature and are found in refrigerants and other temperature exchange devices. The ozone layer, a shield encircling the earth, is weakened by CFCs, allowing dangerous UV radiation to enter. UV exposure can cause many conditions, including cataracts, weakened immune systems, and cancerous skin growth. In addition, 98 million metric tonnes of carbon dioxide equivalents were released into the environment due to improper management of abandoned cooling and freezing equipment (Forti et al. 2020).

### 1.7.3 Effect on Water

E-waste disposal is a problem prevalent in many parts of the world—landfilling computer waste results in contaminated leachates that eventually affect groundwater. For example, Guiyu, Hong Kong, a significant centre of illegal e-waste recycling, is experiencing severe water shortages due to tainted water sources. This results from recycling wastes like acids and sludge being dumped in rivers. As a result, water is now being carried from remote towns to meet the population's needs.

One cell phone battery's cadmium concentration can contaminate 600 $m^3$ of water. In addition, through processes of effluent leaching and diffusing from electric and electronic equipment (EEE) dumping industries or other e-waste disposal locations, processed e-waste toxins can reach aquatic systems (both groundwater and surface water), contaminating the aquatic biota as well. Acidification can kill marine and freshwater organisms, disturb biodiversity, and harm ecosystems.

When lead, barium, mercury, lithium, and other heavy metals from electronic equipment are improperly disposed, they can leak into the groundwater and flow with rainwater, causing water contamination. As a result, small ponds and rivers that receive this water become contaminated (Awasthi et al. 2018b).

### 1.7.4 *Effect on Human Health*

Poor e-waste processing has long-lasting effects beyond those that directly affect human health (Roychowdhury et al. 2019) (Fig. 1.3). Ingesting food cultivated on soil contaminated with E-waste also has indirect health effects (Tiller 1989). Similar to open incineration, acid leaching of E-waste exposes harmful gases into the environment, causing death or permanent damage to the respiratory organs of those involved in the process as well as the local population (Babu et al. 2007; Kiddee et al. 2013; Patil and Ramakrishna 2020).

Once these dangerous compounds of e-waste are introduced into the body, they may accumulate in the fatty tissues and have an adverse impact on the health of nearby residents who live close to unregulated e-waste industries (Zeng et al. 2017; Zhang 2017; Liu et al. 2018). In addition, there may be secondary exposure dangers in remote places due to the alleged long-term transmission of pollutants (Peng et al. 2019). For example, a decline in topsoil fertility brought on by heavy metal contamination in the soil penetrates the food chain. Additionally, metal exposure can lead to genotoxicity, which alters the genetic code and results in diseases like cancer. Children, pregnant women, and workers in processing facilities are most at risk of being impacted.

The environment and people are significantly impacted by the massive influx of e-waste, alongside the reduced collection, reuse rates, incorrect disposal, and management of this e-waste debris. In addition to being the largest producers of e-waste, developing nations with rapid economic expansion, like China and India, are also regarded as the global market for discarded e-waste (Pathak and Srivastava 2017; Zeng et al. 2017). The top recipients of e-waste from developed nations are China, Peru, Ghana, Nigeria, India, and Pakistan (Mmereki et al. 2016). Every living thing is adversely affected when e-wastes are discharged into the atmosphere. Anything that comes into contact with poorly regulated e-waste is at risk. Large quantities of e-waste materials and by-products are dumped in open fields along riverbanks, rivers, wetlands, and irrigation ditches without recycling. The poisoning of drinking water sources has been made worse by indiscriminate dumping and landfills. Dumping in open fields contaminates soil, thus harming grasses, herbs, plants, bushes, trees, and other cash crops. When electronic waste is burned or incinerated, it emits fumes, fly ash, and tiny particles into the air that are harmful to human and animal life when inhaled/exposed (Jeyaraj 2021).

Human exposure to e-waste may modify thyroid function, harm neonates, change cellular function and expression, cause psychological changes in behaviour and temperament, and even cause a decline in lung function (Huang et al. 2016). Leachates can enter the cell and change the pH inside and outside, impacting the

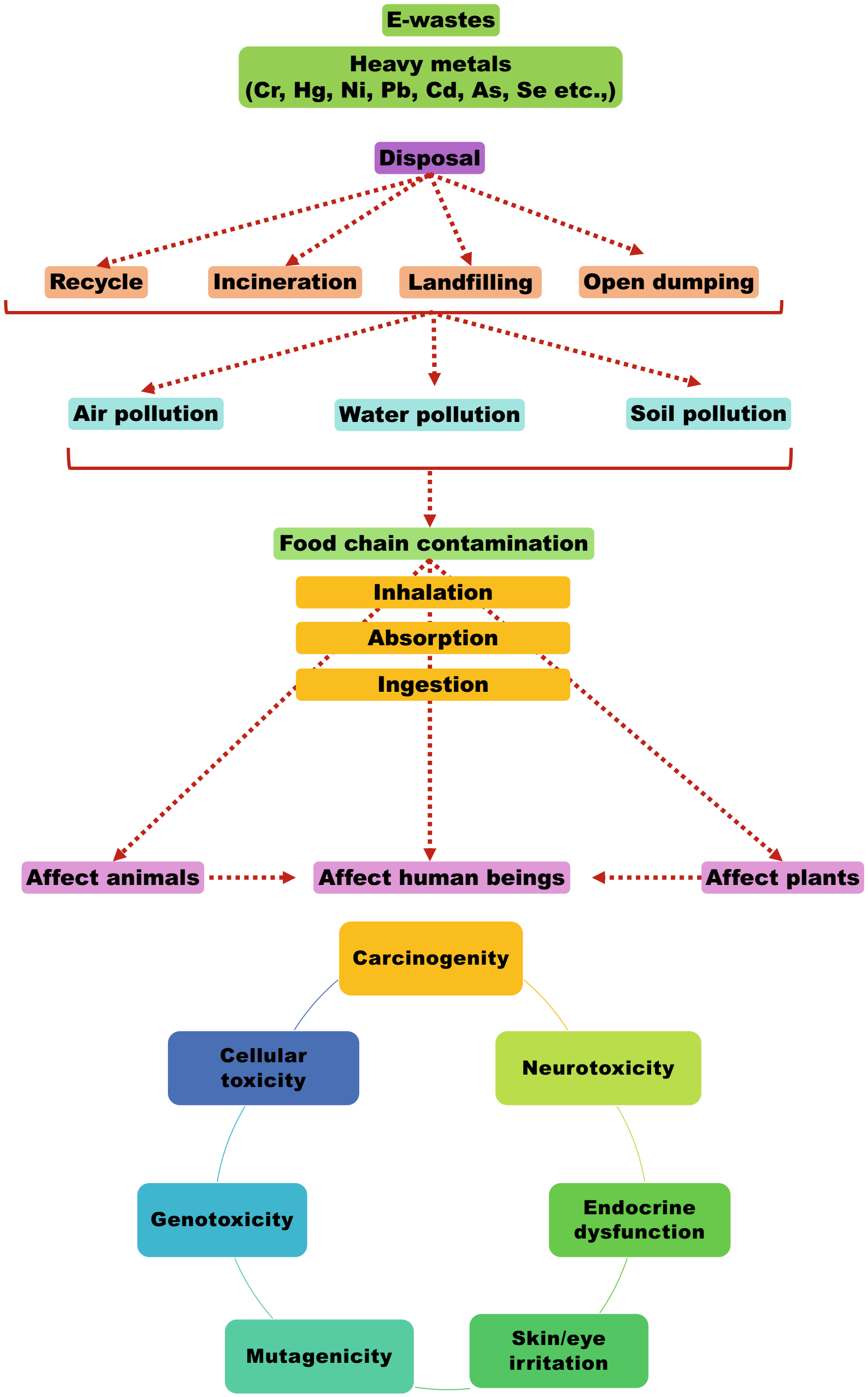



**Fig. 1.3** Impacts of electronic waste on human health

enzymes and changing the DNA's structure (Youcai 2018). Due to recycling e-waste, a significant amount of lead was found in children's blood. IgE is produced as a result, which causes asthma in people and a weakened immune system that makes it difficult for the body to fight off diseases like hepatitis (Xu et al. 2015a; Zeng et al. 2016c). Long-term consumption of these substances or their accumulation in the body for a prolonged period can result in neurological, physical, and muscular degeneration, which may lead to Parkinson's disease, Alzheimer's disease, multiple sclerosis, and muscular dystrophy (Mohod and Dhote 2013).

Various metals have different harmful effects on people. For instance, lead (Pb) has a negative impact on behaviour and cognitive capacities (Sharma et al. 2020b), copper impairs liver function (Danzeisen et al. 2007), and excessive levels of cadmium can lead to lung cancer and kidney damage (Ebrahimi et al. 2020). Even the unborn were affected by e-waste toxins after being exposed in gestation. According to a study using umbilical cord blood lymphocytes and epigenome-wide DNA methylation analyses, high levels of heavy metals were significantly linked to abnormal DNA methylation in 79 genes that are involved in a variety of biological processes, including calcium ion binding, cell adhesion, and embryonic morphogenesis, as well as signalling pathways that are associated to NFkB activation, adherens junction, TGF beta, and apoptosis (Zeng et al. 2019). Additional data analysis suggests that high lead exposure may have hampered the growth of brain neurons in the developing embryos. The same researchers found a connection between preschool children's sensory integration issues and high levels of lead exposure from e-waste sites (Cai et al. 2019). In addition, neonatal development was impacted by increased maternal urine PAH metabolites, which were substantially linked to decreases in new-born weight, head circumference, BMI, and Apgar 1 score (Huo et al. 2019).

Children with recurrent wheezing might have an impaired antioxidant system due to increased serum levels of lead and mercury and low levels of zinc and selenium (Hasan Razi 2011). According to population studies, exposure to heavy metals is associated with hypertension, endothelial damage, arteriosclerosis, and cardiovascular problems (Zeng et al. 2016b). PBDD/Fs are lipophilic and can accumulate in the human body via the food chain (Dai et al. 2020). Incineration of e-waste converts PBDEs into PBDDs and PBDFs, the anthropogenic carcinogens that remain very long (Table 1.4). As a result, long-term health hazards are linked to several genetic abnormalities and other adverse effects, like contamination of human breast milk (Darnerud et al. 2001; Devika 2010).

## 1.8 Regulations Mechanism of E-waste in India and Other Countries

The level of preparedness for handling e-waste and regulations for managing e-waste through laws, rules, and other legal means are essential in both developed and

**Table 1.4** Common hazardous materials found in e-waste and how they affect health

| Substance | Use | Health impact | References |
|---|---|---|---|
| Antimony (Sb) | A melting compound in cathode ray tube glass, plastic computer housings, and a solder alloy in cabling | Antimony has been classified as a carcinogen. It can cause stomach pain, vomiting, diarrhoea, and stomach ulcers through inhalation of high antimony levels over a long period | Herat (2008), Sundar and Chakravarty (2010) |
| Arsenic (As) | Gallium arsenide is used in light-emitting diodes | It has chronic effects that cause skin disease, lung cancer, improper nerve signalling, and damage to the digestive system | Kapp Jr. (2016), Sharma et al. (2020b) |
| Barium (Ba) | Sparkplugs, fluorescent lamps, and vacuum tubes with CRT gutters | Causes short-term exposure that results in heart, liver, and spleen damage and brain oedema, muscular weakness | Oskarsson and Reeves (2015), Peana et al. (2021) |
| Beryllium (Be) | Power supply boxes, motherboards, relays, and finger clips | Exposure to beryllium can lead to berylliosis, lung cancer, and skin disease. Beryllium is a carcinogen | Edmunds (2011), Adanu et al. (2020) |
| Brominated flame retardants (BFRs): polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), and tetrabromobisphenol (TBBPA) | BFRs are used to reduce flammability in printed circuit boards and plastic housings, insulating material in cables and keyboards | Printed circuit boards and plastic housings release noxious vapours during combustion that are known to induce hormonal problems. It may cause impaired memory function, foetus learning, and endocrine disorders | Jarema et al. (2015), Wang et al. (2020), Arvaniti and Kalantzi (2021) |
| Cadmium (Cd) | Infrared detectors, semiconductor chips, rechargeable batteries, and printer ink and toner | The risk of irreversible effects on human health from cadmium compounds is most remarkable for the kidneys. Long-term exposure cause lung cancer and lower cognitive skill in children | Cao et al. (2009), Chen et al. (2011), Liu et al. (2018) |

(continued)

**Table 1.4** (continued)

| Substance | Use | Health impact | References |
|---|---|---|---|
| Chlorofluorocarbons (CFCs) | Cooling equipment and foam insulation | These substances impact the ozone layer, leading to greater skin cancer incidence | Kiddee et al. (2013), Karim et al. (2018) |
| Hexavalent chromium/chromium (Cr VI) | Plastic computer housing, cabling, hard discs, and as a colourant in pigments | Very harmful to the environment, causing DNA damage and permanent eye impairment, causes bronchitis, kidney, and liver damage | Hasan Razi (2011), Xu et al. (2015b), Kuntawee et al. (2020) |
| Lead (Pb) | Printed circuit boards, fluorescent bulbs, wiring, cathode ray tubes, lead acid batteries, and solder | Can harm the kidneys, reproductive system, nervous system, brain, asthma, cause a decline in the immune system, and create blood abnormalities. Low levels of lead can harm the brain and neurological system in foetuses and young children. The consequences of lead build-up in the environment on human health are both immediate and long-term | Sivaramanan (2013), Zeng et al. (2016b), Sharma et al. (2020b), Meem et al. (2021) |
| Mercury (Hg) | Batteries, backlight bulbs, lamps, flat panel displays, switches, and thermostats | Mercury can harm the brain, kidneys, skin, and unborn children | Budnik and Casteleyn (2019), Beula and Sureshkumar (2021) |
| Nickel (Ni) | Batteries, computer cases, the cathode ray tube, and printed circuit boards | It can cause behavioural disorders, allergic reactions, bronchitis, decreased lung capacity, and cancer | Leung (2019), Kuntawee et al. (2020) |
| Polychlorinated biphenyls (PCBs) | Condensers, transformers, and heat transfer fluids | In addition to harming human livers, PCBs cause cancer in animals. Endocrine system and immune system disorder | Kaifie et al. (2020), Verma (2020), Montano et al. (2022) |

(continued)

**Table 1.4** (continued)

| Substance | Use | Health impact | References |
|---|---|---|---|
| Polyvinyl chloride (PVC) | Keyboards, cables, monitors, and plastic computer cases | Hazardous chemicals and dangerous air pollutants are present in PVC. The incomplete combustion of PVC releases enormous amounts of hydrogen chloride gas which form hydrochloric acid after combination with moisture. Respiratory issues might be brought on by hydrochloric acid. It causes cancer, diabetes, endometriosis, and immune system abnormalities | Owusu-Sekyere (2018), Boyle et al. (2020) |
| Selenium (Se) | Old photocopiers | Elevated concentrations result in selenosis, hair loss, and nail brittleness | Laur et al. (2020), Cheng (2021) |

developing nations (Abalansa et al. 2021). The Environment (Protection) Act of 1986 is a broad act, and e-waste regulations are solely the responsibility of the EPA.

### *1.8.1 Regulations for E-waste Management in India*

India faces significant difficulty in managing e-waste effectively. The principal Acts and Regulations for E-Waste Control are given as

- The Batteries (Management and Handling) Rules, 2001
- The Environment Impact Assessment Notification, 2006
- The Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016
- The E-Waste Management Rules, 2016
- The Battery Waste Management Rules, 2022.

The e-waste legislation/regulations/guidelines listed are well-known and substantial endeavours. The Environment (Protection) Act, the first comprehensive environmental law, was passed in 1986 in reaction to the Bhopal Gas Tragedy (Anju et al. 2010). The Hazardous Waste (Management and Handling) Rules and the Batteries

Waste (Management and Handling) Rules are two specific restrictions established under laws concerning e-waste for possible extent. E-waste is not mentioned in the Indian Municipal Solid Wastes (Management and Handling) Rules of 2000 (Singh et al. 2018). In E-waste Management Rules, 2016, by obtaining extended producer responsibility (EPR) authorization, producers are now responsible for managing a system of e-waste collection, storage, transportation, ecologically responsible disassembly, and recycling (Gupt and Sahay 2019). The central government can authorize the treatment or repurposing of hazardous waste. The HWM Rules were amended in 2000 to incorporate import or export requirements of e-waste, expanding their scope (Arya and Kumar 2020). The most current attempt to control e-waste in India is the E-waste (Management and Handling) Rules 2011 (Awasthi et al. 2018a) and Battery Waste Management Rules 2022. Lack of knowledge about the effects of inappropriate e-waste disposal is another challenge in applying the new criterion (Patil and Ramakrishna 2020). Informal recycling of e-waste dominates the sector, making up 90–95% of overall recycling (Chakraborty et al. 2018). Market actors are incentivized to avoid compliance by selling harmful material to informal recyclers, and recyclers can pay more for e-waste (Ganguly 2016). Increasing operational expenditures to organized recyclers already fighting to continue will make organized management difficult (Kumar and Singh 2013).

### *1.8.2 E-waste Regulations—European Union of Countries (EU)*

The EU has tackled e-waste issues and has comprehensive and progressive e-waste regulations since the 1990s. For example, the EU passed the e-waste directive/legislation in 2003 to change product designs, increase recycling rates of discarded e-waste, and restrict the use of some dangerous compounds (Kumar and Singh 2013). In addition, higher target for e-waste collection, proper monitoring standards, and implementation of legal provisions for segregating new, used, and recycled trash items have all been implemented to combat the mismanaging of e-waste (Skinner et al. 2010).

### *1.8.3 E-waste Regulations—USA*

E-waste policies in the USA have undergone fragmented creation and passage of directives, laws, and regulations because of no federal law, particularly the country's management or export of e-waste (Gollakota et al. 2020). The law mandates that anybody who manages or disposes of or ships hazardous waste obtain permission from the EPA or approval from importing countries (Ajibo 2016). Because the federal government does not consider most e-waste hazardous, American recyclers are free to ship the devices overseas (Arain et al. 2020). Individual states in the USA have also started to address their e-waste problems through adequate regulatory and management systems (Kahhat et al. 2008). For starters, while state recycling restrictions are limited in scope, exports are expanding, and the rate of e-waste collected for recycling has been enhanced nowadays (Xavier et al. 2021). The fact that American recyclers and manufacturers export electronic waste to developing and transitional nations may cause the country's deliberate inaction. These nations' recyclers can extract valuable materials more affordably due to more readily available labour, and the ill effects are also transferred (Kumar and Singh 2013).

### *1.8.4 Regulations in China Regarding E-waste*

The government of China has released a flurry of laws, rules, standards, technical directives, and guidelines for the disposal of e-waste over the decade (Schumacher 2016). China has ratified two international environmental treaties: The Basel Convention on the Control of Transboundary Movements and the Disposal of Hazardous Wastes and the Basel Ban Amendment Technical Policy on Pollution Prevention and Control of WEEE, the second significant policy was established in 2006 with the goals of lowering the amount of e-waste, increasing the rate of utilization of electronic equipment, and enhancing the standards for recycling of e-waste (Li et al. 2006). The 3R principle, which stands for reduce, reuse, recycle, and polluter pays, was developed to take environmental precautions to reduce pollution due to storing, reusing, recycling, and disposing of e-waste (Gaur et al. 2022). The specification for the pollution aspect in e-waste management is also provided (Wang et al. 2013). In addition, the rules establish a fund to finance official e-waste collection and recycling (Zeng et al. 2017).

### *1.8.5 E-waste Legislations in Korea*

In Korea, 9455 thousand tonnes of expected e-waste were generated in 2017. The industrial laws and legal initiatives for e-waste management must also consider their impact on ecology and pollution control that include requirements for indirect restrictions for e-waste (Ilankoon et al. 2018). The particularly accessible efforts for e-products and e-wastes are also taken. For example, to encourage producers to recycle their e-waste and inform the government of their findings, the act on the Promotion of Saving and Recycling of Resources was introduced in 2003. The act includes provisions for recycling design and production considerations to eliminate hazardous substances, design products to be easily dismantled, and use easy-to-recycle substances in an environmentally pleasant collection, treatment, and recycling environment (Wath et al. 2010).

### 1.8.6 E-waste Regulations in Bangladesh

Utilizing electronic equipment is an everyday activity in Bangladesh, according to the country's status of e-waste. Bangladesh created its National Environmental Policy in 1992 to govern all actions that degrade and affect the environment (Alam and Bahauddin 2015). The Electrical and Electronic Waste (Management and Handling) Rules, 2011, are the most recent initiative and include the following elements (Khuda 2021). The regulation provided by various schedules are as follows: Schedule 1 discusses the categorization of e-waste, whereas Schedule 2 lists the products that fall into the various categories stated in Schedule I, and Schedule 3 addresses the use of particular hazardous chemicals and their threshold limits. In addition, Bangladesh has signed the Basel Convention, which prohibits the transboundary transfer of hazardous waste (Ananno et al. 2021).

### 1.8.7 Extended Producer Responsibility (EPR)

EPR has been seen as a promising alternative to traditional waste management strategies. However, companies find it expensive and infeasible to operate their EPR activities. Therefore, they contract them to third parties known as producer responsibility organizations (PRO). In a few nations, EPR initiatives have included many items (Mazhandu et al. 2020). Packaging material was one of the first goods to be included, which was introduced in Germany in the 1990s and is currently used in several nations, including the UK, Japan, and Slovakia (Rautela et al. 2021). WEEE is now included in EPR policies in several countries, including the Netherlands, Japan, Switzerland, South Korea, the USA, Taiwan, Colombia, China, Thailand, India, and Argentina (Bhadra and Mishra 2021). In India, EPR is confined to plastic and electronic waste (E-Waste). The Plastic Waste Management Rules and the E-Waste Management Rules in India contain the criteria for EPR implementation (Arya and Kumar 2020). In India, EPR is described as "the producer's duty for the ecologically sound management of the product to the end of its life" (MoEF (Ministry of Environment and Forests) 2010). WEEE scope varies by country, with some including only mobile phones and small equipment and others including large equipment such as air conditioners and refrigerators. Old lead acid batteries (ULAB), polyethylene terephthalate (PET) bottles, metal cans, used oil, oil containers, oil filters, end-of-life vehicles (ELV), end-of-life tyres, and glass are also included (bottles). A wide range of factors led to the success of EPR in various countries around the world (Bhadra and Mishra 2021).

## 1.9 E-waste Management Relevance in SDG and Ecosystem Restoration

Electronic waste generation is increasing gallopingly, and it is now expanding faster in the world than any other waste. The primary forces behind this tendency are rapid socioeconomic progress and technical innovation (Hossain et al. 2015). As a result, the quantity of e-waste is increasing, yet not enough of it is being recycled. Only 20% of the 44.7 million metric tonnes (Mt) of e-waste produced worldwide in 2016 was appropriately recycled. Although e-waste law covers 66% of the world's population, more has to be done to enforce, implement, and motivate more nations to create e-waste rules (Baldé et al. 2017).

Furthermore, electronic waste should be appropriately managed. Or otherwise, it may cause an adverse and severe impact on the environment. This poses a pressing obstacle to accomplishing sustainable development objectives (Hossain et al. 2015).

The ambitious 2030 Agenda for Sustainable Development was endorsed by the United Nations and all of its members in September 2015. To alleviate poverty, safeguard the environment, and assure prosperity for everyone over the next 15 years, this new agenda defined 17 Sustainable Development Goals (SDGs) and 169 goals. However, the environment, human health, and the attainment of the SGDs are seriously threatened by rising volumes of e-waste, incorrect and dangerous treatment, and disposal in landfills or incinerators (Baldé et al. 2017).

Goal 3 (Health and Well-Being), Goal 6 (Clean Water and Sanitation), Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), Goal 14 (Life Below Water), and Goal 8 are all intimately related to a better knowledge and management of e-waste (Decent Work and Economic Growth) (Baldé et al. 2017). E-waste presents significant health risks when improperly handled since it includes dangerous components that may contaminate the air, water, and land and endanger people's lives. Additional risks to people and the environment come from decommissioning procedures that don't use suitable tools, resources, and qualified personnel (Baldé et al. 2017). Therefore, this article adopts the SDG indicators 9.2.1 (manufacturing value added per capita) and 12.4.1 (e-waste per capita) as the two indicators to represent industrial growth and environmental protection within the SDGs framework since they are appropriate and have data readily available (Liu 2020).

The United Nations declared 2021–2030 as "the Decade on Ecosystem Restoration" on March 1st, 2019. Recently, from the studies of Luo et al. (2017a, b), the soil being cleaned up in areas where an e-waste recycling facility has had adverse environmental effects. Various remediation and restoration techniques are already used to remediate and restore polluted ecosystems (Cui and Zhang 2008; Andrade et al. 2019). In addition, bioremediation or microbial collaboration may improve a greener method of e-waste treatment (Pant et al. 2018).

Removing metal from ores and e-wastes has been investigated for a long time, using microbiological techniques to extract copper and other vital metals from e-waste (Cui and Zhang 2008; Andrade et al. 2019). Bioleaching is an ecologically beneficial technique for extracting metals from primary and secondary metal sources (Andrade et al. 2019). Compared to traditional procedures, using microbes for metal extraction has various benefits, including reduced operating costs (an economical approach), less waste production, and effective effluent detoxification (Cui and Zhang 2008; Andrade et al. 2019). Every management approach focuses on the organic e-wastes and inorganic components. The organic component comprises various thermoplastics and thermosetting plastics that include halogenated materials. The inorganic fraction of e-waste, consisting of metallic and non-metallic components, may be managed by microbes during the leaching process (Pant et al. 2018).

Bioleaching techniques used moderate thermophilic bacteria for extracting the most metals from electronic garbage (Ilyas et al. 2014; Xia et al. 2017; Andrade et al. 2019). Hazardous organics (represented by polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and polybrominated diphenyl ethers), and heavy metals were created during the recycling of matching materials from various components of electrical and electronic devices (Li et al. 2022). In the previous decades, the dismantling and disposal of electronic wastes were done by recycling resources, but it negatively affects the soil ecosystem. So, ecosystem restoration is a critical need for the upcoming decades.

Recycling e-waste is essential from an environmental and economic standpoint because it can be quantified as a "secondary ore" or "artificial ore" due to its higher metal concentration, which can be efficiently separated by bioleaching with the help of microbes and other eco-friendly biological techniques can be used for e-waste management (Marappa et al. 2017). The advantages and disadvantages of microbial treatment for e-waste are summarized below:

**Advantages of microbial treatment for e-waste**

i. Microbial leaching of metals from e-waste has provided future possibilities for extractive metallurgy (Gopikrishnan et al. 2020).
ii. Improved microorganisms, bioengineering, mutant enzymes like metal-binding peptides and their cell surface potential, and metallothioneins expression are all breakthroughs that will aid in improved e-waste treatment (Gupta et al. 2016; Awasthi et al. 2019; Sharma et al. 2022).
iii. Microbial consortiums improved the efficiency of the bioremediation process rather than monocultures (Khanpour-Alikelayeh and Partovinia 2021).

**Disadvantages of microbial treatment for e-waste**

i. The physical (oxygen availability, temperature, time, etc.) and chemical (humidity, nutrition, pH, etc.) external conditions have a sensitive impact on the activity of microbes during bioremediation (Mudila et al. 2021).
ii. Microbial functions have revealed their limited efficiency in the contaminated area due to lack of competition and high levels of heavy metals (Sharma et al. 2021).
iii. There has been minimal work identifying microbes that thrive in high-temperature conditions that could be used in e-waste management. The acid

released into the groundwater system via microbial leaching of e-waste is still a significant issue (Gopikrishnan et al. 2020).

iv. Microbial consortium may be rendered inefficient due to antagonistic interactions in which the microbial population produces substances that hinder the growth and function of other species (Hibbing et al. 2010; Khanpour-Alikelayeh and Partovinia 2021).

v. Microbial bioremediation is a time-consuming process that must be monitored regularly, and to assess the microbial activity on the pollutant, monitoring the biodegradation rate is necessary. In addition, controlling volatile organic compounds (VOCs) is complex, and residue in large amounts might be harmful if it persists in the ecosystem (Juwarkar et al. 2010; Mudila et al. 2021).

## 1.10 Challenges and Future Perspectives of E-waste Management

Modern technology has shortened the lifespans of electrical and electronic equipment (EEE) goods. The point at which EEE goods are deemed to be out of date and destroyed as trash (e-waste) is referred to as the end of life (EoL) (Rautela et al. 2021). The challenges in managing the e-waste include illegal e-waste imports and periodic functional testing of imported used EEE, which render it useless garbage (e-scrap), ignorance regarding the nature or toxicity of e-harmful waste, as well as a lack of understanding of the potential dangers of present EoL management among the general public (Osibanjo and Nnorom 2007) (Fig. 1.4).

Most developing countries do not have particular e-waste regulations compared to developed countries. E-waste collection, handling, recycling, and processing are brutal because of their complex combination of ceramics, glass, plastics, halogen


**Fig. 1.4** Challenges in e-waste management

compounds, base, and hazardous elements (Sahle-Demessie et al. 2018; Sahajwalla and Hossain 2020). Lack of area and infrastructure facilities for recycling and managing e-waste, lack of finances, investment, and policies to support sustainable advancements in e-waste recycling, e-waste's thermodynamic constraints in separation, which lead to expense recovery, a lack of eco-friendly chemicals that are permitted for use in e-waste management, and different laws and regulations that vary from country to country are other obstacles in e-waste treatment (Shahabuddin et al. 2022).

In developing countries, inadequate knowledge, planning, and strategies among actively involved stakeholders in e-waste management, as well as a lack of detailed information for the long-term management of products and the generation of significant e-waste, hinder the strategic processing plan for e-waste management systems. Corruption results in improper trash and e-waste collecting system installation (Garg and Adhana 2019), which leads to inadequate funding for e-waste research. The accumulation of e-waste at the domestic level is two other significant problems (Ranasinghe and Athapattu 2020). In addition, in urban local bodies, e-waste management is not handled by a distinct department. Since rag pickers have no social security, they are not successfully integrated into the waste management process and have more occupational risk while working. Furthermore, they are very diverse due to the participation of several stakeholders and the unpredictable aspects they must deal with it. Such reasons will necessitate a multilevel strategy (Ranasinghe and Athapattu 2020; Aslam et al. 2022; Sakhuja et al. 2022).

Furthermore, the operating method of the informal sector's networking is poorly understood, making integrating the formal and informal sectors in e-waste management a considerable problem. In conformity with the cost internalization and polluter pays principle, extended producer responsibility (EPR) forces companies to bear the physical and financial responsibility for end-of-life (EoL) or used item management. This policy reduces the burden on municipalities and transfers management from taxpayers to producers (Leclerc and Badami 2020). However, implementing EPR has been noted as a significant difficulty due to a lack of legislative provisions, the establishment of credit facilities to conduct EPR, and the competition to access e-waste between both the informal and formal sectors (Arya and Kumar 2020; Ranasinghe and Athapattu 2020; Herat 2021).

The sustainability of bitcoin has been a hot topic of discussion because of its rising energy usage (Gundaboina et al. 2022). However, most studies have so far neglected the fact that bitcoin miners are using more and more brittle technology, which might accelerate the increase of global electronic waste. As dangerous compounds and heavy metals seep into the soil and incorrect recycling results in air and water contamination, e-waste threatens the environment. The yearly amount of electronic trash generated by bitcoin, which, as of May 2021, amounts to 30.7 metric kilotonnes. The annual volume of e-waste may exceed 64.4 metric kilotonnes at the peak bitcoin price levels predicted early in 2021 (De Vries and Stoll 2021). So, managing e-wastes from bitcoin and other cryptocurrencies will soon be challenging.

Insufficient data on current public health services and people involved in recycling e-waste in developing nations and lack of data on the types of materials and new chemical products entering the e-waste are some of the existing data gaps and recommended aspects of research needed (Fowler 2017).

i. Without considering the heterogeneity between urban and rural areas, only urban consumption patterns and activities are considered (Islam and Huda 2019), and in future studies, this must be considered.
ii. The primary study interests in this discipline are the handling and recycling of the electronic waste in developing nations, the degradation and extraction of waste metals, the consequences of heavy metals on children's health, and the evaluation of health risks associated with exposure to organic contaminants. As a result, scientists should broaden their research outside the abovementioned areas (Gao et al. 2019).
iii. The assessment of e-waste production from the top thirty countries that produced significant amounts of e-waste revealed that just a few countries, including China and India, could be classified as the most prolific in this research field (Ismail and Hanafiah 2020). Therefore, nations of e-waste origin must perform more productive research and publish their findings to create effective e-waste handling by employing advanced technologies, infrastructure, appropriate laws, and policies.
iv. Most research in this area aims to improve individuals' knowledge of e-waste through education programs, public media, etc. The involvement of government and corporations in encouraging customers to exchange their end-of-life items through incentive programs could be a significant concern in future. Future research on factors influencing e-waste reverse supply chain operations in rural and urban regions can be conducted (Doan et al. 2019).
v. It is necessary to have reliable data to develop more reliable and precise inferences and create appropriate frameworks to tackle the problems of e-waste. Furthermore, it is essential to integrate mechanical, physical, and chemical research methodologies (a multidisciplinary approach), as well as to work collaboratively with other nations and adhere to international law. Finally, develop sustainable technologies for recovering, recycling, and identifying new pollutants (Ghimire and Ariya 2020).
vi. Collaborations with informal e-waste collectors are encouraged to formalize (Yong et al. 2019) and develop the e-waste recycling industry. When incentive and subsidy programs are introduced, the delivery of collected household e-waste by informal e-waste collectors to licensed recovery centres will expand.
vii. More emphasis should be given to global views on e-waste, particularly material-, element- and product-specific studies. Understanding consumer recycling behaviour may provide unique insights into the stock of outmoded material, which is one of the crucial criteria in estimating the material flow of e-waste.

viii. The total lifespan of an item is an essential characteristic that should be taken into account, and a dynamic evaluation of the product's lifetime is required rather than a static value.
ix. The use of online recycling platforms must be promoted. Consumers are more inclined to utilize online-based services for product disposal and buying in today's world, driven by digital data. It has been discovered that incentives and participation in a digital recycling network are connected. The desire to participate in the platforms is more extensive than for informal sector collection and recycling because of the greater financial rewards (Islam et al. 2021b).
x. Recycling discarded parts and materials from old electronic goods and encouraging manufacturers are essential.
xi. To ensure that electronic trash is collected from the appropriate location, an e-waste collecting system must be implemented. Therefore, it is necessary to establish an institutional infrastructure for e-waste collection, storage, distribution, handling, recycling, and disposal (Rode 2012).
xii. Urban mining of metal recovery from discarded electrical and electronic equipment and a rapid transition to circular economic methods of e-waste management (Shittu et al. 2021).
xiii. Promote the full-scale application of the best physicochemical treatment techniques currently available.
xiv. Promote the idea of product life extension, i.e. repairing the damaged products rather than buying a new one. This is accomplished by strengthening repair or servicing facilities (Gollakota et al. 2020).

## 1.11 Conclusion

Booming electronics industries throughout the globe, combined with quick product obsolescence and a lack of end-of-life management solutions, have all contributed to the unsustainable management of e-waste. Thus, developing eco-design devices, proper collection of e-waste, safe material recovery and recycling, proper disposal of e-waste, prohibiting the export of used electronic devices to developing nations, and creating awareness about the effects of e-waste are essential for effective e-waste management. The absence of recycling methods, the lack of cost recovery of e-waste services, inadequate legal constraints, poor civic awareness, and the paucity of approved disposal locations are the major obstacles in e-waste management. No single management technique is sufficient to help and resolve this emerging e-waste disposal problem. To overcome this risk, combined efforts among the community and the government are a must. Each should accept responsibility, and the system for recycling e-waste needs to be updated with the help and support of all industries. Extended producer responsibility (EPR) may help solve the e-waste management problem. EPR is one national program that is an excellent choice for addressing the rising e-waste issues.

## References


Abalansa S, El Mahrad B, Icely J, Newton A (2021) Electronic waste, an environmental problem exported to developing countries: the good, the bad and the ugly. Sustainability 13:5302

Adanu SK, Gbedemah SF, Attah MK (2020) Challenges of adopting sustainable technologies in e-waste management at Agbogbloshie, Ghana. Heliyon 6:e04548

Ahmed S, Panwar RM, Sharma A (2014) Forecasting e-waste amounts in India. Int J Eng Res Gen Sci 2:2091–2730

Ajibo KI (2016) Transboundary hazardous wastes and environmental justice: implications for economically developing countries. Environ Law Rev 18:267–283

Alabi OA, Bakare AA, Xu X et al (2012) Comparative evaluation of environmental contamination and DNA damage induced by electronic-waste in Nigeria and China. Sci Total Environ 423:62–72. https://doi.org/10.1016/j.scitotenv.2012.01.056

Alam M, Bahauddin K (2015) Electronic waste in Bangladesh: evaluating the situation, legislation and policy and way forward with strategy and approach. Present Environ Sustain Dev 81–102

Alkorta I, Garbisu C (2001) Phytoremediation of organic contaminants in soils. Bioresour Technol 79:273–276. https://doi.org/10.1016/S0960-8524(01)00016-5

Ananno AA, Masud MH, Dabnichki P et al (2021) Survey and analysis of consumers' behaviour for electronic waste management in Bangladesh. J Environ Manage 282:111943

Andrade DF, Romanelli JP, Pereira-Filho ER (2019) Past and emerging topics related to electronic waste management: top countries, trends, and perspectives. Environ Sci Pollut Res 26:17135–17151

Anju A, Ravi SP, Bechan S (2010) Water pollution with special reference to pesticide contamination in India. J Water Resour Prot 2010

Arain AL, Pummill R, Adu-Brimpong J et al (2020) Analysis of e-waste recycling behavior based on survey at a Midwestern US University. Waste Manag 105:119–127

Arain AL, Neitzel RL, Nambunmee K et al (2022) Material flow, economic and environmental life cycle performances of informal electronic waste recycling in a Thai community. Resour Conserv Recycl 180:106129

Arvaniti OS, Kalantzi O-I (2021) Determinants of flame retardants in non-occupationally exposed individuals—a review. Chemosphere 263:127923

Arya S, Kumar S (2020) E-waste in India at a glance: current trends, regulations, challenges and management strategies. J Clean Prod 271:122707

Aslam S, Ali F, Naseer A, Sheikh Z (2022) Application of material flow analysis for the assessment of current municipal solid waste management in Karachi, Pakistan. Waste Manag Res 40:185–194

Awasthi AK, Zeng X, Li J (2016) Environmental pollution of electronic waste recycling in India: a critical review. Environ Pollut 211:259–270

Awasthi AK, Cucchiella F, D'Adamo I et al (2018a) Modelling the correlations of e-waste quantity with economic increase. Sci Total Environ 613:46–53

Awasthi AK, Wang M, Wang Z et al (2018b) E-waste management in India: a mini-review. Waste Manag Res 36:408–414

Awasthi AK, Hasan M, Mishra YK et al (2019) Environmentally sound system for E-waste: biotechnological perspectives. Curr Res Biotechnol 1:58–64. https://doi.org/10.1016/j.crbiot.2019.10.002

Babu BR, Parande AK, Basha CA (2007) Electrical and electronic waste: a global environmental problem. Waste Manag Res 25:307–318

Baldé CP, Forti V, Gray V et al (2017) The global e-waste monitor 2017: quantities, flows and resources. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna

Barbieri L, Giovanardi R, Lancellotti I, Michelazzi M (2010) A new environmentally friendly process for the recovery of gold from electronic waste. Environ Chem Lett 8:171–178

Beula D, Sureshkumar M (2021) A review on the toxic E-waste killing health and environment—today's global scenario. Mater Today Proc 47:2168–2174

Bhadra U, Mishra PP (2021) Extended producer responsibility in India: evidence from Recykal, Hyderabad. J Urban Manag 10:430–439

Bhaskar K, Turaga RMR (2018) India's E-waste rules and their impact on E-waste management practices: a case study. J Ind Ecol 22:930–942

Birloaga I, Coman V, Kopacek B, Vegliò F (2014) An advanced study on the hydrometallurgical processing of waste computer printed circuit boards to extract their valuable content of metals. Waste Manag 34:2581–2586

Borthakur A (2020) Policy approaches on E-waste in the emerging economies: a review of the existing governance with special reference to India and South Africa. J Clean Prod 252:119885

Boyle D, Catarino AI, Clark NJ, Henry TB (2020) Polyvinyl chloride (PVC) plastic fragments release Pb additives that are bioavailable in zebrafish. Environ Pollut 263:114422

Brandl H, Lehmann S, Faramarzi MA, Martinelli D (2008) Biomobilization of silver, gold, and platinum from solid waste materials by HCN-forming microorganisms. Hydrometallurgy 94:14–17

Brusseau ML, Anderson RH, Guo B (2020) PFAS concentrations in soils: background levels versus contaminated sites. Sci Total Environ 740. https://doi.org/10.1016/j.scitotenv.2020.140017

Budnik LT, Casteleyn L (2019) Mercury pollution in modern times and its socio-medical consequences. Sci Total Environ 654:720–734

Cai H, Xu X, Zhang Y et al (2019) Elevated lead levels from e-waste exposure are linked to sensory integration difficulties in preschool children. Neurotoxicology 71:150–158

Campos VM, Merino I, Casado R, Gómez L (2008) Phytoremediation of organic pollutants: a review. Span J Agric Res 6:38–47. https://doi.org/10.5424/sjar/200806S1-372

Cao Y, Chen A, Radcliffe J et al (2009) Postnatal cadmium exposure, neurodevelopment, and blood pressure in children at 2, 5, and 7 years of age. Environ Health Perspect 117:1580–1586

Chakraborty P, Selvaraj S, Nakamura M et al (2018) PCBs and PCDD/Fs in soil from informal e-waste recycling sites and open dumpsites in India: levels, congener profiles and health risk assessment. Sci Total Environ 621:930–938

Chatterjee S (2012) Sustainable electronic waste management and recycling process. Am J Environ Eng 2:23–33

Chatterjee R (2017) Bioremediation: a tribute to green chemistry. CONSCIENTIA 35

Chaurasia PK (2014) E-waste management approaches in India. Int J Eng Trends Technol 15:21–24

Chen Y, Tang X, Cheema SA et al (2010) β-cyclodextrin enhanced phytoremediation of aged PCBs-contaminated soil from e-waste recycling area. J Environ Monit 12:1482–1489

Chen A, Dietrich KN, Huo X, Ho S (2011) Developmental neurotoxicants in e-waste: an emerging health concern. Environ Health Perspect 119:431–438

Cheng W-H (2021) Revisiting selenium toxicity. J Nutr 151:747–748

Choi B-C, Shin H-S, Lee S-Y, Hur T (2006) Life cycle assessment of a personal computer and its effective recycling rate (7 pp). Int J Life Cycle Assess 11:122–128

Cong X, Xu X, Xu L et al (2018) Elevated biomarkers of sympatho-adrenomedullary activity linked to e-waste air pollutant exposure in preschool children. Environ Int 115:117–126. https://doi.org/10.1016/j.envint.2018.03.011

Copani G, Picone N, Colledani M et al (2019) Highly evolvable E-waste recycling technologies and systems. In: Factories of the future. Springer, Cham, pp 109–128

Cui J, Zhang L (2008) Metallurgical recovery of metals from electronic waste: a review. J Hazard Mater 158:228–256

Dai Q, Xu X, Eskenazi B et al (2020) Severe dioxin-like compound (DLC) contamination in e-waste recycling areas: an under-recognized threat to local health. Environ Int 139:105731

Danzeisen R, Araya M, Harrison B et al (2007) How reliable and robust are current biomarkers for copper status? Br J Nutr 98:676–683

Darnerud PO, Eriksen GS, Jóhannesson T et al (2001) Polybrominated diphenyl ethers: occurrence, dietary exposure, and toxicology. Environ Health Perspect 109:49–68

Davis JM, Garb Y (2019) A strong spatial association between e-waste burn sites and childhood lymphoma in the West Bank, Palestine. Int J Cancer 144:470–475. https://doi.org/10.1002/ijc.31902

Decharat S, Kiddee P (2020) Health problems among workers who recycle electronic waste in southern Thailand. Osong Public Health Res Perspect 11(1):34–43

De Meester S, Nachtergaele P, Debaveye S et al (2019) Using material flow analysis and life cycle assessment in decision support: a case study on WEEE valorization in Belgium. Resour Conserv Recycl 142:1–9

de Oliveira Neto JF, Monteiro M, Silva MM et al (2022) Household practices regarding e-waste management: a case study from Brazil. Environ Technol Innov 102723

Devika S (2010) Environmental impact of improper disposal of electronic waste. In: Recent advances in space technology services and climate change 2010 (RSTS & CC-2010). IEEE, pp 29–31

De Vries A, Stoll C (2021) Bitcoin's growing e-waste problem. Resour Conserv Recycl 175:105901

Diep P, Mahadevan R, Yakunin AF (2018) Heavy metal removal by bioaccumulation using genetically engineered microorganisms. Front Bioeng Biotechnol 6:157

Directive EU (2002) 96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Off J Eur Union L 37:24–38

Directive EU (2003) Directive 2003/108/EC of the European Parliament and of the Council of 8 December 2003 amending Directive 2002/96/EC on waste electrical and electronic equipment (WEEE). Off J Eur Communities L 345:12

Doan LT, Amer Y, Lee S-H et al (2019) E-waste reverse supply chain: a review and future perspectives. Appl Sci 9

Ebrahimi M, Khalili N, Razi S et al (2020) Effects of lead and cadmium on the immune system and cancer progression. J Environ Health Sci Eng 18:335–343

Edmunds WM (2011) Beryllium: environmental geochemistry and health effects

Forti V, Balde CP, Kuehr R, Bel G (2020) The global e-waste monitor 2020: quantities, flows and the circular economy potential

Fowler B (2017) Current e-waste data gaps and future research directions, pp 77–81

Ganguly R (2016) E-waste management in India—an overview. Int J Earth Sci Eng 9:574–588

Gangwar C, Choudhari R, Chauhan A et al (2019) Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. Environ Int 125:191–199

Gao Y, Ge L, Shi S et al (2019) Global trends and future prospects of e-waste research: a bibliometric analysis. Environ Sci Pollut Res 26:17809–17820. https://doi.org/10.1007/s11356-019-05071-8

Garfi M, Tondelli S, Bonoli A (2009) Multi-criteria decision analysis for waste management in Saharawi refugee camps. Waste Manag 29:2729–2739

Garg N, Adhana D (2019) E-waste management in India: a study of current scenario. Int J Manag Technol Eng 9

Gaur A, Gurjar SK, Chaudhary S (2022) Circular system of resource recovery and reverse logistics approach: key to zero waste and zero landfill. In: Advanced organic waste management. Elsevier, pp 365–381

Gautam A, Shankar R, Vrat P (2022) Managing end-of-life solar photovoltaic e-waste in India: a circular economy approach. J Bus Res 142:287–300

Ghimire H, Ariya P (2020) E-wastes: bridging the knowledge gaps in global production budgets, composition, recycling and sustainability implications. Sustain Chem 1:154–182. https://doi.org/10.3390/suschem1020012

Gollakota ARK, Gautam S, Shu C-M (2020) Inconsistencies of e-waste management in developing nations—facts and plausible solutions. J Environ Manage 261:110234. https://doi.org/10.1016/j.jenvman.2020.110234

Gopikrishnan V, Vignesh A, Radhakrishnan M et al (2020) Microbial leaching of heavy metals from e-waste: opportunities and challenges. In: Biovalorisation of wastes to renewable chemicals and biofuels, pp 189–216

Gunarathne V, Gunatilake SR, Wanasinghe ST et al (2020) 7—Phytoremediation for E-waste contaminated sites. In: Prasad MNV, Vithanage M, Borthakur A (eds) Handbook of electronic waste management. Butterworth-Heinemann, pp 141–170

Gundaboina L, Badotra S, Bhatia TK et al (2022) Mining cryptocurrency-based security using renewable energy as source. Secur Commun Netw 2022

Gupt Y, Sahay S (2019) Waste management and extended producer responsibility. Econ Polit Wkly 54:35

Gupta A, Joia J, Sood A et al (2016) Microbes as potential tool for remediation of heavy metals: a review. J Microb Biochem Technol 8:364–372

Habib H, Wagner M, Baldé CP et al (2022) What gets measured gets managed—does it? Uncovering the waste electrical and electronic equipment flows in the European Union. Resour Conserv Recycl 181:106222

Hasan Razi C (2011) Serum heavy metal and antioxidant element levels of children with recurrent wheezing. Allergol Immunopathol (Madr) 39:248. https://doi.org/10.1016/j.aller.2011.04.004

Hatami-Marbini A, Tavana M, Moradi M, Kangi F (2013) A fuzzy group Electre method for safety and health assessment in hazardous waste recycling facilities. Saf Sci 51:414–426

Hazra A, Das S, Ganguly A et al (2019) Plasma arc technology: a potential solution toward waste to energy conversion and of GHGs mitigation. In: Waste valorisation and recycling. Springer Singapore, pp 203–217

Herat S (2008) Contamination of solid waste from toxic materials in electronic waste (E-waste). J Solid Waste Technol Manag 34:1–18

Herat S (2021) E-waste management in Asia Pacific region: review of issues, challenges and solutions. Nat Environ Pollut Technol 20:45–53

Hibbing ME, Fuqua C, Parsek MR, Peterson SB (2010) Bacterial competition: surviving and thriving in the microbial jungle. Nat Rev Microbiol 8:15–25

Hossain MS, Al-Hamadani SMZF, Rahman MT (2015) E-waste: a challenge for sustainable development. J Health Pollut 5:3–11

Huang C-L, Bao L-J, Luo P et al (2016) Potential health risk for residents around a typical e-waste recycling zone via inhalation of size-fractionated particle-bound heavy metals. J Hazard Mater 317:449–456

Hula A, Jalali K, Hamza K et al (2003) Multi-criteria decision-making for optimization of product disassembly under multiple situations. Environ Sci Technol 37:5303–5313

Huo X, Wu Y, Xu L et al (2019) Maternal urinary metabolites of PAHs and its association with adverse birth outcomes in an intensive e-waste recycling area. Environ Pollut 245:453–461

Ibanescu D, Cailean D, Teodosiu C, Fiore S (2018) Assessment of the waste electrical and electronic equipment management systems profile and sustainability in developed and developing European Union countries. Waste Manag 73:39–53

Ilankoon I, Ghorbani Y, Chong MN et al (2018) E-waste in the international context—a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag 82:258–275

Ilyas S, Lee J, Kim B (2014) Bioremoval of heavy metals from recycling industry electronic waste by a consortium of moderate thermophiles: process development and optimization. J Clean Prod 70:194–202

Islam MT, Huda N (2019) Material flow analysis (MFA) as a strategic tool in E-waste management: applications, trends and future directions. J Environ Manage 244:344–361. https://doi.org/10.1016/j.jenvman.2019.05.062

Islam MT, Dias P, Huda N (2021a) Young consumers' e-waste awareness, consumption, disposal, and recycling behavior: a case study of university students in Sydney, Australia. J Clean Prod 282:124490

Islam MT, Huda N, Baumber A et al (2021b) A global review of consumer behavior towards e-waste and implications for the circular economy. J Clean Prod 316:128297. https://doi.org/10.1016/j.jclepro.2021.128297

Ismail H, Hanafiah MM (2020) A review of sustainable e-waste generation and management: present and future perspectives. J Environ Manage 264:110495
Jadhav U, Hocheng H (2015) Hydrometallurgical recovery of metals from large printed circuit board pieces. Sci Rep 5:1–10
Jarema KA, Hunter DL, Shaffer RM et al (2015) Acute and developmental behavioral effects of flame retardants and related chemicals in zebrafish. Neurotoxicol Teratol 52:194–209
Jeyaraj P (2021) Management of E-waste in India—challenges and recommendations. World J Adv Res Rev 11:193–218
Jha MK, Lee J, Kumari A et al (2011) Pressure leaching of metals from waste printed circuit boards using sulfuric acid. JOM 63:29–32
Jiang C, Bo J, Xiao X et al (2020) Converting waste lignin into nano-biochar as a renewable substitute of carbon black for reinforcing styrene-butadiene rubber. Waste Manag 102:732–742
Joo J, Kwon EE, Lee J (2021) Achievements in pyrolysis process in E-waste management sector. Environ Pollut 287:117621
Juwarkar AA, Singh SK, Mudhoo A (2010) A comprehensive overview of elements in bioremediation. Rev Environ Sci Biotechnol 9:215–288
Kahhat R, Kim J, Xu M et al (2008) Exploring e-waste management systems in the United States. Resour Conserv Recycl 52:955–964
Kaifie A, Schettgen T, Bertram J et al (2020) Informal e-waste recycling and plasma levels of non-dioxin-like polychlorinated biphenyls (NDL-PCBs)—a cross-sectional study at Agbogbloshie, Ghana. Sci Total Environ 723:138073
Kapp Jr RW (2016) Arsenic: toxicology and health effects
Karim SM, Sharif SI, Anik M, Rahman A (2018) Negative impact and probable management policy of E-waste in Bangladesh. arXiv Preprint arXiv:1809.10021
Karn B, Kuiken T, Otto M (2009) Nanotechnology and in situ remediation: a review of the benefits and potential risks. Environ Health Perspect 117:1813–1831
Karthika S, Lakshmanan A, Rajkishore SK et al (2019) The green synthesis and characterisation of zero valent iron nanoparticles using azolla and blue green algal systems. Int J Agric Sci Res 9:13–20
Kaya M (2016) Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manag 57:64–90
Khanpour-Alikelayeh E, Partovinia A (2021) Synergistic and antagonistic effects of microbial co-culture on bioremediation of polluted environments. In: Microbial rejuvenation of polluted environment. Springer, pp 229–265
Khaobang C, Sarabhorn P, Siripaiboon C et al (2022) Pilot-scale combined pyrolysis and decoupling biomass gasification for energy and metal recovery from discarded printed circuit board and waste cable. Energy 245:123268
Khuda K-E (2021) Electronic waste in Bangladesh: its present statutes, and negative impacts on environment and human health. Pollution 7:633–642
Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manag 33:1237–1250
Kim S, Hwang T, Overcash M (2001) Life cycle assessment study of color computer monitor. Int J Life Cycle Assess 6:35–43
Kumar U, Singh DN (2013) E-waste management through regulations. Int J Eng Invent 3:6–14
Kumar A, Holuszko M, Espinosa DCR (2017) E-waste: an overview on generation, collection, legislation and recycling practices. Resour Conserv Recycl 122:32–42
Kuntawee C, Tantrakarnapa K, Limpanont Y et al (2020) Exposure to heavy metals in electronic waste recycling in Thailand. Int J Environ Res Public Health 17:2996
Lanzerstorfer C (2015) Air classification: potential treatment method for optimized recycling or utilization of fine-grained air pollution control residues obtained from dry off-gas cleaning high-temperature processing systems. Waste Manag Res 33:1041–1044
Laur N, Kinscherf R, Pomytkin K et al (2020) ICP-MS trace element analysis in serum and whole blood. PLoS ONE 15:e0233357

Laurmaa V, Kers J, Tall K et al (2011) Mechanical recycling of electronic wastes for materials recovery. In: Recycling of electronic waste II, proceedings of the second symposium. TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA

Leclerc SH, Badami MG (2020) Extended producer responsibility for E-waste management: policy drivers and challenges. J Clean Prod 251:119657

Leung AOW (2019) Environmental contamination and health effects due to E-waste recycling. In: Electronic waste management and treatment technology, pp 335–362

Li J, Tian B, Liu T et al (2006) Status quo of e-waste management in mainland China. J Mater Cycles Waste Manag 8:13–20

Li Y, Richardson JB, Mark Bricka R et al (2009) Leaching of heavy metals from E-waste in simulated landfill columns. Waste Manag 29:2147–2150. https://doi.org/10.1016/j.wasman.2009.02.005

Li C, Zhou K, Qin W et al (2019a) A review on heavy metals contamination in soil: effects, sources, and remediation techniques. Soil Sediment Contam Int J 28:380–394

Li T-Y, Ge J-L, Pei J et al (2019b) Emissions and occupational exposure risk of halogenated flame retardants from primitive recycling of e-waste. Environ Sci Technol 53:12495–12505

Li X, Wu Y, Tan Z (2022) An overview on bioremediation technologies for soil pollution in E-waste dismantling areas. J Environ Chem Eng 107839

Liu S (2020) Interactions between industrial development and environmental protection dimensions of sustainable development goals (SDGs): evidence from 40 countries with different income levels. Environ Socio-Econ Stud 8:60–67

Liu Y, Huo X, Xu L et al (2018) Hearing loss in children with e-waste lead and cadmium exposure. Sci Total Environ 624:621–627

Liu J, Xu H, Zhang L, Liu CT (2020) Economic and environmental feasibility of hydrometallurgical process for recycling waste mobile phones. Waste Manag 111:41–50

Luo J, Cai L, Qi S et al (2017a) Improvement effects of cytokinin on EDTA assisted phytoremediation and the associated environmental risks. Chemosphere 185:386–393

Luo J, Cai L, Qi S et al (2017b) A multi-technique phytoremediation approach to purify metals contaminated soil from e-waste recycling site. J Environ Manage 204:17–22

Ma H, Liao X, Liu X, Shi B (2006) Recovery of platinum (IV) and palladium (II) by bayberry tannin immobilized collagen fiber membrane from water solution. J Memb Sci 278:373–380

Maheswari H, Yudoko G, Adhiutama A, Agustina H (2020) Sustainable reverse logistics scorecards for the performance measurement of informal e-waste businesses. Heliyon 6:e04834

Manhart A, Osibanjo O, Aderinto A, Prakash S (2011) Informal e-waste management in Lagos, Nigeria—socio-economic impacts and feasibility of international recycling co-operations. Final Rep Compon 3:1–129

Marappa N, Dharumadurai D, Thajuddin N (2017) Biological recovery of metals from electronic waste polluted environment using microorganisms, pp 149–172

Mazhandu ZS, Muzenda E, Mamvura TA et al (2020) Integrated and consolidated review of plastic waste management and bio-based biodegradable plastics: challenges and opportunities. Sustainability 12:8360

Meem RA, Ahmed A, Hossain MS, Khan RA (2021) A review on the environmental and health impacts due to electronic waste disposal in Bangladesh. GSC Adv Res Rev 8:116–125

Mishra S (2020) Electronic waste: management, material flows, present and future scenario

Mmereki D, Li B, Baldwin A, Hong L (2016) The generation, composition, collection, treatment and disposal system, and impact of E-waste. In: E-waste in transition—from pollution to resource, pp 65–93

MoEF (Ministry of Environment and Forests) (2010) Draft for E-waste (management and handling) rules, 2010

Mohod CV, Dhote J (2013) Review of heavy metals in drinking water and their effect on human health. Int J Innov Res Sci Eng Technol 2:2992–2996

Montano L, Pironti C, Pinto G et al (2022) Polychlorinated biphenyls (PCBs) in the environment: occupational and exposure events, effects on human health and fertility. Toxics 10:365

Mudila H, Prasher P, Kumar M et al (2019) An insight into cadmium poisoning and its removal from aqueous sources by graphene adsorbents. Int J Environ Health Res 29:1–21

Mudila H, Prasher P, Kumar A et al (2021) E-waste and its hazard management by specific microbial bioremediation processes. In: Panpatte DG, Jhala YK (eds) Microbial rejuvenation of polluted environment: volume 2. Springer Singapore, Singapore, pp 139–166

Muñoz I, Gazulla C, Bala A et al (2009) LCA and ecodesign in the toy industry: case study of a teddy bear incorporating electric and electronic components. Int J Life Cycle Assess 14:64–72

Needhidasan S, Samuel M, Chidambaram R (2014) Electronic waste—an emerging threat to the environment of urban India. J Environ Health Sci Eng 12:36. https://doi.org/10.1186/2052-336X-12-36

Nowakowski P (2020) Reconfigurable recycling systems of E-waste. In: E-waste recycling and management. Springer, pp 19–38

Nti AAA, Arko-Mensah J, Botwe PK et al (2020) Effect of particulate matter exposure on respiratory health of e-waste workers at Agbogbloshie, Accra, Ghana. Int J Environ Res Public Health 17. https://doi.org/10.3390/ijerph17093042

OECD (2001) Extended producer responsibility: a guidance manual for governments. OECD, Paris

Osibanjo O, Nnorom IC (2007) The challenge of electronic waste (e-waste) management in developing countries. Waste Manag Res 25:489–501

Oskarsson A, Reeves AL (2015) Handbook on the toxicology of metals

Owusu-Sekyere SO (2018) Cardio-respiratory function among formal sector workers at Agbogbloshie E-waste recycling site in Accra, Ghana

Pahari AK, Dubey BK (2018) Waste from electrical and electronics equipment. In: Plastics to energy: fuel, chemicals, and sustainability implications. Elsevier, pp 443–468

Panchal R, Singh A, Diwan H (2021) Economic potential of recycling e-waste in India and its impact on import of materials. Resour Policy 74:102264

Panda S, Biswal A, Mishra S et al (2015) Reductive dissolution by waste newspaper for enhanced meso-acidophilic bioleaching of copper from low grade chalcopyrite: a new concept of biohydrometallurgy. Hydrometallurgy 153:98–105

Pant VK, Kumar S (2018) Global and Indian perspective of E-waste and its environmental impact. In: 2018 international conference on system modeling & advancement in research trends (SMART). IEEE, pp 132–137

Pant D, Joshi D, Upreti MK, Kotnala RK (2012) Chemical and biological extraction of metals present in E waste: a hybrid technology. Waste Manag 32:979–990. https://doi.org/10.1016/j.wasman.2011.12.002

Pant D, Giri A, Dhiman V (2018) Bioremediation techniques for E-waste management. In: Waste bioremediation. Springer, pp 105–125

Parajuly K, Kuehr R, Awasthi AK et al (2019) Future E-waste scenarios. StEP Initiative, UNU ViE-SCYCLE, UNEP IETC

Park P-J, Tahara K, Jeong I-T, Lee K-M (2006) Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine. Resour Conserv Recycl 48:71–85

Patel S, Kasture A (2014) E (electronic) waste management using biological systems—overview. Int J Curr Microbiol Appl Sci 3:495–504

Pathak P, Srivastava RR (2017) Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. Renew Sustain Energy Rev 78:220–232

Patil RA, Ramakrishna S (2020) A comprehensive analysis of e-waste legislation worldwide. Environ Sci Pollut Res 27:14412–14431

Paul H, Helmut R (2004) Practical handbook of material flow analysis. Lewis Publishers, Washington, DC

Peana M, Medici S, Dadar M et al (2021) Environmental barium: potential exposure and health-hazards. Arch Toxicol 95:2605–2612

Peng Y, Wu J, Luo X et al (2019) Spatial distribution and hazard of halogenated flame retardants and polychlorinated biphenyls to common kingfisher (*Alcedo atthis*) from a region of South China affected by electronic waste recycling. Environ Int 130:104952

Philp JC, Atlas RM (2005) Bioremediation of contaminated soils and aquifers. In: Bioremediation: applied microbial solutions for real-world environmental cleanup, pp 139–236

Pokhrel P, Lin S-L, Tsai C-T (2020) Environmental and economic performance analysis of recycling waste printed circuit boards using life cycle assessment. J Environ Manage 276:111276

Pollock D, Coulon R (1996) Life cycle assessment: of an inkjet print cartridge. In: Proceedings of the 1996 IEEE international symposium on electronics and the environment. ISEE-1996. IEEE, pp 154–160

Ponder SM, Darab JG, Mallouk TE (2000) Remediation of Cr (VI) and Pb (II) aqueous solutions using supported, nanoscale zero-valent iron. Environ Sci Technol 34:2564–2569

Prek M (2004) Environmental impact and life cycle assessment of heating and air conditioning systems, a simplified case study. Energy Build 36:1021–1027

Queiruga D, Walther G, Gonzalez-Benito J, Spengler T (2008) Evaluation of sites for the location of WEEE recycling plants in Spain. Waste Manag 28:181–190

Ramachandra TV, Saira-Varghese K (2004) Environmentally sound options for e-wastes management. Envies J Hum Settl

Ranasinghe WW, Athapattu BCL (2020) 13—Challenges in E-waste management in Sri Lanka. In: Prasad MNV, Vithanage M, Borthakur A (eds) Handbook of electronic waste management. Butterworth-Heinemann, pp 283–322

Rautela R, Arya S, Vishwakarma S et al (2021) E-waste management and its effects on the environment and human health. Sci Total Environ 773:145623

Rode S (2012) E-waste management in Mumbai metropolitan region: constraints and opportunities. Theor Empir Res Urban Manag 7:89–103

Rohwerder T, Gehrke T, Kinzler K, Sand W (2003) Bioleaching review. Part A: progress in bioleaching: fundamentals and mechanisms of bacterial metal sulfide oxidation. Appl Microbiol Biotechnol 248

Rotter VS, Maehlitz P, Korf N et al (2016) ProSUM deliverable 4.1—waste flow studies, pp 1–100

Rousis K, Moustakas K, Malamis S et al (2008) Multi-criteria analysis for the determination of the best WEEE management scenario in Cyprus. Waste Manag 28:1941–1954

Roychowdhury P, Alghazo JM, Debnath B et al (2019) Security threat analysis and prevention techniques in electronic waste. In: Waste management and resource efficiency. Springer, pp 853–866

Sahajwalla V, Hossain R (2020) The science of microrecycling: a review of selective synthesis of materials from electronic waste. Mater Today Sustain 9:100040

Sahle-Demessie E, Glaser J, Richardson T (2018) Electronics waste management challenges and opportunities. In: American chemical society 2018 national meeting

Sakhuja D, Ghai H, Bhatia RK, Bhatt AK (2022) Management of e-Waste: technological challenges and opportunities. In: Handbook of solid waste management, pp 1523–1557

Salhofer S (2017) E-waste collection and treatment options: a comparison of approaches in Europe, China and Vietnam. In: Source separation and recycling, p 227

Scharnhorst W, Althaus H-J, Classen M et al (2005) The end of life treatment of second generation mobile phone networks: strategies to reduce the environmental impact. Environ Impact Assess Rev 25:540–566

Schumacher KA (2016) Electronic waste management in the US practice and policy. University of Delaware

Secretariat RS (2011) E-waste in India. India research unit (Larrdis). Rajya Sabha Secretariat, New Delhi

Seith R, Arain AL, Nambunmee K et al (2019) Self-reported health and metal body burden in an electronic waste recycling community in northeastern Thailand. J Occup Environ Med 61:905–909. https://doi.org/10.1097/JOM.0000000000001697

Sepúlveda A, Schluep M, Renaud FG et al (2010) A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environ Impact Assess Rev 30:28–41

Shahabuddin M, Uddin MN, Chowdhury JI et al (2022) A review of the recent development, challenges, and opportunities of electronic waste (e-waste). Int J Environ Sci Technol 1–8

Shaikh S, Thomas K, Zuhair S, Magalini F (2020) A cost-benefit analysis of the downstream impacts of e-waste recycling in Pakistan. Waste Manag 118:302–312

Sharma M, Joshi S, Kumar A (2020a) Assessing enablers of e-waste management in circular economy using DEMATEL method: an Indian perspective. Environ Sci Pollut Res 27:13325–13338

Sharma S, Wakode S, Sharma A et al (2020b) Effect of environmental toxicants on neuronal functions. Environ Sci Pollut Res 27:44906–44921

Sharma J, Goutam J, Dhuriya YK, Sharma D (2021) Bioremediation of industrial pollutants. In: Microbial rejuvenation of polluted environment. Springer, pp 1–31

Sharma P, Bano A, Singh SP et al (2022) Engineered microbes as effective tools for the remediation of polyaromatic aromatic hydrocarbons and heavy metals. Chemosphere 135538

Sheel A, Pant D (2018) Recovery of gold from electronic waste using chemical assisted microbial biosorption (hybrid) technique. Bioresour Technol 247:1189–1192

Shen Y, Yuan R, Chen X et al (2018) Co-pyrolysis of E-waste nonmetallic residues with biowastes. ACS Sustain Chem Eng 6:9086–9093

Shi J, Xiang L, Luan H et al (2019) The health concern of polychlorinated biphenyls (PCBs) in a notorious e-waste recycling site. Ecotoxicol Environ Saf 186:109817

Shittu OS, Williams ID, Shaw PJ (2021) Global E-waste management: can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Manag 120:549–563. https://doi.org/10.1016/j.wasman.2020.10.016

Shuey SA, Taylor P (2005) Review of pyrometallurgical treatment of electronic scrap. Min Eng 57:67–70

Sinduja M, Sathya V, Maheswari M et al (2022a) Chemical transformation and bioavailability of chromium in the contaminated soil amended with bioamendments. Bioremediat J 1–22. https://doi.org/10.1080/10889868.2022.2049677

Sinduja M, Sathya V, Maheswari M et al (2022b) Evaluation and speciation of heavy metals in the soil of the Sub Urban Region of Southern India. Soil Sediment Contam Int J 1–20. https://doi.org/10.1080/15320383.2022.2030298

Singh C, Lin J (2010) Bioaugmentation efficiency of diesel degradation by *Bacillus pumilus* JLB and *Acinetobacter calcoaceticus* LT1 in contaminated soils. Afr J Biotechnol 9:6881–6888

Singh M, Thind PS, John S (2018) Health risk assessment of the workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India. Chemosphere 203:426–433

Sivaramanan S (2013) E-waste management, disposal and its impacts on the environment. Univers J Environ Res Technol 3

Skinner A, Dinter Y, Lloyd A, Strothmann P (2010) The challenges of E-waste management in India: can India draw lessons from the EU and the USA. Asien 117:26

Srivastava RR, Pathak P (2020) Policy issues for efficient management of E-waste in developing countries. In: Handbook of electronic waste management. Elsevier, pp 81–99

Streicher-Porte M, Bader H-P, Scheidegger R, Kytzia S (2007) Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies. Clean Technol Environ Policy 9:325–345

Sundar S, Chakravarty J (2010) Antimony toxicity. Int J Environ Res Public Health 7:4267–4277

Tiller KG (1989) Heavy metals in soils and their environmental significance. In: Advances in soil science. Springer, pp 113–142

Tratnyek PG, Johnson RL (2006) Nanotechnologies for environmental cleanup. Nano Today 1:44–48

Tutton CG, Young SB, Habib K (2022) Pre-processing of e-waste in Canada: case of a facility responding to changing material composition. Resour Environ Sustain 9:100069

Vats MC, Singh SK (2014) E-waste characteristic and its disposal. Int J Ecol Sci Environ Eng 1:49–61

Verma AK (2020) E-wastes and their impact on environment and public health. Int J Appl Res

Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014

Wang D, Cai Z, Jiang G et al (2005) Determination of polybrominated diphenyl ethers in soil and sediment from an electronic waste recycling facility. Chemosphere 60:810–816

Wang F, Huisman J, Meskers CEM et al (2012) The best-of-2-worlds philosophy: developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag 32:2134–2146

Wang F, Kuehr R, Ahlquist D, Li J (2013) E-waste in China: a country report

Wang C, Chen H, Li H et al (2020) Review of emerging contaminant tris (1, 3-dichloro-2-propyl) phosphate: environmental occurrence, exposure, and risks to organisms and human health. Environ Int 143:105946

Wath SB, Vaidya AN, Dutt PS, Chakrabarti T (2010) A roadmap for development of sustainable E-waste management system in India. Sci Total Environ 409:19–32

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D et al (2005) Global perspectives on e-waste. Environ Impact Assess Rev 25:436–458

Williams E (2005) International activities on E-waste and guidelines for future work. In: Proceedings of the third workshop on material cycles and waste management in Asia. National Institute of Environmental Sciences, Tsukuba, Japan

Xavier LH, Ottoni M, Lepawsky J (2021) Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks. J Clean Prod 297:126570

Xia M-C, Wang Y-P, Peng T-J et al (2017) Recycling of metals from pretreated waste printed circuit boards effectively in stirred tank reactor by a moderately thermophilic culture. J Biosci Bioeng 123:714–721

Xu X, Chen X, Zhang J et al (2015a) Decreased blood hepatitis B surface antibody levels linked to e-waste lead exposure in preschool children. J Hazard Mater 298:122–128. https://doi.org/10.1016/j.jhazmat.2015.05.020

Xu X, Yekeen TA, Liu J et al (2015b) Chromium exposure among children from an electronic waste recycling town of China. Environ Sci Pollut Res 22:1778–1785

Xu L, Huo X, Liu Y et al (2020) Hearing loss risk and DNA methylation signatures in preschool children following lead and cadmium exposure from an electronic waste recycling area. Chemosphere 246:125829

Yong YS, Lim YA, Ilankoon IMSK (2019) An analysis of electronic waste management strategies and recycling operations in Malaysia: challenges and future prospects. J Clean Prod 224:151–166. https://doi.org/10.1016/j.jclepro.2019.03.205

Youcai Z (2018) Leachate generation and characteristics. In: Pollution control technology for leachate from municipal solid waste, pp 1–30

Zanghelini GM, Cherubini E, Soares SR (2018) How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation. J Clean Prod 172:609–622

Zeng G, Luo S, Deng X et al (2013) Influence of silver ions on bioleaching of cobalt from spent lithium batteries. Miner Eng 49:40–44

Zeng J, Gou M, Tang YQ et al (2016a) Effective bioleaching of chromium in tannery sludge with an enriched sulfur-oxidizing bacterial community. Bioresour Technol 218:859–866. https://doi.org/10.1016/j.biortech.2016.07.051

Zeng X, Xu X, Boezen HM, Huo X (2016b) Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148:408–415

Zeng X, Xu X, Zheng X et al (2016c) Heavy metals in PM2.5 and in blood, and children's respiratory symptoms and asthma from an e-waste recycling area. Environ Pollut 210:346–353

Zeng X, Duan H, Wang F, Li J (2017) Examining environmental management of e-waste: China's experience and lessons. Renew Sustain Energy Rev 72:1076–1082

Zeng Z, Huo X, Zhang Y et al (2019) Differential DNA methylation in newborns with maternal exposure to heavy metals from an e-waste recycling area. Environ Res 171:536–545

Zhang W (2003) Nanoscale iron particles for environmental remediation: an overview. J Nanopart Res 5:323–332

Zhang M (2017) Air pollution and human health risk assessment in e-waste recycling sites and urban indoor environment in South China

Zhang S, Forssberg E (1997) Mechanical separation-oriented characterization of electronic scrap. Resour Conserv Recycl 21:247–269

Zhang S, Forssberg E (1999) Intelligent liberation and classification of electronic scrap. Powder Technol 105:295–301

Zhang Y, Xu X, Chen A et al (2018) Maternal urinary cadmium levels during pregnancy associated with risk of sex-dependent birth outcomes from an e-waste pollution site in China. Reprod Toxicol 75:49–55. https://doi.org/10.1016/j.reprotox.2017.11.003

# Chapter 2
# Electronic Waste and Their Management Strategies

**Madhumita Ghosh Datta**

**Abstract** Currently, e-waste is experiencing an exceptional growth. This increase is accelerated by the COVID-19 pandemic due to people's dependence on electronic products. Massive waste production has created diverse demands over current reprocessing options with harmful impacts on the environment and human health owing to the presence of noxious synthetic substances. Developed nations are likely to have advanced e-waste supervision technologies, specialized expertise, and multiple information sources integrated into one system. There are obstacles and a lack of a plan of action, which makes the situation different from that in less advanced countries. Among the foremost difficulties impacting e-waste conversion into a finished product in India are the lack of a database on e-waste management, the illegal disposal of waste in open landfills, and lack of handling options. Hence, this manuscript is concerned with the current state of e-waste, its management along with environmentally friendly alternatives. The implementation of current regulations for the production of upgraded products carved out of e-waste, reducing environmental effects and ensuring sustainable development. Environmentally friendly methods of waste management include the design of digital electronic and electrical devices, resource management through the concept of zero waste production, removal of e-devices by consumers after they have used them, levying taxes on polluters, monitoring of product lifecycles, instilling the 4R's principle among common people, and bioleaching. It is extremely critical to transform the informal sector into a transparent reprocessing system.

**Keywords** E-waste · Management · Legal framework · Eco-friendly management

M. G. Datta (✉)
Department of Environmental Science, Tezpur University, Napaam, Sonitpur, Assam 784028, India
e-mail: mghosh@tezu.ernet.in



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_2

## 2.1 Introduction

The term “electronic waste” refers to anything made of electronic goods (e-goods) and their components but not intended for reuse. Supervising e-waste generation is challenging, since it is often referred to as one of the fastest-growing solid wastes. This is the result of unplanned disposal of e-waste, which makes it potentially hazardous (Parajuly et al. 2019). Additionally, the use of clean energy has led to the production of e-products such as photovoltaic cells and panels fitted with heavy metals that produce toxic e-wastes. With the advent of online services like transmitting or receiving multimedia data, computer system storage, and procurement of amenities instead of direct usage of devices, it may reduce dependence on e-goods in the near future but the use of e-goods, and therefore e-waste effluents, is definitely projected to increase with the increase in number of consumers and e-goods users. As the size of e-devices is getting smaller and more sophisticated day by day, numerous components are needed to achieve multiple functionalities with a desired quality all fitted in small microchips. For instance, more than 70 metals are required for efficient functionality of a smartphone. In contrast, e-devices’ lifespans are short due to technological advancements rendering obsolete existing products either due to the incapacity to repair, or the incongruity of computer programs. The availability of advanced electronic equipment with enhanced features promotes replacement of existing equipment generating e-waste effluents.

India produces 3.23 Mt of e-waste annually, after China and the USA. The amount of e-waste generated increased by 43% between 2018 and 2020 (www.statista.com). As a result of the pandemic, electronic equipment is increasingly used in the workplace and education. Moreover, the lockdown imposed during the COVID-19 pandemic restricted movement of the common people and increased the use of electronic devices like game consoles, mobile phones, ovens, and laptop computers. The current pandemic will highlight this issue further in the near future (www.businesstoday.in).

The volume of e-waste escalated in India varies across regions. Maharashtra, Andhra Pradesh, and Tamil Nadu produces the highest e-wastes. Punjab, Delhi, Gujarat, Uttar Pradesh, Madhya Pradesh, and West Bengal are also contributors to the waste stream in northern and middle India (Fig. 2.1). Even Karnataka brings out a considerable amount of e-waste. Moreover, e-waste is bizarrely disposed of in 65 Indian cities, producing more than 60% of India’s entire e-waste. Mumbai tops the e-waste generator list, closely followed by Delhi, Kolkata Bengaluru, and Chennai.

The evolution of mobile phones into smart phones poses a ticking bomb for rural India. The durability of appliances in village areas is much higher, because people prefer to patch-up a bit and use rather than alter them. In the near future, what has mostly been an urban problem could affect villages in India as well.

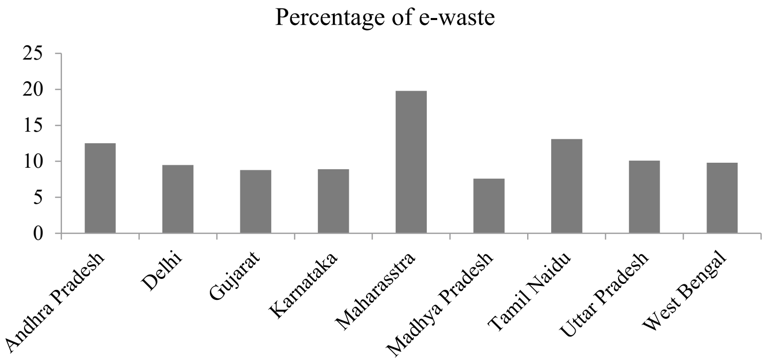



**Fig. 2.1** E-waste in different states of India in percentage

This chapter describes the current state of e-waste, its management along with environmentally friendly alternatives. It is divided into four sections. In the first section, we examine the sources and composition of e-waste streams. Waste disposal and e-waste regulation are discussed in the second section. The third segment discusses the global situation and e-waste minimization practices in some countries. Based on the literature review, this study concludes with recommendations regarding effective supervision of e-waste in the fourth section.

## 2.2 Root-Cause and Constituents of E-waste

Solid waste stream containing e-waste is growing hugely, with an annual increase of 2 metric tons (Mt) per year. Over the previous year 2018–2019, it increased by 31% in 2019–2020 and is expected to increase further. Newly developed e-products, repairs and maintenance accessories, as well as their eventual decomposition constitute e-waste, the fast-moving waste surge (Forti et al. 2020). It contains products used in daily life, such as timeworn phones, televisions, air conditioners, handsets, personal stereos, and discarded computers, ovens, electric kettles, and cameras. Generally, e-waste consists of small electronics like microwaves and telecommunications equipment. The waste surge also includes metals and plastics that are rare and expensive (Kaya 2016). In India, e-waste is projected to include computer accessories (70%), telecommunication tools (12%), electrical gadgets (8%), health devices (7%), and bits and pieces arising from household appliances (5%) (KPMG and ASSOCHAM). Trade in e-waste together with metals such as lanthanum, neodymium, silver, gold, palladium, platinum is booming because gold and silver are essential for manufacturing (Nazari et al. 2021).

The components of e-waste are usually mixed and come from different devices. These devices comprise more than thousands of different materials, grouped as hazardous or non-hazardous. Roughly, it is made up of metals of ferrous and non-ferrous nature; printed circuit boards plastics, glass, wood, plywood, harden cement paste, harden clay, latex, and other substances (Purchase et al. 2020).

A ferrous metal such as iron and its alloy steel or tin makes up about half of the e-waste, followed by plastics (21%), costly metals like copper, nickel, aluminum, silver, and gold (13%), as well as hazardous metals such as lead, zinc, mercury, arsenic, cadmium, selenium, and chromium above threshold quantities (Srivastava and Pathak 2020). E-waste is mainly made up of chips comprising scarce and expensive metals such as rhodium, iridium, ruthenium, osmium, platinum, and palladium (Abdelbasir et al. 2018a, b).

E-waste management requires more than strict vigilance and implementing the "E-Waste (Management) Rules 2016." Producer responsibility targets should be met along with improved facts and figures on e-waste in order to ensure enhanced supervision. It is possible to bring additional capital into the e-waste management companies through tax incentives. Consumer awareness, however, cannot be overstated. This can play a critical role. The planet's greatest threat is the belief that someone else will save it. Although some producer responsibility organizations source waste, small-scale e-waste dealers or laborers continue to thrive. There are many responsible companies that buy e-waste at low cost from small-scale e-waste dealers to obtain large volumes of e-waste as well as to dispose of it legally.

## 2.3 E-waste and Toxicity

E-waste covers an array of chemicals that are harmful to people and their surroundings. Inappropriate management and treatment of e-waste toxic materials enter into the human food chain as well as the surrounding land, air, and runoff water. When continuously exposed, the hazardous chemical affects bacteria, fungi, and *actinomycetes* flourishing in soil and at higher levels of the food chain and food web. They decrease the organic component of the polluted area by reducing microbial populations such as *firmicutes* and *proteobacteria*, microbial biomass, and their role in maintaining ecosystem functions (Beattie et al. 2018; Salam and Varma 2019; Zou et al. 2021) through secretion of exo-enzymes and endo-enzymes. Toxicity of metals hampers the structure and function of microorganisms in the soil environment (Abdu et al. 2017). It is observed that continuous contact of soil microbiota with heavy and toxic metals may cause them to grow resistance toward the ill-effects of metal exposure.

### 2.3.1 Effect on Humans

The effects of e-waste on human well-being include changes in the function of cells and organs such as the lungs and thyroid, as well as changes in character. DNA injuries were more common at e-waste recycling sites than non-recycling sites. Cells can absorb leachates, altering pH, which affects enzymes and alters DNA structure creating lesions, telomere attrition. People become unresponsive to vaccines, impair immunity and respond to stress (Parvez et al. 2021). The presence of free radicals in the cell may also cause the membrane to peroxide when they react with lipids. Splitting DNA strands would result from this. Free radicals can also substitute one base for another and cause mutations.

There is evidence that dioxins from e-waste are absorbed into the human body in high concentrations, indicating that they have entered the body through the food chain or through breathing polluted air, leading to serious health problems. Decomposing printed circuit boards containing toxic metals may leach and contaminate agricultural land and groundwater and eventually become a part of living systems (Kaifie et al. 2020).

Pollutant exposure affects people of all ages; however, it differs between vulnerable and non-vulnerable age groups (www.unep.org). Adolescence involved in recycling e-waste has high levels of lead in their blood when compared to children who do not recycle e-waste, which results in lower cognitive skills and respiratory problems such as coughing. In humans, lead contributes to the production of immunoglobulin E, which causes asthma. It also weakens the immune system, making the body incapable of defending against hepatitis. Prolong exposure to these materials may lead to neurological, physical, and muscular degeneration diseases.

When metals, such as antimony, arsenic, chromium, and cadmium, enter the human body via several means, they do not disintegrate. Instead, they remain in the environment for a longer period of time, accumulate in plants, animals and then enter humans through the ingestion of contaminated food. Metals have different adverse effects on humans when they come into contact with them. Copper adversely affects liver function and high levels of cadmium result in harm to the kidney and lung (Ebrahimi et al. 2020). E-waste manufacturers and recyclers are more likely to suffer adverse effects. In the air, lead can persist for ten days before settling on the ground and contaminating nearby water and soil. As a carcinogen, lead has also been well documented.

### 2.3.2 Effects on Plants

E-waste has not yet been fully investigated for its toxicity on plants, but many of its constituents, especially heavy metals, are cytotoxic and somatic mutants. There are often bi-nucleate cells and anaphase bridges in cells exposed to e-waste leachates. Metals such as iron, nickel, chromium, arsenic, zinc, lead, and cadmium have been found to cause anomalies in *Alium cepa*. E-waste leachates affect photosynthesis performance and reduce the quantity of reaction centers for photosystem II and affect chlorophyll content and development and growth of microalga. Some synthetic chemical pollutants, such as heavy metals and polybrominated diphenyl ethers, can generate more free radicals than they can be detoxified by algae, as well as interfere with anti-oxidative enzyme function. Copper has been shown to disrupt plant physiological processes in e-waste leachates. In algae, copper may reduce chlorophyll A content and change the energy storage capacity. High concentrations of heavy metals adversely affect plants and accumulate in them via the roots (Yan et al. 2020). The metals inhibit the normal function of the cytoplasmic enzymes and cause damage to the plant as they create reactive oxygen species and interfere with the cation exchange capacity of the plant (Dutta et al. 2018). Lead, cadmium, mercury, chromium, arsenic, etc., are the most common heavy metals involved in the process. Plants react differently to the different types of heavy metals. Some of the metals exert positive effects on plant growth, while copper, iron, and aluminum do so to a certain extent.

## 2.4 E-waste Disposal

According to the Global E-Waste Monitor Report of 2020, the amount of e-waste will reach 3.23 million metric tons by 2019. Because of this, the e-waste stream is high in India, but not with the established players, instead retailers and small businesses turn to metal scrapers or their local "kabadiwalas" for disposal. Metals are extracted by acid digestion or by burning. As far as scrapers are concerned, they mostly break apart unused or worn-out laptops, handsets, televisions, LED bulbs, tube lights, and coolers. The scattered pieces degrade nearby ground water and soil (www.downtoearth.org). Also, networks in the form of shops, vendors, and e-commerce sites collect a significant amount of the discarded electronics for reuse after dismantling parts and components. The formal sector does not participate due to high handling and procurement costs, low margins, and underutilization of capacity. With its expensive purchase prices, the formal sector has no choice but to compete with scrap metal pickers.

While nothing enters into a landfill, the key concern is that almost all of the e-waste is handled by local players. There are many health hazards and risks associated with e-waste disposal that are not known to those who are disposing of it (Rautela et al. 2021). There are legal restrictions on scavenging and dealing with the materials. Vans and trucks must be covered. Workers must be provided with personal protective equipment. There is no way to cut back on this expenditure.

Thus, the administration may well look at teaming up with the industry to draw out standard norms and procedures for e-waste management and a phased approach toward the plan of dropping e-wastes generation to the minimum. Otherwise, the administration may also refer to approaches agreed by other countries for effective collection and recycling of e-wastes. For instance, South Korea, one of the main producers of electronics, managed to reuse 21% of the entire 0.8 Mt of e-wastes that it created in the year 2015 (www.teriin.org).

## 2.5 Rules and Regulations of the Land

Electronic waste is one of the leading sources of valuable and precious metals. There has been a lot of attention focused on mining metals from waste, especially in urban areas. This is due to its lucrative profit potential, source of livelihood, and potential fulfillment of Sustainable Development Goals for 2030. The significant amount of e-waste poses a substantial hardship owing to the existence of deadly chemicals. At present, India stands at the bottom position among 180 countries on the Environmental Performance Index 2022 (frontline.thehindu.com). If the rule is strictly implemented, adequate awareness is created, skill sets are trained, and affordable technology is provided to the informal sector, we could see a change in e-waste stream management.

The Department of Environment, Forests, and Climate Change is largely accountable for rules concerning e-wastes. In addition, the Central Pollution Control Board and State Pollution Control Board provide execution mechanisms for smooth running of instructions fixed by the Ministry of Environment, Forest, and Climate Change. In 1992, India ratified the export of e-waste permitted by the Basel convention. The Hazardous Waste Rules, passed in 1989 and amended in 2003, failed to address bulk collection, carriage, and removal of this heterogeneous waste. The watchdogs were unable to check and control the local metal scrapers.

The first rules for coping with e-waste in India were presented in 2011. They were put into action in the year 2012. The e-waste rules were amended in the year 2016 and 2018. Despite the fact that the guidelines of the revised rule of 2012 instructed takebacks, the rule did not include directives, targets, or impetus. Changes made in 2016 delivered stricter monitoring by stating stricter takeback goals. The E-Waste (Management) Rules, 2016 require manufacturers to run a system of e-waste bulk assemblage, storing warehouse, transference, and environmentally sound disposal and reprocessing to be carried out under extended producer responsibility (EPR) policy. Furthermore, the rules endorse and support the establishment of an efficient e-waste collection mechanism. The data, however, show that not even 25% of the e-waste generated is being managed properly. Similarly, untreated e-waste is not managed properly. It is dumped in open waste and water bodies (thehindubusinesline.com).

Under EPR, the most recent alterations done in the year 2018 altered takeback goals by 10% each year till 2023. Subsequently, the goal of tack back has been fixed to 70% of the total e-waste production. This modification eases certain parts of the stringent e-waste (Management Rules of 2016). The modification relates to the waste assemblage goals, which are set at 10% in the first year and increase to 20 and

30% in subsequent years. As part of this adjustment, the Central Pollution Control Board has the authority to handpick e-devices from the shopping mall to examine for compliance with guidelines. The funds required for testing are the obligation of the authority, whereas previously, this was the responsibility of the manufacturer.

The majority of large companies have rescheduled their supervision procedures for e-waste streams after legislative compulsion. Hewlett-Packard (HP), a multinational company, has established a pool or group for assembling used or worn-out devices and storage products related to information technology, along with an e-waste management consortium. Clients can replace their old HP devices and deliveries under HP's Planet Partners Program. The company has a relationship with small and medium businesses to dispose of their empty HP ink containers at the e-waste assemblage or pool hub managed by an e-waste handling consortium.

One of the largest software companies in the world, Lenovo, has started a unique group of services called Lenovo Asset Recovery Services for traders in India. These services handle information technology devices by returning damaged or useless devices, destroying information, and performing restoration and recycling. Any Lenovo product can be recycled for free. They will also receive a certificate showing their device was recycled ethically.

Several organizations are working to bring local scrap metal pickers into mainstream society. Saahas, a non-government organization that focuses on waste management and is also a producer responsibility organization, sort out 1500–2000 Mt of e-waste each year. By bringing foragers and unorganized e-waste dealers under the company's roof, it offers them a safe and secure environment.

EPR is an international practice that ensures the return of worn-out and damaged electronic devices. A brand-new plan called PRO is introduced. Producers should meet targets of 20% of the waste generated from the production and sale of e-products. The goals of the PRO scheme will rise by 10% yearly for the next five years. Moreover, the regulation emphasizes that the duty of producers is not limited to waste assemblage, but also to ensure that the waste reaches the accredited people involved in reprocessing and disposing of e-waste.

The pandemic is also a factor contributing to more e-devices added to the work environment and teaching–learning moving toward virtual modes. Though law and instructions have made significant progress and grew over time, to bring small industrial players under the ambit of regulation is a significant challenge. This can be done through incentive methods.

## 2.6 Capability of Reprocessing of E-waste in India

It has established cheap schemes for recycling valuable plastics in a natural way, including two reprocessing know-how processes. One with capacity of thousand kg of flat modules per day (35 Mt e-wastes) and another with hundred kg flat modules/batch (3.5 Mt e-waste) processes. The thousand kg of flat modules per day provided by a treatment plant is suitable for design of an eco-park in the country, while the hundred kg flat modules per batch treatment facility is appropriate for unorganized or daily wage collectors. This initiative may promote the well-being of daily e-waste collectors.

Approximately, one-fourth of the total weight of e-waste is made up of polystyrene type plastic. A unique method for retrieving, altering, and upscaling plastic obtained from e-waste has also been established. It has been verified that the established process is adept at altering approximately three-fourths of waste plastics into proper substances for the production of virgin plastics. Commercialization of the technology has already begun. The establishment of small-scale mills in India will convert e-waste into recyclable material such as terra cotta and filaments made out of plastics of a polylactic acid nature for three-dimensional printing.

It is possible to separate superior quality metals such as gold, silver, copper, and palladium from e-waste and repurchase them under secure conditions. Burning plastic unnecessarily gives out black carbon. Plastic waste can be compressed in a temperature-controlled environment, in micro-factories to create filament. It is possible to build a modular micro-factory wherever waste is piled up, which would require a space of 50 $m^2$. Local operators will be empowered if initial capital for expenditures is provided.

In India, recycling of e-waste has an enormous potential. There have been some positive developments in this regard. There are still many issues to address, including preparedness campaigns, proficiency development, building human resources, and technology adaptation. Additionally, the informal sector needs to adopt adequate safety measures.

PCs account for 70% of e-waste annually, 12% comes from telecommunication companies, 8% from health monitoring devices, and 7% from electric devices. Nearly, 75% of e-waste is generated by the administration and other sectors, with only 16% being generated by individual households.

Progress in the information technology and communication sectors has increased the use of electronic equipment rampantly. Electronic product upgradation is forcing consumers to discard outdated products very quickly, which, in turn, add e-waste stream. The problem of e-waste is getting bigger and calls for increased emphasis on reprocessing of e-waste and improvement in supervision of e-wastes. The ability to get and recover stuff from e-waste helps to reduce the need to dig them from subsoil. This preserves natural resources globally. The United Nations found that precious metal deposits in electronic waste are between 40 and 50 times richer than found in ore mined from the earth.

Reprocessing authorized e-waste is widely recognized as the right way to manage e-waste, which lowers greenhouse gas emissions and contributes to minimizing environmental degradation. Thus, recycling of e-waste will lower air and water pollution if proper disposal of e-waste is done.

The following salvaging and reusing methods are used for reprocessing printed circuit board waste: air classification method, magnetic separation method, mechanical recycling, pyrolysis method, hydrometallurgical method, and biometallurgical method (Abdelbasir et al. 2018a, b). Pyrolysis is a method of melting printed circuit boards so that copper can be extracted through subsequent leaching. The boards are heated to a high temperature so that they melt. After the residue has been burned, it can be heated with ammonia chloride to extract more types of metals. Under the heating conditions of 300 °C for 4 h with 3 g ammonia chloride per burned residue about 93% copper, 100% nickel 100% zinc, and 100% lead could be salvaged or restored (Panda et al. 2020). In the hydrometallurgical method, the metal components are thawed in strong acids and the metals are recovered (Rao et al. 2021). Bioleaching is used in biometallurgical recycling to recover the metals. After recycling of printed circular boards, metals are restored, and non-metallic material is left aside. After different levels of recycling, this non-metallic portion can be used as filler material.

## 2.7 Global Scenario on E-waste Generation (2019–2030)

In 2019, 54 Mt of damaged or end-of-life electronic commodities was generated worldwide. In the past few decades, e-waste has increased due to factors such as consumer spending power and the availability of electronics. Globally, e-waste will increase by 30% by 2030 (Forti et al. 2020). E-waste is mass-produced worldwide at an estimated rate of seven kilograms per capita per year. There is a wide variation in regional amounts. While Asia produces the maximum e-waste worldwide, people in richer nations produce higher per capita than people in emerging nations. In contrast, Asia generates only five kilograms of e-waste per capita, while Europe generates more than 16 kg. The figure is even lower in Africa, where it is only 2.5 kg per capita per year.

Global E-waste Statistics is partnered with Global E-waste Monitor. In its third edition published in 2020, it provides comprehensive insights into the world's e-waste challenge (www.itu.int). Thousands of people are attracted to the digital economy and global information society. E-commodities use is increasing as incomes of common people have risen in a suburban environment, resulting in waste. Approximately, 53.6 million Mt of e-waste were produced world-wide in 2019, an increase of 9.2 Mt from last five years ago. They contain harmful and unsafe materials such as mercury, bromine and chlorofluorocarbons. People's fitness and well-being are at risk if these substances are not handled properly.

In 2019, only 17.4% of e-waste was accumulated and reprocessed. The ITU's Plenipotentiary Conference, the highest policy-making body, set a goal of increasing global e-waste recycling to 30% by 2023. If that target is to be met, the authorized accumulation and reprocessing amount must rise much more rapidly. Between 2014 and 2019, the total number of countries that ratified national e-waste policies, legislation, or rules increased from 61 to 78. Many regions struggle with regulation, execution, and the collection and proper disposal of e-waste.

Governments and environmental officials around the world work with the environmental protection administration (EPA) to manage e-waste. US EPA and Taiwan's EPD organize the International E-Waste Management Network (IEMN), bringing together environmental e-waste management players from North America, Latin

America, the Caribbean, Africa, and Asia to discuss best practices for e-waste handling. This policy aligns with the USA government's vision, which outlines the local government's vision for managing electronics over their lifetimes. As part of the EPA's efforts to address the e-waste problem in developing countries, it also cooperates with the Solving the E-Waste Problem program (STEP), previously known as UNU-Step, was developed by United Nations University (UNU). In November 2010, the EPA and UNU entered into an agreement to work jointly on e-waste through 2015. UNU-Step's work focuses on tracking the global flow of e-waste, the "Person-in-the-Port" project in Nigeria, the balancing of an e-waste dismantling facility in Ethiopia, and the expansion of a device to collect data about the capacities of e-waste generated in the countries and those wastes shipped abroad.

## 2.8 Future Scenario in E-waste Management

There will be an increase in demand for e-products due to the mass growth of people, increased spending power, and enhanced accessibility. As technology advances, the number of e-products will not increase as rapidly. Smart phones are an example of a device that can replace several other devices, such as GPS devices, cameras, and music players. E-commodities and e-parts will be combined into single units, such as wood, vehicles, and buildings. In the near future, commodities will have additional characteristics that are both impressive and complex in terms of outlook and use. This will not accelerate the retrieval of substances from worn-out devices even further. Additionally, gaining relevant expertise might result in less investment in making finished products, reducing the overall lifecycle and toxic side effects. Certain artifacts used in clean energy production, such as solar batteries, displays, solar panels, and lighting tools, will have a big impact. With an increase in extreme temperatures and heat waves in summer months, which is expected to increase in the future, there will be more purchases of appliances used for cooling buildings. This could lead to safer materials and the launch of eco-design items. Novelties and global political issues would drive and affect efforts to retrieve end-of-life material.

## 2.9 Difference in E-waste Management in India with the Other Selected Countries

In 2019, as per the Global E-waste Monitor, India ranked third in terms of the amount of e-waste produced. More than 10.12 million tons of e-waste was generated by China in 2019, followed by the USA with 6.91 million tons, and India with 3.23 million tons. China reprocesses fewer than 2% of its total e-waste each year. In 2018, India generated and imported over two million tons of e-waste. Most waste is disposed of in open landfills. In six years to 2019, India's e-waste almost doubled to

3.23 million metric tons, as per article of 2020 of the Global E-waste Monitor Report. E-waste management technologies, technical expertise, and recycling handling units are available in most developed countries (Andrade et al. 2019). Comparatively, the situation differs in emerging nations due to numerous hardships and the lack of an appropriate plan of action. In India, there are multiple obstacles affecting the whole e-waste chain, including the disintegration of data, unreliable disposal, and a lack of reprocessing options. Since 2011, India is the only nation in South-Asia with appropriate guidelines for control of e-waste.

Televisions, handsets, computers, and hard copy peripherals (scanners, printer and fax machines) made up 2.37 million tons of wastes which were disposed of by US consumers and businesses in 2009. Around 25% of these semiconductor technology goods were collected for reprocessing, and the rest were disposed of in landfills without recovering the precious metals.

E-waste is recycled less than 40% in the EU, while the remainder is not sorted. Different Member States have different recycling rates. According to Eurostat, Croatia had the highest rate of recycling e-waste in 2017 with 81.3%, followed by Malta with 20.8%, and Romania with only 25%, ranking sixth overall. Globally, if little is done in comparison to what is being done now, the amount of waste will double by 2050 and beyond. The information comes from the WEF report titled "A New Circular Vision for Electronics-2019."

In the revised Circular Economy Action Plan (CEAP), the European Commission prioritizes reducing electronic and electrical waste. Objectives of the plan include eco-design, the right to repair and improving reusability in general, as well as introducing a common charger for mobile phones and other similar devices and implementing a reward system to encourage recycling of electronic devices.

Because of the increasing use of worn-out EEE, countries like China, Indonesia, India, and Malaysia have become dump sites for e-waste from wealthy and advanced nations. These nations lack the infrastructure and services necessary for proper reprocessing of e-waste using well-organized scientific skills.

Internationally, 53.6 Mt of e-wastes were formed in 2019, as per UN's Global E-waste Monitor 2020 with a 21% surge during the five-year period. The report estimated that global discarded products like batteries or plugs will reach 74 Mt by 2030, more than doubling in 16 years. It is primarily driven by increasing usage rates of devices, short lifespans, and few renovations, that e-waste have become the fastest-growing domestic waste stream. Only 17.4% of e-waste was collected and recycled in 2019. As a result, precious metals and valuable salvage materials worth US $57 billion are disposed of haphazardly rather than reprocessed and reused.

Asia produced the highest amount of e-waste (24.9 Mt) in 2019, followed by the USA (13.1 Mt), Europe (12 Mt), Africa (2.9 Mt), and Oceania (0.7 Mt). Prior to previous year's data, the weight of e-waste was as heavy as all the grown-ups in Europe, or as bulky as 350 cruise ships put together in a straight column, sufficient to make a contour of 125 km. There is uncertainty about the outcome of 82.6% (44.3 Mt) of e-waste generated in 2019, as well as the influence on the location and

**Table 2.1** Factors influencing current e-waste scenario

| Factors | | | | | |
|---|---|---|---|---|---|
| Technical expertise | Trade | Impacts | Users | Management of e-waste | Schemes to reduce e-waste |
| Novel material | Raw material retrieval | Toxicity | Conduct | Collection targets | Basal conventions |
| Growth on clean energy based area | Product-service supply chain | Material utilization | Sustainability and environment awareness | Resource losses | Nonlinear model or platform based model |
| Improved e-devices | Scheme like EOL | Ecosystem | Purchasing capacity | Waste shipments | Sustainable-design of e-products |

surrounding area. In rich countries, waste recycling setup is typically developed, and only 8% of e-waste is discarded in waste bins before being landfilled or incinerated. Most of these are small implements and small IT devices.

It is common for cast-off products to be refurbished and reused, and they are usually exported from economical stable countries to economically less stable countries. Despite this, a huge amount of e-waste is illegally exported to other countries or disguised as scrap metal or recycled. Around 7–20% of e-waste generated comes from the transboundary movement of used EEE. It is likely that household and business-related e-wastes are combined with other waste streams, including plastics and metals. Therefore, reprocess able portions cannot be reused, under substandard conditions without damaging the environment or without salvage of all precious materials. It is not recommended to engage in this type of practice. The infrastructure for managing e-waste in middle- and low-income countries is inadequate or non-existent (Table 2.1). In the informal sector, most e-waste is disposed of. There is often a problem of e-waste being handled improperly, posing serious health risks to workforces and to those who reside, work, and spend time near e-waste handling facilities.

## 2.10 Eco-friendly Way of Waste Management

Electronic products have gained increasing popularity in recent decades, changing how we get information and entertained. Donating used electronics extends the life of valuable items. Recycling electronics also prevents valuable materials from entering landfills. Taking note of signs indicating recyclables/reusable materials is useful. Composting consumes more natural resources and increases carbon dioxide emissions. Reusable products are a better choice. The most effective way to manage electronics is to take a comprehensive approach. By reducing, managing waste streams, the 4R's provide an ecologically sound and environmentally friendly method. By using the 4R's approach, waste streams are dealt with rationally and efficiently. The steps are reduce, reuse, recycle, and reduce again.

Recover incremental fractions from a waste stream. The larger the proportion of waste you wish to minimize, the greater the economic challenge will be. Therefore, you will have to justify costs continuously. Thus, you will be able to reduce the problem or challenge and apply the appropriate solution.

Managing e-waste properly requires not only strict surveillance and the implementation of the E-Waste (Management) Guidelines 2019 to ensure the EPR goals are met, but also a more reliable data source on e-waste accounting for adequate supervision. Tax incentives could also encourage further investment in the organized sector. Consumers play a crucial role in this. Our planet is under threat from the belief that it will be saved by someone else. The informal sector, however, continues to flourish as some producer responsibility organizations source waste from here to achieve their goals.

Virtualization, cloud computing, energy conservation, and reducing hazardous substances in electronic devices are some examples. Though most attention is focused on energy minimization, other approaches such as cloud computing have emerged as new subjects. There are several aspects to green computing. One is the management of e-waste. E-waste, or end-of-life electronic equipment, poses a threat to the entire planet.

In cloud computing, users have on-demand access to computer resources, such as storage and processing power, without having to manage them directly. Cloud services are often distributed across multiple data centers.

As well as green information technology, green computing is the analysis and practice of making productive use of computational resources. This includes reducing lethal materials, improving energy efficiency, and reducing factory waste.

In an analysis of the material flow of the e-waste trade, cathode ray tubes were traced during their pull to bits processes. The survey for market stock was used to estimate the amount of e-waste for each item. A sensitivity analysis conducted on PCs found that PCs had a maximum durability life of seven years. Additionally, a similar study showed that TVs have a maximum durability life of 12 years. In the final e-waste analysis, other factors such as e-waste inflowing the survey zone from outside were included when estimating obsolescence. The sensitivity analysis also considered effective use, use again after reprocessing, and storing of electronic items, as well as consumers' habits.

E-waste is handled in manufacturing companies through four stages which are listing or recording of e-waste generation, manufacturing-process management, bulk reduction and reprocessing and use. In the listing or recoding phase, the components used to manufacture electronic devices can be controlled, which minimizes the amount of waste produced. By forming a review of procurement items and controlling manufacturing, as well as creating an inventory tracking system, the volume of e-waste can be minimized on two fronts. Waste can be reduced in the manufacturing-process phase by improving functional and repairing processes, by varying materials used to make finished goods, and by altering the present way devices and goods are made. To minimize the volume of waste, the third step involves removing the hazardous fraction of waste from the non-hazardous fraction, thus decreasing the bulk material. Separating the waste at the source reduces the amount of e-waste generated. End-to-end, in the recycling stage, waste is salvaged and reused, protecting the environment as the hazardous substances are converted to non-hazardous substances, which can be discarded. The phrase urban mining is used when recycling e-waste (Anwer et al. 2021). India is the second largest producer of e-waste in Asia and the third among the countries listed in the world. An overwhelming proportion of e-waste is traded unorganized, while 312 registered e-waste recyclers are not functioning to their full potential. The E-Waste Management Rules of the year 2016 (modified in 2018) emphases on extended producer responsibility, whereas the blueprint of national resource efficiency scheme of the year 2019 is based on the ideas of circular economy. India is recognized as the country that abides by the principle of "unity in diversity," and this unlocks numerous prospects to unite stakeholders from numerous and similar industries to explore the options of application of the circular economy.

Eco-design or environmentally friendly design refers to the process of designing commodities and amenities that pay attention to their effect on the environment. This extends through their entire life cycle of manufacturing and disposal. It aimed to include environmental considerations in design but turned more toward eco-design practices such as product systems, individual products, and even entire industries. With the introduction of life cycle modeling, environmentally friendly design was linked to the new discipline of industrial ecology.

If the amount of e-waste could be predicted in advance, disposing of it would be more productive. Decomposition-ensemble-based hybrid forecasting techniques are employed to combine vibrational mode decomposition with exponential smoothing models and gray modeling methods for estimating e-waste quantities. As part of the verification process, samples were submitted by the US Environmental Protection Agency, Washington State, and the UK Environment Agency. In addition to predicting e-waste variations more accurately than standard models, VMD-ESM-GM methodology also provides an accurate forecast result for e-waste information. It is a valuable tool. The model is useful for estimating e-waste amounts and can help policymakers to develop recycling plans for e-waste and strategies for aiming resource efficiency (Fetanat et al. 2021).

In recent years, research has highlighted the importance of microbial remediation of metals, or biometallurgy, as an environmentally friendly technique. For bioleaching, acidophilic bacteria are commonly used. *Aspergillus niger*, *Penicillium simplicissimum*, *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Phytophthora putida*, and *Acidithiobacillus ferrooxidans* are the most common microorganisms examined in this process. Copper is recovered from bacteria in this group (65–100%) as well as lithium, nickel, aluminum, and zinc. To facilitate the bioleaching process, a temperature range between 25 and 55 °C and a pH range between 0.5 and 2.5 is necessary. The leaching efficiency of gold of *Chromobacterium violaceum* was reported to be over 70% (Liu et al. 2016). Additionally, *Pseudomonas aeruginosa* and *Pseudomonas fluorescens* can increase gold leaching efficiency by strengthening cyanide generation in the leaching process.

## 2.11 Conclusion

The E-Waste Management Rules must be strictly monitored and enforced in order to ensure EPR targets are met for successful e-waste management. Though the latest regulations require manufacturers to participate in the reprocessing of e-waste, India needs a multifaceted tactic to control e-waste generation, including boosting formal e-waste handlers, reducing purchasing prices of wastes, stopping unlawful trades and dumping, and creating awareness among informal sectors. Various problems exist related to electronic waste in the Indian context, including a lack of reprocessing options, a lack of inventory and management, and a lack of public awareness. Consequently, strategies such as environmentally friendly design of electronic and electrical devices, resource management through the concept of zero waste formation, recycling of e-devices after consumers have used them, tax levying on polluters, strict adherence to 4R principle by common people, and bioleaching are some of the ways to manage waste in an environmentally friendly manner. The need of the hour is to transform the recycling sector handled by the local e-waste pickers into a complete reprocessing and disposal system.

## References

Abdelbasir SM, El-Sheltawy CT, Abdo DM (2018a) Green processes for electronic waste recycling: a review. J Sustain Metall 4:295–311. https://doi.org/10.1007/s40831-018-0175-3

Abdelbasir SM, Hassan SSM, Kamel AH et al (2018b) Status of electronic waste recycling techniques: a review. Environ Sci Pollut Res 25(4):16533–16547. https://doi.org/10.1007/s11356-018-2136-6

Abdu N, Abdullahi AA, Abdulkadir A (2017) Heavy metals and soil microbes. Environ Chem Lett 15(1):65–84. https://doi.org/10.1007/s10311-016-0587-x

Andrade DF, Romanelli JP, Pereira-Filho ER (2019) Past and emerging topics related to electronic waste management: top countries, trends, and perspectives. Environ Sci Pollut Res 26:17135–17151. https://doi.org/10.1007/s11356-019-05089-y

Anwer S, Panghal A, Majid I et al (2021) Urban mining: recovery of metals from printed circuit boards. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-021-03662-y

Beattie RE, Henke W, Campa MF, Hazen TC, McAliley LR, Campbell JH (2018) Variation in microbial community structure correlates with heavy-metal contamination in soils decades after mining ceased. Soil Biol Biochem 126:57–63. https://doi.org/10.1016/J.SOILBIO.2018.08.011

Dutta S, Mitra M, Agarwal P, Mahapatra K, De S, Sett U, Roy S (2018) Oxidative and genotoxic damages in plants in response to heavy metal stress and maintenance of genome stability. Plant Signal Behav 13(8):e1460048. https://doi.org/10.1080/15592324.2018.1460048

Ebrahimi M, Khalili N, Razi S, Keshavarz-Fathi M, Khalili N, Rezaei N (2020) Effects of lead and cadmium on the immune system and cancer progression. J Environ Health Sci Eng 18(1):335–343. https://doi.org/10.1007/s40201-020-00455-2

Fetanat A, Tayebi M, Shafipour G (2021) Management of waste electrical and electronic equipment based on circular economy strategies: navigating a sustainability transition toward waste management sector. Clean Technol Environ Policy 23:343–369. https://doi.org/10.1007/s10098-020-02006-7

Forti V, Balde CP, Kuehr R, Bel G (2020) The global E-waste monitor 2020: quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR)—Co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam. ISBN Digital: 978-92-808-9114-0. ISBN Print: 978-92-808-9115-7

Global E-waste monitor 2020. https://www.itu.int/en/ITU-D/Environment/Pages/Spotlight/Global-Ewaste-Monitor-2020.aspx. Accessed 29 July 2022

https://frontline.thehindu.com/dispatches/india-ranks-at-the-bottom-in-a-list-180-countries-in-the-2022-environmental-performance-index/article65497256.ece. Accessed 29 July 2022

Kaifie A, Schettgen T, Bertram J, Lohndorf K, Waldschmidt S, Felten MK, Kupper T (2020) Informal e-waste recycling and plasma levels of non-dioxin-like polychlorinated biphenyls (NDL-PCBs)—a cross-sectional study at Agbogbloshie, Ghana. Sci Total Environ 723:138073. https://doi.org/10.1016/j.scitotenv.2020.138073

Kaya M (2016) Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manage 57:64–90. https://doi.org/10.1016/j.wasman.2016.08.004

Liu R, Li J, Ge Z (2016) Review on *Chromobacterium violaceum* for gold bioleaching from E-waste. Procedia Environ Sci 31:947–953. https://doi.org/10.1016/j.proenv.2016.02.119

Nazari L, Xu C, Ray MB (2021) Recovery of metals from electronic waste. In: Advanced and emerging technologies for resource recovery from wastes. Green chemistry and sustainable technology. Springer, Singapore. https://doi.org/10.1007/978-981-15-9267-6_5

Panda R, Jadhao PR, Pant KK, Naik SN, Bhaskar T (2020) Eco-friendly recovery of metals from waste mobile printed circuit boards using low temperature roasting. J Hazard Mater 395:122642. https://doi.org/10.1016/j.jhazmat.2020.122642. ISSN 0304-3894

Parajuly K, Kuehr R, Awasthi AK, Fitzpatrick C, Lepawsky J, Smith E, Widmer R, Zeng X (2019) Future E-waste scenarios. http://hdl.handle.net/20.500.11822/30809

Parvez SM, Jahan F, Brune MN, Gorman JF, Rahman MJ, Carpenter D, Islam Z, Rahman M, Aich N, Knibbs LD, Sly PD (2021) Health consequences of exposure to e-waste: an updated systematic review. Lancet Planet Health 5(12):e905–e920. https://doi.org/10.1016/S2542-5196(21)00263-1

Purchase et al (2020) Global occurrence, chemical properties, and ecological impacts of E-wastes (IUPAC technical report)

Rao MD, Shahin C, Jha R (2021) Optimization of leaching of copper to enhance the recovery of gold from liberated metallic layers of WPCBs. Mater Today Proc 46(3):1515–1518. https://doi.org/10.1016/j.matpr.2021.01.052

Rautela R, Shashi A, Vishwakarma S, Lee J, Kim K-H, Kumar S (2021) E-waste management and its effects on the environment and human health. Sci Total Environ 773:145623. https://doi.org/10.1016/j.scitotenv.2021.145623

Salam MD, Varma A (2019) A review on impact of E-waste on soil microbial community and ecosystem function. Pollution 5(4):761–774

Srivastava RR, Pathak P (2020) Policy issues for efficient management of E-waste in developing countries. In: Handbook of electronic waste management. Butterworth-Heinemann, pp 81–99

Yan A, Wang Y, Tan SN, Yusof MLM, Ghosh S, Chen Z (2020) Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. Front Plant Sci 11:359. https://doi.org/10.3389/fpls.2020.00359

Zou L, Lu Y, Dai Y, Khan MI, Gustave W, Nie J et al (2021) Spatial variation in microbial community in response to As and Pb contamination in paddy soils near a Pb-Zn mining site. Front Environ Sci 9:630668. https://doi.org/10.3389/fenvs.2021.630668

# Chapter 3
# E-waste Management Practices in India: Challenges and Approaches

**Puneeta Pandey and Raj Kumar Singh**

**Abstract** In the current era of rising consumerism and information technology, e-waste has emerged as a serious problem besides plastic pollution. The rising concern for e-waste has both economic, environmental and health consequences. It is observed that wealthy nations with advanced technology dump their electronic waste disproportionately in developing nations. The management and recycling of waste in these developing countries is mostly carried out in informal sector, where workers (both adults and children) are exposed to health hazards. Further, the sound management practices, if not employed properly, are a cause of environmental concern. The present study attempts to throw some light on India's issues in managing e-waste, the techniques available for e-waste management and legislations and international efforts in combating the menace of e-waste.

**Keywords** E-waste · Recycling · Legislations · E-waste management

## 3.1 Introduction

With rising urbanization and rampant use of internet technology, there has been an unprecedented growth in consumerism across the globe. As a result, there has been tremendous growth in the electronic sector coupled with the production and use of electronic gadgets. These pose an important opportunity for the growth of the economy, but have also become a challenge in the recent times since terms such as "e-waste" or "electronic waste" are gaining more attention. Generally speaking, waste is anything undesirable, unwanted and unusable. Therefore, waste is classified into various categories, such as agricultural waste, biomedical waste, municipal solid waste, radioactive waste and more recently, electronic waste. The majority of the time, electronic waste consists of costlier and long-lasting devices utilized in private homes, enterprises and telecommunications networks for data processing, entertainment or various other purposes. "E-waste", "electronic waste", "e-scrap" and "end-of-life

P. Pandey (✉) · R. K. Singh
Department of Environmental Science and Technology, School of Environment and Earth Sciences, Central University of Punjab, Bathinda, Punjab 151401, India
e-mail: puneeta.pandey@cup.edu.in

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_3

electronics" are terms often used to describe worn out electronic items that are abandoned, donated or sent to a recycler because they are very close to the end of their utility. Though "e-waste" is the commonly used term, *United States Environmental Protection Agency* (USEPA) defines e-waste (electronic waste) as those electronic equipments that are nearing the end of their useful life and are discarded, donated or given to recyclers to minimize the waste that might be dumped in a landfill or not disposed in a proper manner (USEPA 2022). International E-Waste Day has been observed on 14th October every year since 2018 to raise consciousness about the threats due to e-waste.

The e-waste is classified into various categories based on their sources, nature or application. Therefore, e-waste can also be considered both in the category of "white goods" that comprise home utility appliances such as microwave ovens, refrigerators or washing machines and "brown goods" such as mobile phones, televisions (TVs) and computer systems. Broadly speaking, the e-waste is classified into following categories:

i. **Electrical and electronic equipments (EEE)**: These include major appliances such as refrigerators, washing machines, dryers; small appliances such as vacuum cleaners, irons, blenders and fryers; and computer and electronic appliances such as laptops, PCs, chargers, telephones, cellphones, musical instruments and headphones.
ii. **Electrical devices** (drills, saws, incandescent light bulbs, LED bulbs, fluorescent tubes, etc.).
iii. **Toys, leisure** (electronic toys, models, sports equipment).
iv. **Laboratory equipments and medical devices** (all medical equipment except implants, detectors, thermostats, laboratory equipments).
v. **Miscellaneous items**: These include dispensers and vending machines.

### *3.1.1 Rationale*

The global contribution of e-waste to the municipal solid waste (MSW) is approximately 5%. This proportion is increasing at quite an alarming pace. Further, the global e-waste generated during 2019 was 53.6 million metric tonnes (Mt) with a per capita of 7.3 kg. In 2021, it is estimated to be 57.4 million tonnes, and by 2030, the global e-waste market is expected to reach 74.7 Mt, with per capita waste amounting to 9 kg (Hindu Business Line 2022; CSE 2022).

The collection, recycling or disposal of e-waste is a major challenge in India in the current scenario. Table 3.1 depicts the percentage of e-waste generated in India during 2017–2020. It is estimated that nearly 15 billion tonnes of e-waste material will be generated by 2030.

**Table 3.1** Percentage of e-waste generated per year

| S. No. | Year | Percentage of e-waste |
|---|---|---|
| 1 | 2017–18 | 9.79 |
| 2 | 2018–19 | 21.35 |
| 3 | 2019–20 | 22.7 |

## *3.1.2 Effects of E-waste*

### 3.1.2.1 Effects on Human Health

The pollution caused by e-waste is more severe in underdeveloped nations as they serve as dumping grounds of e-waste generated by developed countries. Most of the world's electronic waste is recycled in underdeveloped nations, where the informal sector is responsible for processing the e-waste and recovery of metals for resale. As a result, there are environmental and public health concerns since adequate processing facilities and trained personnel for e-waste management might not exist in developing countries. E-waste contains several complex and harmful substances such as heavy metals (Pb, Cd, Cr, Pt, Hg, As), plastics, glass and other persistent organic pollutants (POPs), which are potentially toxic to environment and human health; if not handled in a scientific manner (Johri 2008). The conventional methods of dismantling, wet chemical processing, reprocessing, incineration and recycling of waste by untrained personnel have led to various health issues in these developing countries such as India and China (The Logical Indian 2021). These commonly used practices for e-waste management are responsible for direct inhalation of toxic fumes of acids and other organic pollutants (dioxins, furans, PBDEs) among the workers as majority of them do not have access to safety accessories such as gloves or masks. Table 3.2 lists the harmful effects of various components of e-waste.

### 3.1.2.2 Effects on Environment

The components of electrical and electronic equipment (EEE) when processed, recycled or disposed can impact the environment negatively. The burning or incineration of EEE releases toxic gases, fumes and particulate matter into the atmosphere. The perilous materials in EEE can leach from dumping sites of e-waste to groundwater, wells and drainage systems can pollute rivers, ponds and surface water bodies.

Besides, mining of precious metals, alloys and metal oxides in EEE by means of resource recovery in dumping sites or urban areas exerts a pressure on the natural resources of the area.

**Table 3.2** Effects of various components of e-waste on human health

| Component | Effects on human health |
|---|---|
| Arsenic (As) | Longer exposure to arsenic may cause lung damage or cancer, nerve damage |
| Lead (Pb) | A majority of electronic components and assemblies, cathode ray tubes (CRT), and printed circuit boards are the main sources of lead (PCBs). Exposure to lead causes damage to the brain, kidneys and nervous systems besides blood disorders |
| Cadmium (Cd) | Cadmium is found in batteries, semiconductors, electroplated products, chip resistors and monitors/CRTs, which damages the kidneys, liver and bones |
| Chromium (Cr) | Chromium is found in anti-corrosive coatings, and metal housings. Longer exposure to chromium can cause strong allergic reactions and DNA damage to cells |
| Mercury (Hg) | Mercury is found in switches and flat screen monitors. It is carcinogenic and long term exposure can damage the kidney and the bones |
| Copper (Cu) | The insulated wires contain copper, which when burnt to recover from e-waste causes neurological disorders on inhalation |
| Polyvinyl chloride (PVC) | It is the most commonly used plastic found in e-waste. When PVC/plastic is burnt, massive fumes of HCl are produced that cause respiratory problems on inhalation |
| Selenium (Se) | High levels of selenium exposure create a condition called selenosis, which exacerbates neurological problems, brittle nails, and hair loss |
| Persistent organic pollutants (POPs) | Skin difficulties, liver issues, and immune system impairment are brought on by prolonged exposure to dioxins and furans. Further, polychlorinated biphenyls and PBD/PBDE are found in capacitors and transformers and in plastic parts of electronics respectively; and affect the human central nervous system, reproductive system, endocrine system and immune system |

## 3.2 E-waste Management in India: Challenges

The Yale Center of Environmental Law and Policy publishes the report, "The Environmental Performance Index (EPI)" using 40 performance indicators along 11 issued categories (https://epi.yale.edu/ Environmental Performance Index, EPI, 2022). The ranking is based on climatic change, environmental health and ecosystem vitality. India ranked 180th out of 180 countries with an EPI score of 18.90; thus, needing a lot of effort to improve the environmental quality.

According to a report published by WHO called "*The Global E-Waste Monitor 2020*", it is reported that out of the 53.6 million tonnes of e-waste generated globally in 2019 about 40–50% of the waste was supposed to be recycled. But practically, only 17.4% of the waste could be recycled (Forti et al. 2020). As a result, management of e-waste becomes an even greater challenge in the current times since the production of e-waste is at an alarming rate. If not managed properly, it will be a nuisance that will eventually deplete the natural resources of any region.

Further, due to stringent regulations and high economic cost of waste disposal in developed countries, it has been observed that the developed countries dump their e-waste for processing in the developing countries. As a result, frequent transboundary movement of e-waste occurs from developed to developing countries where laws for e-waste disposal are not stringent, the labor is cheap and abundant and open dumping/disposal is prevalent.

The rising concern for recycling of e-waste has gained momentum in the recent years as a significant environmental issue because the traditional treatment technologies for e-waste have risk of contamination, are not cost-effective and have low efficiency. As a result, there is an urgent need to develop new technologies for effective management of e-waste.

According to a report published in Deccan Herald on February 14, 2022, 468 authorized dismantlers or recyclers in 22 states have a processing capacity of 13.8 lakh tonnes of e-waste in the country (Deccan Herald 2022). Among all Indian states, Gujarat processed most of the electronic waste, followed by Karnataka, Uttarakhand, Telangana and Tamil Nadu. The generation of e-waste was 7.71 lakh tonnes in the year 2018–19 and 10.14 lakh in 2019–20 with an increase of 31% as mentioned by the Central Pollution Control Board (CPCB 2022). As per information given by the Minister of State for Environment, Forest and Climate Change, Shri Ashwini Kumar Choubey, in a written reply in Lok Sabha on August 8, 2022, Table 3.3 describes the quantity of e-waste, collected, dismantled, recycled/disposed (in tonnes) during 2017–20 in India (PIB Delhi 2022).

**Table 3.3** The quantity of e-waste, collected, dismantled, recycled/disposed (in tonnes) during 2017–20 in India (PIB Delhi 2022)

| S. No. | Year | Quantity of e-waste collected, dismantled, recycled/disposed (tonnes) |
|---|---|---|
| 1 | 2017–18 | 69,414 |
| 2 | 2018–19 | 164,663 |
| 3 | 2019–20 | 224,041 |
| 4 | 2020–21 | 354,291.22 |

## 3.3 E-waste Recycling Practices in India

### *3.3.1 Informal Sector*

In India, 95% of e-waste is recycled in the informal sector while only 5% in the formal sector (Dutta and Goel 2021). It is estimated that a large number of non-formal recyclers are clustered in and around the states of Delhi, Uttar Pradesh, Rajasthan, West Bengal, Maharashtra, Gujarat, Tamil Nadu, Karnataka, Kerala and Andhra Pradesh. The process generally adopted in non-formal units begins with collection of the e-waste, dismantling the products to collect components having high resale value. To recover precious metals from the residual material, chemical treatment is used. This step of utilization of harsh chemicals for treating the e-waste is a cause of concern as it contaminates the soil by means of leachate and poses health hazards for the workers in that dumping site (Monika and Kishore 2010).

### *3.3.2 Formal Sector*

The contribution of the formal sector in e-waste recycling in India is very little, amounting to about 5% with very few recyclers operating in the formal sector. The procedures used in the formal sector are primarily restricted to segregation, shredding (for size reduction), dismantling of e-waste and preprocessing. This is then transported to smelting units for recovery of metals like gold, silver, platinum, palladium, etc., and then treating the left-over residues. If we examine clearly, a thorough elucidation of e-waste recycling is currently not commonly prevalent in India (Kumar et al. 2022). Compared to the informal sector, recycling in the formal sector is carried out following due protection measures with minimization of occupational health hazards. This also results in minimal wastage of resources, is economically viable and efficient recovery of precious metals.

### *3.3.3 Current Technologies in E-waste Management*

Thus, this method of e-waste management in the formal sector is environmentally sound besides utilizing sophisticated equipment and techniques for efficient recovery of metals. A few technologies in this sector work on a zero-landfill approach. In India, Ministry of Environment, Forest and Climate Change (MoEF&CC) issued an advisory to all the government departments/offices to dispose e-waste generated in various offices in an environmentally sound manner pursuant to the Hazardous Wastes (Management, Handling and Transboundary) Rules, 2008. Further, the units handling collection, segregation, dismantling and recycling of e-wastes have to register with the Central Pollution Control Board (CPCB). A few recent methods employed to treat e-waste are as follows:

- **Electrokinetic Remediation (EKR)**: It is based on applying a direct electric current to the pervious media that needs to be decontaminated, in which the contaminants are gathered near the electrodes and treated. Electrokinetic Remediation (EKR) is an up-and-coming soil remediation approach. Further, electrokinetics must be used in conjunction with bioremediation, Fenton methods and ultrasonic remediation for hydrophobic substances like POPs.
- **Phytoremediation**: Plants are used in phytoremediation to collect, store and/or decompose contaminants from the soil. As a result, it is taken into consideration as a potential technique for cleaning up e-waste contaminated places. Another effective method would be utilizing microbes, individually or in consortia to bioremediate the e-waste contaminated site without the use of harsh chemicals (Saxena et al. 2021).
- **Electrochemical techniques** are important for converting metallic ions to bare metals, which can be later utilized as secondary resources for the metal industries.
- **Nanotechnology** is emerging as a vital application technique for sustainable management of e-waste. Despite the fact that numerous methods have undergone laboratory testing, efficient technical process development is still required to recover metals, metal oxides and alloys from e-waste. Recovery and reuse of nanomaterials by an effective engineering process may help in reducing the burden of extraction of these metals or alloys.
- **Circular Economy**: The circular solutions for e-waste primarily focus on prolonging the usage life of an electronic item and then refurbished professionally or reused or repaired to minimize the damage due to e-waste. Then, the valuable components within them are separated and recycled. A policy paper by Ministry of Electronics and Information Technology, Government of India, New Delhi, emphasizes on principles of circularity by ensuring producers to be made responsible for cradle-to-cradle management of the products under the scope of Extended Producer Responsibility (EPR), a key component of the E-Waste Management Rules, 2016 (Ministry of Electronics and Information Technology 2021; Goosey and Goosey 2020).

A case study in India by Jatindra and Sudhir (2009) was conducted to assess the management and recycling of e-waste, its collection, flow and recycling systems in Bangalore city of India. Bangalore is also known as the Silicon Valley of India and is an information technology hub of more than 67,000 registered IT companies making India's largest IT hub. In the present study, a model was designed using personal computers as the tracer. Field survey and analysis of available data was carried out to depict the life cycle of tracer, from production to consumption—including reuse and refurbishment—to material recovery in the formal recycling industry. The findings show that such models might be duplicated in other Indian cities, and that one of the main factors driving the pre-recycling procedures is the refurbishment and upgrading of personal computers and monitors. The study intends to reduce the environmental and health impacts from unscientific e-waste management and for understanding of e-waste collection, flow and recycling.

## 3.4 International Efforts

Various initiatives have been carried out by international agencies to look into problems of climate change. It is pertinent to mention that National Environmental Policy (NEP) conveys the Sustainable development Goals (SDGs) of UNESCO. The NEP also promotes legalizing the collecting and recycling of different materials as well as supporting the informal sectors for resource recovery.

Further, the USEPA and the Taiwan Environmental Protection Administration (EPAT) got into a cooperative agreement known as International E-Waste Management Network (IEMN) where government officials from both the countries yearly gathering to share best practices and hear about e-waste management advancements from professionals. The IEMN first began in 2011 and since then, officials from the governments of Asia, Africa, Latin America, the Caribbean and North America have attended the event (USEPA 2019).

On August 4, 2014, EPA, CEQ and GSA joined the US Postal Service in Washington, DC, to release a report "*Moving Sustainable Electronics Forward: A Update to the National Strategy for Electronics Stewardship*", that lists the development of statistics on international circulation of e-waste and the consolidation of management strategies of e-waste.

Another report titled **Children and Digital Dumpsites** published by WHO on June 15, 2021 emphasizes on the menace of women and children working in the informal sector of e-waste recycling. It is estimated that 18 million children as young as 5 years and 12.9 million women work at these e-waste dumpsites every year; who become vulnerable to cancer, cardiovascular diseases and damage to lungs and the genetic structure, besides expecting mothers suffering from premature births and stillbirth.

## 3.5 Legislations Related to E-waste

i. **Basel Convention**

At its twelfth meeting, the conference of the parties to the Basel Convention adopted the Basel Convention, on an interim basis (Decision BC-12/5). It consisted of 170 parties and came into enforcement from 1992. It ordains the technical rules for transboundary transfers of used electrical and electronic equipment, particularly with reference to the Basel Convention's distinction between waste and non-waste (UNEP 2022).

ii. **E-Waste Management, 2016**

The government of India launched the E-Waste Management Rule in 2016 with the objective of managing e-waste falling under both hazardous and non-hazardous categories.

The legislation was issued by the Ministry of Environment, Forest and Climate change (MoEF&CC), where emphasis was laid on the responsibilities assigned to the manufacturers, producers, collection centers, dealers, refurbishers, bulk consumers, dismantlers, recyclers and also to the state governments for environmentally sound management of e-waste. Further, this rule contains I–VI chapters and I–IV schedules.

The details of chapters are given below:

CHAPTER I: Deals with preliminary details (Short title and commencement, application and definitions).

CHAPTER II: Defines the responsibilities given to all the sectors from manufacturers to recyclers.

CHAPTER III: Focuses on procedure for seeking and grant of authorization for management of e-waste.

CHAPTER IV: Deals with the methods to store e-waste. It emphasizes that each manufacturer, producer, bulk consumer, collection center, dealer, refurbisher, dismantler and recycler may store the e-waste for a time limit not to exceed one hundred and eighty days. They must also keep a record of the wastes they collect, sell, transfer and store and make this record available for inspection. It also reiterates that the State Pollution Control Board in question may extend the time limit up to 365 days if it is necessary to hold the waste particularly in order to find a method for its recycling or reuse.

CHAPTER V: Focuses on reducing the use of hazardous materials in the production of electrical and electronic equipment, as well as the parts, consumables and spares that go with it.

CHAPTER VI: Focuses on miscellaneous things such as duties of authorities, annual report, transportation of e-waste and accident reporting.

Further, the Schedules of the E-Waste Management Rules focus on the following:

**SCHEDULE I**: It focuses on the categories of electrical and electronic equipments (EEE) including their components, consumables, parts and spares and also, the responsibilities of the stakeholders.

Accordingly, responsibility of the manufacturer is to collect all the e-waste which is being produced during the manufacturing of any electrical and electronic equipment and steer it to recycling and disposal and maintain all the documents and records of the produced e-waste. Responsibility of the collection center is to check and ensure that e-waste is stored in a safe and secure manner and also to guarantee that no environmental harm occurs while it is being stored. Dealer responsibility is to collect e-waste on behalf of the producer and pay back to depositors as per the "deposit fund scheme" of producer. Under this scheme, the producer levies an additional amount as a deposit at the time of sale of the electrical and electronic equipment (EEE) which is returned to the consumer at the time of return of these goods along with interest. They are also responsible for the safe transportation of e-waste to authorized dismantlers.

Further, dismantler's responsibility is to ensure that all processes of dismantling should be under the standards and guidelines of the Central Pollution Control Board, and no damage should be caused to the environment. Responsibility of the recycler is to follow the standards and guidelines for the recycling process and to ensure the components of waste produced during the recycling process needs to be disposed of in facilities for treatment, storage and disposal. The overall process is as follows:

$$\begin{aligned}&\text{Manufacturer} \rightarrow \text{Producer} \rightarrow \text{Collection center} \rightarrow \text{Dealer}\\&\rightarrow \text{Recycler} \rightarrow \text{Dismantle} \rightarrow \text{Bulk consumer} \rightarrow \text{Refurbisher}\end{aligned}$$

**SCHEDULE II**: It focuses on the applications, which are exempted from the requirements of sub-rule (1) of rule 16.

**SCHEDULE III**: It defines the targets for extended producer responsibility.

**SCHEDULE IV**: Discusses the duties of authorities such as the Central Pollution Control Board (CPCB), State Pollution Control Board (SPCB), Urban Local Bodies (ULBs) and Port authorities.

Besides, the rule explicitly mentions the following forms:

| | |
|---|---|
| Form 1 | Authorization for extended producer responsibility |
| Form 1a | Authorization for generation or storage or treatment or disposal of e-waste by manufacturer or refurbisher |
| Form 1b | Format for granting permission for the manufacture or refurbisher to create, store, treat, reuse or dispose e-waste |
| Form 2 | Form for maintaining records of e-waste handled or generated |
| Form 3 | Form for filing annual returns |
| Form 4 | Form for authorization of facilities possessing environmental sound management practice for dismantling or recycling of e-waste |
| Form 5 | Form for annual report to be submitted by the State Pollution Control Board to the central pollution control board |
| Form 6 | E-waste manifest |
| Form 7 | Application for filing appeal against the order passed by Central Pollution Control Board/State Pollution Control Board |

Further, it is pertinent to mention that these rules are not applicable to items covered under Batteries (Management and Handling) Rules, 2001; Micro, Small and Medium Enterprises Development Act, 2006 (27 of 2006); and Atomic Energy Act, 1962 (33 of 1962).

The E-Waste Management Rule, 2016, was amended with minor modifications in 2018 for effective management of e-waste in India and is called as E-Waste (Management) Amendment Rules, 2018.

## 3.6 Summary

In the current environment, the phenomenon of sustainable production and consumption places e-waste among the top waste problems. Although both formal and informal sectors are involved in management of e-waste, it cannot be denied that e-waste collection, dismantling and recycling processes are the main sources of income and livelihood for sizeable amount of population in developing countries. Therefore, it becomes pertinent to make them aware about the hazards related to the processes of dismantling and recycling, so that they can be well equipped to protect themselves. Further, circular economy can provide a viable solution to the problem of e-waste management; since it emphasizes using EEE for much longer periods, and not just "use and throw" strategy. Further, repaired or refurbished electronic items should be made economically viable or incentivized; so that more and more people purchase it, thus, minimizing the e-waste dumping. People can buy second hand electronic devices or can try to fix the problem of their existing electronic devices before going for the new one. Further, strict implementation of existing legislations and formulation of new policies for the recycling, reusing or dismantling is necessary for workers health as well as environmental health. Spreading awareness and educating the population about the potential consequences and impact of electrical and electronic equipment on the environment can lead to better results in the coming future.

## References

Central Pollution Control Board (CPCB) (2022) https://cpcb.nic.in/. Accessed 29 Aug 2022

Centre for Science and Environment (CSE) (2022) https://www.cseindia.org/. Accessed 20 Aug 2022

Deccan Herald (2022) https://www.deccanherald.com/national/generation-of-e-waste-in-india-sees-31-annual-growth-1081505.html. Accessed 29 Aug 2022

Dutta D, Goel S (2021) Understanding the gap between formal and informal e-waste recycling facilities in India. Res J Waste Manag 125:163–171

EPI (2022) Environmental Performance Index. https://epi.yale.edu/. Accessed 18 Aug 2022

Forti V, Baldé CP, Kuehr R, Bel G (2020) The global E-waste monitor 2020: quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations

Institute for Training and Research (UNITAR)—Co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam

Goosey E, Goosey M (2020) Introduction and overview, chap 1. In: Eduljee GH, Harrison RM (eds) Electronic waste management. Issues in environmental science and technology, vol 49, 2nd edn. The Royal Society of Chemistry. ISBN: 9780128170304. www.rsc.org

Hindu Business Line (2022) https://www.thehindubusinessline.com/. Accessed 29 Aug 2022

Jatindra PK, Sudhir K (2009) E-waste management: a case study of Bangalore, India. Res J Environ Earth Sci 1(2):111–115. ISSN: 2041-0492

Johri R (2008) E-waste: implications, regulations, and management in India and current global best practices. TERI Press, pp 1–36. ISBN: 9788179931530. https://bookstore.teri.res.in/books/9788179931530

Kumar S, Agarwal N, Anand SK, Rajak BK (2022) E-waste management in India: a strategy for the attainment of SDGs 2030. Res J Mater Today Proc 60(2):811–814

Ministry of Electronics and Information Technology (2021) Circular economy in electronics and electrical sector (policy paper). Ministry of Electronics and Information Technology, Government of India, New Delhi. https://www.meity.gov.in/writereaddata/files/Circular_Economy_EEE-MeitY-May2021-ver7.pdf. Accessed 20 Sept 2022

Monika, Kishore J (2010) E-waste management: as a challenge to public health in India. Indian J Community Med 35(3):382–385. http://www.ijcm.org.in/

PIB Delhi (2022) https://pib.gov.in/PressReleasePage.aspx?PRID=1849863. Accessed 2 Nov 2022

Saxena G, Maulin PS, Vineet K (2021) Bioremediation for environmental sustainability: toxicity, mechanisms of contaminants degradation, detoxification and challenges. Elsevier. ISBN: 9780128205242. https://doi.org/10.1016/C2019-0-01053-9

The Logical Indian (2021) https://thelogicalindian.com/trending/electronic-waste-generation-32756. Accessed 29 Aug 2022

UNEP (2022) Basel Convention. http://www.basel.int/. Accessed 29 Aug 2022

USEPA (2019) https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste. Accessed 29 Aug 2022

USEPA (2022) US Environmental Protection Agency. https://www.epa.gov/. Accessed 20 Aug 2022

# Chapter 4
# Bioleaching for Heavy Metal Extraction from E-waste: A Sustainable Approach

**Vaanie Godbole, Sweta Kukrety, Pankaj Gautam, Manisha Bisht, and Manoj Kumar Pal**

**Abstract** The globalization has brought forth a plethora of innovations and gadgets that make life easier; however, these advancements along with increasing demands for better technologies have led to the accumulation of electronic waste in the environment. E-waste encompasses all discarded, broken, or obsolete electronic items, viz. mobile phones, refrigerators, and printed circuit boards (PCBs). The main cause for concern is the non-biodegradable nature of these wastes which allows them to persist and accumulate in the ecosystem. The heavy metal counterparts of the waste can leach out and accumulate in the food chain, damaging the flora and fauna. Despite their environmental concerns, e-wastes are good source of recovering heavy metals and reusing them for industrial purposes. Bioleaching is an eco-friendly method which utilizes microbes to aid in leaching out heavy metals from e-wastes and has gained popularity owing to its sustainability. This method is applicable for a large range of metal ions, has lower energy requirements, and produces less pollutants. This chapter discusses the types of bioleaching processes, their use, and applicability in recovering heavy metals from printed circuit boards (PCBs) and spent batteries.

**Keywords** Bioleaching · E-waste · Metal recovery

## 4.1 Introduction

The modernization of civilization is accredited to technological advancements and innovations that have made life easier. The usage of multiple gadgets like mobile phones, laptops, televisions, and refrigerators has become a necessity. However, with the advent of such technologies, coupled with a consumeristic society and production of updated models has given rise to another environmental issue: "Electronic

V. Godbole · S. Kukrety · P. Gautam · M. K. Pal (✉)
Department of Life Sciences, Graphic Era (Deemed to be) University, 566/6, Bell Road, Society Area, Clement Town, Dehradun, Uttarakhand 248002, India
e-mail: manojpal.bt@geu.ac.in

M. Bisht
Department of Chemistry, L.S.M. Government P.G College, Pithoragarh, Uttarakhand 262501, India

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_4

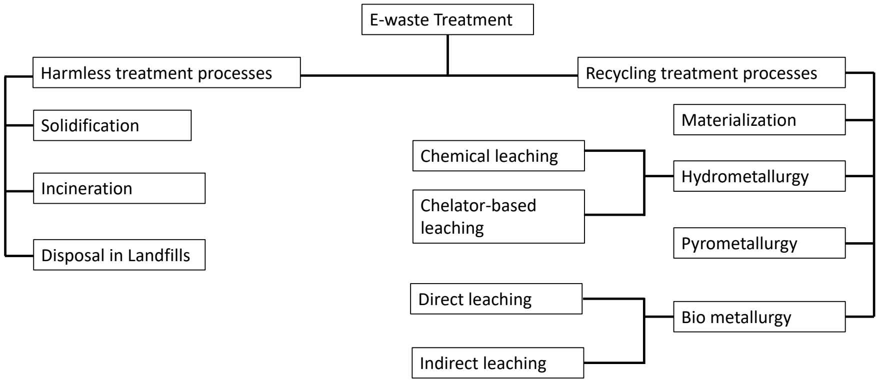



**Fig. 4.1** Various strategies employed for e-waste treatments

waste" (Grace Pavithra et al. 2020; Kaur et al. 2022). E-waste or electronic waste are discarded, broken, or obsolete electronic items, viz. mobile phones, refrigerators, and printed circuit boards (PCBs). These parts comprised heavy metals like mercury (Hg), arsenic (As), zinc (Zn), antimony (An), lead (Pb), and other organic compounds. The main concern regarding e-waste is that it persists and accumulates in the environment due to its non-biodegradability (Ayangbenro and Babalola 2017). Heavy metals can accumulate in the food chain and can cause irreparable damage to the ecosystem and biota (Manna et al. 2018). Therefore, there is an urgent need to form regulations for the proper disposal and extraction of precious metals from e-waste and create awareness about the long-term repercussions of e-waste contamination (Rubio et al. 2002) (Fig. 4.1).

E-waste is a good resource to recover precious metals and can potentially prevent mining and the cumbersome processes that follow for the purification of metals. A report by the Global e-waste monitor informs that 53.6 million metric tons of e-waste was generated alone in 2019 in the entire world and this quantity is said to rise to 74 million metric tons by 2030 (Forti et al. 2020). Currently, only 15% of the e-waste generated is subjected to heavy metal extraction and the rest is unused and unaccounted for (Heacock et al. 2016). Therefore, in order to easily extract metals from e-waste, the concept of "Urban mining" has gained popularity over the years (Arora et al. 2017). An eco-friendly approach used in urban mining is bioleaching. Bioleaching or microbial leaching is a type of bio-metallurgical technique that utilizes microbes to extract heavy metals from e-waste by direct and/or indirect methods (Cui and Zhang 2008). Bioleaching has gained popularity over the years for treating mining industry wastes, sewage waste, and e-waste; it can extract heavy metals via different techniques, viz. adsorption, dissolution, exchange, oxidation, and reduction (Quatrini and Johnson 2018).

This chapter sheds light on the disadvantages of current recycling technologies and how the use of bioleaching can help mitigate those issues. The types of bioleaching and their recent applications in heavy metal extraction from printed circuit boards (PCBs) and spent batteries using microbes that perform bioleaching have been discussed.

## 4.2 Bioleaching

The accumulation of e-waste in the environment is an issue that needs to be addressed swiftly due to the health risks associated with heavy metals (Table 4.1). Currently, the most common methods of e-waste disposal are incineration, solidification, or disposing waste in a landfill (Bai et al. 2019). In terms of the recycling process, two techniques, i.e., pyrometallurgy and hydrometallurgy, are used to extract heavy metals from e-waste. However, these methods are not sustainable as they generate hazardous secondary waste that is difficult to dispose; moreover, the commercial facilities developed for these procedures have high operating costs and risks to personnel (Baniasadi et al. 2019).

In order to circumvent these issues, bioleaching is gaining popularity. Bioleaching is a bio-metallurgical method that utilizes microorganisms to extract heavy metals from e-wastes by either secreting organic acids, inorganic acids, and cyanide or by forming metal complexes that can then be refined and purified to obtain the desired heavy metal (Xiang et al. 2010; Vakilchap et al. 2016). Bioleaching has many advantages over the other physical and chemical methods, namely leaching of a large range of metal ions, a high rate of dissolution, and lower energy requirements; moreover, biological methods are eco-friendly and produce less pollutants (Yaashikaa et al. 2022). *Acidithiobacillus ferrooxidans* was discovered in 1947 by Colmer and Hinkle as a potential bioleaching microbe (Colmer and Hinkle 1947). Many microbes have been discovered with the capability to perform bioleaching, namely *Acidithiobacillus thiooxidans*, *Aspergillus niger*, *Chromobacterium violaceum*, and *Thiobacillus ferrooxidans* (Pant and Dhiman 2020).

Metal recovery from e-waste by bioleaching is a cumbersome process owing to the varying physical and chemical properties. Moreover, various heavy metals are toxic to the microorganisms and can render them inactive. Therefore, e-waste has to undergo pre-treatment processes, viz. sorting, crushing, shredding, and sieving to tackle these issues (Jowkar et al. 2018; Zhou et al. 2020) (Fig. 4.2).

### *4.2.1 Direct Bioleaching Pathway*

The direct pathway depends on the direct interaction of microbes with the waste material. Metal oxidation is brought about by the enzymes secreted by the microbes. The initiation of bioleaching can be done by the inoculation of bioleaching agents in

**Table 4.1** Heavy metal components of various electronic wastes and their health hazards

| S. No. | Type of E-waste | Heavy metal component | Health consequences | References |
|---|---|---|---|---|
| 1. | Printed circuit boards (PCBs) | Mercury | Vision problems, muscle weakness, tremors, nervous system dysfunction | Palanisamy et al. (2022) |
| 2. | Copper wires | Copper | Wilson's disease, stomach pains and cramps, liver damage | Gopikrishnan et al. (2020) |
| 3. | Cathode ray tubes (CRTs) | Lead, barium | Cardiovascular, neurological and kidney dysfunction | Rautela et al. (2021), Ribeiro et al. (2022) |
| 4. | Mobile phone batteries | Lithium, nickel | Lung cancer, dermatitis, and bronchitis | Genchi et al. (2020), Hedya et al. (2022) |
| 5. | Resistors and semiconductors | Cadmium | Damage to the nervous system, liver, and kidneys | Beula and Sureshkumar (2021) |
| 6. | Galvanized steel plates and steel decorations | Chromium | Neurodevelopmental problems in infants, gastrointestinal problems, lung cancer | Beula and Sureshkumar (2021) |
| 7. | Capacitors, batteries | Silver | Gastrointestinal discomfort, nephrotoxicity, and neurological damage | Nayek et al. (2021) |
| 8. | Plastic, fire retardant | Antimony | Lung inflammation, chronic emphysema, and bronchitis | Jiang et al. (2021) |

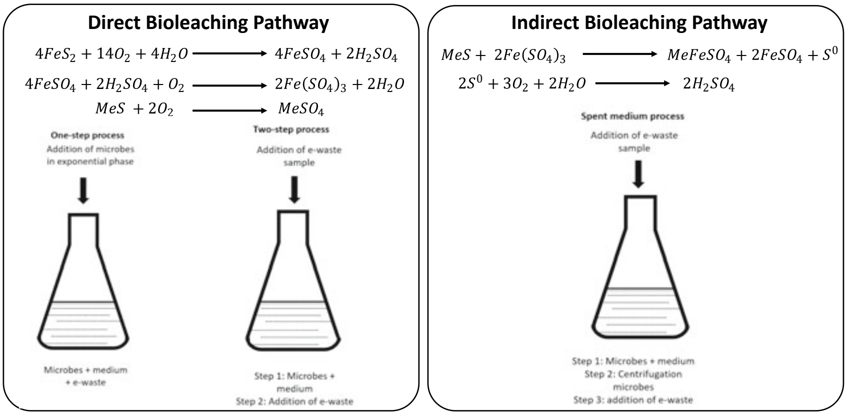



**Fig. 4.2** Direct and indirect pathways of bioleaching. Methods used for bioleaching processes: **a** one-step, **b** two-step, **c** spent medium

either the one-way or two-way stages (Arya and Kumar 2020; Baniasadi et al. 2021). The oxidation of $Fe^{2+}$ to $Fe^{3+}$ is done by *T. ferrooxidans*, an acidophilic bacterium (Miao et al. 2020). The reaction mechanism has been elucidated in Fig. 4.2.

In the one-step bioleaching process, the inoculum consists of the bioleaching microbe in the exponential phase, followed by its addition to another container containing sterile media and pre-treated e-waste. The entire process is carried out in sterile conditions and can be used for the extraction of copper, nickel zinc, and aluminum (Qu and Lian 2013; Awasthi et al. 2019). The two-step bioleaching process is used due to circumvent the metal toxicity issues that arise in the one-step process that can inhibit microbial growth (Brandl et al. 2001). The first step leads to microbial growth in sterile medium to the exponential stage (Shah et al. 2015). In the second step, the e-waste is added to the microbial culture to initiate bioleaching. This method reduces the risk of microbial inactivation by the release of heavy metal ions and can improve the rate of metal solubilization (Sand et al. 2001; Mishra and Rhee 2010).

### *4.2.2 Indirect Bioleaching Pathway*

The indirect pathway, as the name suggests, does not rely on direct microbial contact to the e-waste; instead, the microbes secrete strong oxidizing agents that assist the bioleaching phenomenon (Sajjad et al. 2019). The spent medium bioleaching process is used to maximize metal ion release. Herein, microorganisms are added to sterile media to promote the secretion and accumulation of oxidizing agents, followed by the removal microbes of from the "spent" medium via centrifugation and addition of e-waste. This process completely bypasses the microbial inactivation issue as only the secreted lixiviants biochemically interact with the e-waste to release metal ions (Arya and Kumar 2020). This method uses cyanogenic microbes and is quite efficacious in releasing gold from e-waste (Natarajan and Ting 2015).

## 4.3 Extraction of Heavy Metals from PCBs

Printed circuit boards (PCBs) are a crucial component of motherboards in computers or mobile phones, and PCBs that outlived their use are a source of heavy metals like copper, lead, iron, nickel, zinc, and tin (Anaya-Garzon et al. 2021). They comprise 3–5% of the total e-waste content; however, they are the main source for metal extraction (Moosakazemi et al. 2020). Three major groups of microbes are routinely used in bioleaching from PCBs: chemolithotrophs (e.g., *A. thiobacillus*, *A. ferrooxidans*), heterotrophs (e.g., *Bacillus megaterium*, *Pseudomonas* spp.), and fungi (e.g., *Penicillium* spp., *Aspergillus fumigatus*) (Ji et al. 2022).

In a recent study, *Acidiphilium acidophilum* was used in a two-step process to leach copper from a 4 $cm^2$ piece of PCB in 2.5 h (Chandane et al. 2020). Actinobacteria are commonly used in bioleaching, a study which used *Streptomyces albidoflavus*

TN10 showed optimal metal recovery at pH 6. The metals recovered were aluminum, copper, cadmium, zinc, lead, nickel, and mercury (Table 4.2) (Kaliyaraj et al. 2019). Marappa et al. used nitrogen-fixing bacteria *Frankia* sp. for heavy metal recovery via two-step method and were successful (Marappa et al. 2020). Higher aeration rates were achieved by employing the use of a bubble column bioreactor to recover iron, nickel, and copper metals over a span of 44 days with the aid of *A. ferrooxidans*. The use of a bioreactor can potentially lead industrial applications in the future (Arshadi et al. 2021). In an innovative approach, bioleaching and electrowinning processes were used concurrently to achieve high yields of copper with almost 99% purity. *A. ferrooxidans* produced the bioleachate, followed by electrowinning which generated copper foils that can be used in the production of new PCBs (Baniasadi et al. 2021). This is an efficient method of recycling PCBs. Patel et al. employed *A. fumigatus* A2DS with a one-step leaching method and obtained high yields of nickel and copper. The study also studied the effect of temperature, pH, and pulp density and observed maximum yields at 0.5% pulp densities (Patel and Lakshmi 2021). In a new study, *Sulfobacillus thermosulfidooxidans* was used for the successful recovery of zinc, nickel, and copper at 55 °C and 10% pulp density (Ilyas et al. 2022). A study by Zhang et al. utilized a microbial consortium from a volcanic spring near the Wudalianchi area, China, and studied its bioleaching potential. The consortium showed a dominance of *Acidithiobacillus* spp. and showed potential for the recovery of copper (89.9%) and nickel (68.52%) from PCBs (Zhang et al. 2022) (Table 4.2).

## 4.4 Extraction of Heavy Metals from Spent Batteries

Spent batteries are another good source of extracting useful metals and can be a major environmental hazard if not recycled. They are mainly of two types: primary non-rechargeable batteries (zinc-manganese batteries (ZMBs)) and secondary rechargeable batteries (nickel–cadmium batteries and lithium-ion batteries (LIBs)) (Baniasadi et al. 2019). ZMBs and LIBs are widely used and comprise a large portion of battery e-waste (Sethurajan et al. 2019). Many heavy metals with a plethora of industrial applications can be extracted from spent batteries, namely nickel, zinc, cadmium, lithium, and manganese (Roy et al. 2021a). Commonly, after dismantling and separation of various parts, hydrometallurgical and pyrometallurgical processes are used to recycle batteries and recover precious metals; however, bio-metallurgical processes are also gaining popularity owing to their benefits (Zhou et al. 2020; Alavi et al. 2021) (Fig. 4.3).

In an inspired study, Alavi et al. used a mixed culture of *A. niger* and *Aspergillus tubingensis* with sucrose and vinasse in the media to enable bioleaching of LIBs via one-step, two-step, and spent medium methods. Successful recovery of lithium, manganese, cobalt, aluminum, and nickel was achieved in the presence of vinasse with spent medium method. The use of vinasse, a waste from ethanol production, confers dual advantages of bioremediation and metal recovery through one process (Alavi et al. 2021). Roy et al. were able to extract 60% lithium and 94% cobalt

**Table 4.2** Bioleaching processes in PCBs

| S. No. | Microorganism used | Method | Heavy metal recovered | References |
|---|---|---|---|---|
| 1. | *Acidiphilium acidophilum* | Two-step | Cu | Chandane et al. (2020) |
| 2. | *Streptomyces albidoflavus* TN10 | Shake flask | Al (66%), Cu (68%), Cd (65%), Fe (42%), Ni (81%), Zn (82%), Pb (46%), Hg (59%) | Kaliyaraj et al. (2019) |
| 3. | *Frankia casuarinae* DDNSF-02 and *Frankia* sp. DDNSF-01 | Two-step | Cu (94%) | Marappa et al. (2020) |
| 4. | *Acidithiobacillus ferrooxidans* | Bubble column bioreactor | Cu (54%), Fe (55%), Ni (75%) | Arshadi et al. (2021) |
| 5. | *A. ferrooxidans* | Bioleaching and electrowinning | Cu (75.8%) | Baniasadi et al. (2021) |
| 6. | *Leptospirillum ferriphilum* and *Sulfobacillus benefaciens* | Continuous flow bioreactor | Cu (96%), Zn (85%), Co (93%), Ni (73%) | Hubau et al. (2020) |
| 7. | *Aspergillus fumigatus* A2DS | One-step | Ni (42.37%), Cu (62%) | Patel and Lakshmi (2021) |
| 8. | *Sulfobacillus thermosulfidooxidans* | – | Zn (94%), Cu (93%), Ni (91%) | Ilyas et al. (2022) |
| 9. | *Acidithiobacillus* spp. | – | Ni (68.52%), Cu (89.9%) | Zhang et al. (2022) |

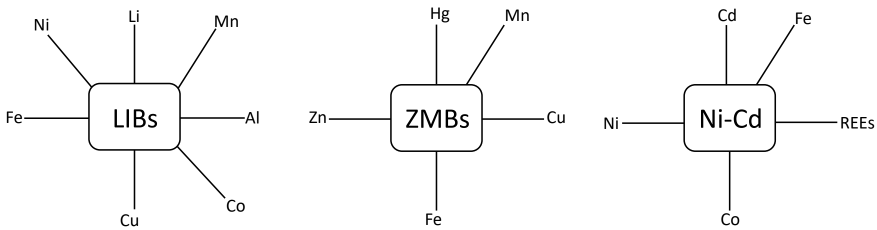



**Fig. 4.3** Heavy metal components of LIBs, ZMBs, and Ni–Cd batteries

(Table 4.3) from 1% (w/v) pulp density of LIBs using *A. ferrooxidans* in 3 days (Roy et al. 2021b). Another study conducted by the same group used nickel, manganese, and cobalt-based (NMC) LIBs to achieve metal recovery at high pulp densities and high concentrations of sulfuric acid using *A. ferrooxidans* (Roy et al. 2021c). A new approach utilized spent nickel metal hydride batteries for bioleaching using *Gluconobacter oxydans*. The use of yeast extract instead of potassium hydrogen phosphate resulted in a 1.5 times higher metal recovery in 1% (w/v) pulp density in just one day (Rasoulnia et al. 2022). Cai et al. combined two consortia obtained from wastewater treatment facilities in China and combined them to produce a novel and efficacious consortium which was able to bioleach manganese and lithium from LIBs in 7 days. The dominant strain was *A. ferrooxidans*, and novel species of Leptospirillum and Sulfobacillus were also found (Cai et al. 2021). The recovery of manganese and cobalt was done from laptop LIBs in a new study. The study employed *A. ferrooxidans* and *A. thiooxidans* with a 99.95% metal recovery using the spent medium method in 3 days (Noruzi et al. 2022). In recent work, Liao et al. showed improved bioleaching of lithium and cobalt from LIBs by using reduced iron and a mixed culture of *S. thermosulfidooxidans* and *Acidithiobacillus caldus* (Liao et al. 2022) (Table 4.3).

**Table 4.3** Bioleaching processes in spent batteries

| S. No. | Type of battery | Microorganism used | Method used | Heavy metal recovered | References |
|---|---|---|---|---|---|
| 1. | LIB | *Aspergillus niger* and *Aspergillus tubigensis* | Spent medium | Li, Mn, Co, Al, Ni | Alavi et al. (2021) |
| 2. | LIB | *Acidithiobacillus ferrooxidans* | Two-step | Co (94%), Li (60%) | Roy et al. (2021b) |
| 3. | LIB | *A. ferrooxidans* | Two-step | Ni (90%), Li (89%), Mn (92%), Co (82%) | Roy et al. (2021c) |
| 4. | NiMH | *Gluconobacter oxydans* | Spent medium | Mn (28.8%), Ni (12%), Fe (52.8%), Co (22.9%) | Rasoulnia et al. (2022) |
| 5. | LIB | Mixed consortium | – | Mn (67.60%), Li (69.46%) | Cai et al. (2021) |
| 6. | LIB | *A. ferrooxidans* and *Acidithiobacillus thiooxidans* | Spent medium | Co (45.2%), Ni (71.5%) | Noruzi et al. (2022) |
| 7. | LIB | *Sulfobacillus thermosulfidooxidans* and *Acidithiobacillus caldus* | – | Co (99.31%), Li (100%) | Liao et al. (2022) |

## 4.5 Conclusion

The continuous improvement in technologies and consumerism has led to the generation of e-waste, and its improper disposal poses serious risks to the ecosystem. Incineration and landfills have been used for the disposal of e-waste; however, recycling the waste to obtain and re-use the metal component is more cost-effective and eco-friendlier compared to mining for the respective metallic ores. Currently, on a commercialized scale, the use of pyrometallurgical and hydrometallurgical facilities are used to recover heavy metals from spent or discarded e-wastes. However, they also produce secondary pollutants which are detrimental to the environment, and also, the operating costs and risks posed to the personnel working in these facilities cannot be understated. In order to circumvent these issues, efforts are being focused on bio-metallurgical processes to safely extract heavy metals from e-waste with no damage to the environment and minimal risks. Multiple lab-scale studies have been conducted on different types of e-wastes with promising results. Bioleaching studies are still in their nascent, stages and optimal operational parameters are still being established and researched for different microbes and microbial consortia; however, the construction of large-scale bioleaching facilities still poses a challenge. Future efforts should concentrate on scale-up studies for bioleaching, combining different recycling techniques to overcome the pitfalls of one method.

## References

Alavi N et al (2021) Bioleaching of metals from cellphones batteries by a co-fungus medium in presence of carbon materials. Bioresour Technol Rep 15:100768. https://doi.org/10.1016/j.biteb.2021.100768

Anaya-Garzon J et al (2021) Bioleaching of E-waste: influence of printed circuit boards on the activity of acidophilic iron-oxidizing bacteria. Front Microbiol 12. https://doi.org/10.3389/fmicb.2021.669738

Arora R et al (2017) Potential and relevance of urban mining in the context of sustainable cities. IIMB Manag Rev 29(3):210–224. https://doi.org/10.1016/j.iimb.2017.06.001

Arshadi M et al (2021) Green recovery of Cu–Ni–Fe from a mixture of spent PCBs using adapted *A. ferrooxidans* in a bubble column bioreactor. Sep Purif Technol 272:118701. https://doi.org/10.1016/j.seppur.2021.118701

Arya S, Kumar S (2020) Bioleaching: urban mining option to curb the menace of E-waste challenge. Bioengineered 11(1):640–660. https://doi.org/10.1080/21655979.2020.1775988

Awasthi AK et al (2019) Environmentally sound system for E-waste: biotechnological perspectives. Curr Res Biotechnol 1:58–64. https://doi.org/10.1016/j.crbiot.2019.10.002

Ayangbenro A, Babalola O (2017) A new strategy for heavy metal polluted environments: a review of microbial biosorbents. Int J Environ Res Public Health 14(1):94. https://doi.org/10.3390/ijerph14010094

Bai J et al (2019) Bioleaching for extracting heavy metals from electronic waste sludge. In: Industrial and municipal sludge. Elsevier, pp 525–551. https://doi.org/10.1016/B978-0-12-815907-1.00023-4

Baniasadi M et al (2019) Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J Ind Eng Chem 76:75–90. https://doi.org/10.1016/j.jiec.2019.03.047

Baniasadi M et al (2021) Closed-loop recycling of copper from waste printed circuit boards using bioleaching and electrowinning processes. Waste Biomass Valorization 12(6):3125–3136. https://doi.org/10.1007/s12649-020-01128-9

Beula D, Sureshkumar M (2021) A review on the toxic E-waste killing health and environment—today's global scenario. Mater Today Proc 47:2168–2174. https://doi.org/10.1016/j.matpr.2021.05.516

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59(2–3):319–326. https://doi.org/10.1016/S0304-386X(00)00188-2

Cai X et al (2021) Phylogenetically divergent bacteria consortium from neutral activated sludge showed heightened potential on bioleaching spent lithium-ion batteries. Ecotoxicol Environ Saf 223:112592. https://doi.org/10.1016/j.ecoenv.2021.112592

Chandane P et al (2020) Bioleaching of copper from large printed circuit boards for synthesis of organic-inorganic hybrid. Environ Sci Pollut Res 27(6):5797–5808. https://doi.org/10.1007/s11356-019-07244-x

Colmer AR, Hinkle ME (1947) The role of microorganisms in acid mine drainage. Science 106(2751):253–256. https://doi.org/10.1126/science.106.2751.253

Cui J, Zhang L (2008) Metallurgical recovery of metals from electronic waste: a review. J Hazard Mater 158(2–3):228–256. https://doi.org/10.1016/j.jhazmat.2008.02.001

Forti V et al (2020) The global e-waste monitor 2020: quantities, flows and the circular economy potential

Genchi G et al (2020) Nickel: human health and environmental toxicology. Int J Environ Res Public Health 17(3):679. https://doi.org/10.3390/ijerph17030679

Gopikrishnan V et al (2020) Microbial leaching of heavy metals from e-waste. In: Biovalorisation of wastes to renewable chemicals and biofuels. Elsevier, pp 189–216. https://doi.org/10.1016/B978-0-12-817951-2.00010-9

Grace Pavithra K et al (2020) Sustainable electronic-waste management: implications on environmental and human health. In: E-waste recycling and management, pp 201–218. https://doi.org/10.1007/978-3-030-14184-4_11

Heacock M et al (2016) E-waste and harm to vulnerable populations: a growing global problem. Environ Health Perspect 124(5):550–555. https://doi.org/10.1289/ehp.1509699

Hedya S, Avula A, Swoboda H (2022) Lithium toxicity. In: StatPearls [Internet]. StatPearls Publishing. Available at: https://www.ncbi.nlm.nih.gov/books/NBK499992/. Accessed 28 Aug 2022

Hubau A et al (2020) Recovery of metals in a double-stage continuous bioreactor for acidic bioleaching of printed circuit boards (PCBs). Sep Purif Technol 238:116481. https://doi.org/10.1016/j.seppur.2019.116481

Ilyas S et al (2022) Biotechnological recycling of hazardous waste PCBs using *Sulfobacillus thermosulfidooxidans* through pretreatment of toxicant metals: process optimization and kinetic studies. Chemosphere 286:131978. https://doi.org/10.1016/j.chemosphere.2021.131978

Ji X et al (2022) Bioleaching of typical electronic waste—printed circuit boards (WPCBs): a short review. Int J Environ Res Public Health 19(12):7508. https://doi.org/10.3390/ijerph19127508

Jiang J et al (2021) Characteristics, accumulation, and potential health risks of antimony in atmospheric particulate matter. ACS Omega 6(14):9460–9470. https://doi.org/10.1021/acsomega.0c06091

Jowkar MJ et al (2018) Bioleaching of indium from discarded liquid crystal displays. J Clean Prod 180:417–429. https://doi.org/10.1016/j.jclepro.2018.01.136

Kaliyaraj D et al (2019) Bioleaching of heavy metals from printed circuit board (PCB) by *Streptomyces albidoflavus* TN10 isolated from insect nest. Bioresour Bioprocess 6(1):47. https://doi.org/10.1186/s40643-019-0283-3

Kaur P et al (2022) Biosorption and bioleaching of heavy metals from electronic waste varied with microbial genera. Sustainability 14(2):935. https://doi.org/10.3390/su14020935

Liao X et al (2022) Feasibility of reduced iron species for promoting Li and Co recovery from spent $LiCoO_2$ batteries using a mixed-culture bioleaching process. Sci Total Environ 830:154577. https://doi.org/10.1016/j.scitotenv.2022.154577

Manna A et al (2018) Efficient removal of cadmium using edible fungus and its quantitative fluorimetric estimation using (*Z*)-2-(4 *H*-1,2,4-Triazol-4-yl)iminomethylphenol. ACS Omega 3(6):6243–6250. https://doi.org/10.1021/acsomega.8b00342

Marappa N et al (2020) Recovery of gold and other precious metal resources from environmental polluted E-waste printed circuit board by bioleaching *Frankia.* Int J Environ Res 14(2):165–176. https://doi.org/10.1007/s41742-020-00254-5

Miao B et al (2020) Bioinformatics and transcriptional study of the Nramp gene in the extreme acidophile *Acidithiobacillus ferrooxidans* strain DC. Minerals 10(6):544. https://doi.org/10.3390/min10060544

Mishra D, Rhee Y-H (2010) Current research trends of microbiological leaching for metal recovery from industrial wastes. In: Méndez-Vilas A (ed) Current research, technology and education topics in applied microbiology and microbial biotechnology, pp 1289–1296

Moosakazemi F et al (2020) Regeneration of Sn–Pb solder from waste printed circuit boards: a hydrometallurgical approach to treating waste with waste. J Hazard Mater 385:121589. https://doi.org/10.1016/j.jhazmat.2019.121589

Natarajan G, Ting Y-P (2015) Gold biorecovery from e-waste: an improved strategy through spent medium leaching with pH modification. Chemosphere 136:232–238. https://doi.org/10.1016/j.chemosphere.2015.05.046

Nayek S et al (2021) Toxicological alterations induced by subacute exposure of silver nanoparticles in Wistar rats. J Appl Toxicol 41(6):972–986. https://doi.org/10.1002/jat.4086

Noruzi F et al (2022) Complete bioleaching of Co and Ni from spent batteries by a novel silver ion catalyzed process. Appl Microbiol Biotechnol 106(13–16):5301–5316. https://doi.org/10.1007/s00253-022-12056-0

Palanisamy MM et al (2022) A comparative review on recovery of heavy metals from printed circuit boards (PCB's) by chemical and bio-leaching. J Ceram Process Res 90–98. Available at: http://www.jcpr.or.kr/journal/archive/view/2632. Accessed 28 Aug 2022

Pant D, Dhiman V (2020) An overview on environmental pollution caused by heavy metals released from e-waste and their bioleaching. In: Advances in environmental pollution management: wastewater impacts and treatment technologies. Agro Environ Media—Agriculture and Environmental Science Academy, Haridwar, India, pp 41–53. https://doi.org/10.26832/aesa-2020-aepm-04

Patel F, Lakshmi B (2021) Bioleaching of copper and nickel from mobile phone printed circuit board using *Aspergillus fumigatus* A2DS. Braz J Microbiol 52(3):1475–1487. https://doi.org/10.1007/s42770-021-00526-y

Qu Y, Lian B (2013) Bioleaching of rare earth and radioactive elements from red mud using *Penicillium tricolor* RM-10. Bioresour Technol 136:16–23. https://doi.org/10.1016/j.biortech.2013.03.070

Quatrini R, Johnson DB (2018) Microbiomes in extremely acidic environments: functionalities and interactions that allow survival and growth of prokaryotes at low pH. Curr Opin Microbiol 43:139–147. https://doi.org/10.1016/j.mib.2018.01.011

Rasoulnia P et al (2022) Low residual dissolved phosphate in spent medium bioleaching enables rapid and enhanced solubilization of rare earth elements from end-of-life NiMH batteries. Miner Eng 176:107361. https://doi.org/10.1016/j.mineng.2021.107361

Rautela R et al (2021) E-waste management and its effects on the environment and human health. Sci Total Environ 773:145623. https://doi.org/10.1016/j.scitotenv.2021.145623

Ribeiro JN et al (2022) E-waste and its consequence for environment and public health: perspectives in covid-19 pandemic times. Glob J Health Sci 14(3):54. https://doi.org/10.5539/gjhs.v14n3p54

Roy JJ, Cao B, Madhavi S (2021a) A review on the recycling of spent lithium-ion batteries (LIBs) by the bioleaching approach. Chemosphere 282:130944. https://doi.org/10.1016/j.chemosphere.2021.130944

Roy J, Srinivasan M, Cao B (2021b) Bioleaching as an eco-friendly approach for metal recovery from spent NMC-based lithium-ion batteries at a high pulp density. ACS Sustain Chem Eng 9(8):3060–3069. https://doi.org/10.1021/acssuschemeng.0c06573

Roy JJ, Madhavi S, Cao B (2021c) Metal extraction from spent lithium-ion batteries (LIBs) at high pulp density by environmentally friendly bioleaching process. J Clean Prod 280:124242. https://doi.org/10.1016/j.jclepro.2020.124242

Rubio J, Souza M, Smith R (2002) Overview of flotation as a wastewater treatment technique. Miner Eng 15(3):139–155. https://doi.org/10.1016/S0892-6875(01)00216-3

Sajjad W et al (2019) Metals extraction from sulfide ores with microorganisms: the bioleaching technology and recent developments. Trans Indian Inst Met 72(3):559–579. https://doi.org/10.1007/s12666-018-1516-4

Sand W et al (2001) (Bio)chemistry of bacterial leaching—direct vs. indirect bioleaching. Hydrometallurgy 59(2–3):159–175. https://doi.org/10.1016/S0304-386X(00)00180-8

Sethurajan M et al (2019) Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes—a review. Crit Rev Environ Sci Technol 49(3):212–275. https://doi.org/10.1080/10643389.2018.1540760

Shah MB et al (2015) Development of two-step process for enhanced biorecovery of Cu–Zn–Ni from computer printed circuit boards. J Biosci Bioeng 120(2):167–173. https://doi.org/10.1016/j.jbiosc.2014.12.013

Vakilchap F, Mousavi SM, Shojaosadati SA (2016) Role of *Aspergillus niger* in recovery enhancement of valuable metals from produced red mud in Bayer process. Bioresour Technol 218:991–998. https://doi.org/10.1016/j.biortech.2016.07.059

Xiang Y et al (2010) Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. J Hazard Mater 184(1–3):812–818. https://doi.org/10.1016/j.jhazmat.2010.08.113

Yaashikaa PR et al (2022) A review on recent advancements in recovery of valuable and toxic metals from e-waste using bioleaching approach. Chemosphere 287:132230. https://doi.org/10.1016/j.chemosphere.2021.132230

Zhang S et al (2022) An Fe(II)-oxidizing consortium from Wudalianchi volcano spring in Northeast China for bioleaching of Cu and Ni from printed circuit boards (PCBs) with the dominance of *Acidithiobacillus* spp. Int Biodeterior Biodegrad 167:105355. https://doi.org/10.1016/j.ibiod.2021.105355

Zhou L-F et al (2020) The current process for the recycling of spent lithium ion batteries. Front Chem 8. https://doi.org/10.3389/fchem.2020.578044

# Chapter 5
# Bioremediation Strategies for Sustainable E-waste Management

**Hemant Sharma and Arun Kumar Rai**

**Abstract** Electronic items and gadgets are rapidly increasing their continuous presence in a typical household due to the considerable advancement in usability, needs, operational efficiency, etc., in this fast-paced world. Day-to-day work undoubtedly becomes a challenge without an electronic device be it in the transportation sector, hospitals, modern industries, workplaces, houses, etc. However, obsolete or old electronic devices end up in dump yards or recycling centers which poses modern challenges to key policymakers and in mitigating its environmental hurdles. Electronic waste or E-waste is one of the emerging problems in both developed and developing countries around the world. It typically consists of numerous components purportedly containing valuable materials, some of which have toxic substances that can adversely affect human health and the environment. This chapter carefully presents a comprehensive overview of the successful management of generated electronic waste with particular reference to the remediation of the waste through biological approaches.

**Keywords** Electronic waste · Bioleaching · Bioremediation

## 5.1 Introduction

Increasing demand for various electronic equipment around the globe has typically resulted in increased production of upgraded or advanced electronic gadgets ultimately resulting in the dumping of obsolete devices, thereby leading to gradual accumulation of considerable electronic waste (E-waste) at a faster rate than in earlier days (Alblooshi et al. 2022). Electronic waste typically denotes any items, electronic items used in business or by consumers, and necessary hardware used in modern information technology that is at the effective end of its operational lifespan. The

H. Sharma · A. K. Rai (✉)
Department of Botany, Sikkim University, 6th Mile Tadong, Gangtok, Sikkim 737102, India
e-mail: akrai@cus.ac.in



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_5

standard definition of E-waste varies considerably but the terms waste electrical and electronic equipment and E-waste have been used synonymously by Bhutta et al. (2011).

E-waste has been broadly classified by Pinto (2008) as follows:

a. Large household appliances such as washing machines, and refrigerators.
b. Telecom and modern IT equipment like personal computers (PC), laptops, and monitors.
c. Standard consumer equipment typically consists of television sets.

As per reliable estimates, over 82% of E-waste that is generated annually remains undocumented and possibly handled or discarded poorly, shipped illegally, with limited regulations related to operational safety, local environment, and health, technological limitations, and improper procedures related to the treatment of such waste (Forti et al. 2020; Purchase et al. 2020). The expanding market for electrical and electronic items undoubtedly continues to expand tremendously across the globe while the active life of such modern devices progressively reduces every year. As the newer devices are considerably more affordable than repairing the older ones, the gradual accumulation of E-waste undoubtedly continues to increase every day. Such being the case, tackling E-waste has undoubtedly become a paramount concern for key policymakers.

Managing E-waste in progressively developing countries is of grave concern due to the considerable import of more primitive versions of electronic goods from developed countries which accounts for about 80% of all the E-waste that is exported by a developed country (Hicks et al. 2005). The apparent lack of suitable amenities and appropriate measures for the recycling and proper disposal undoubtedly possess significant hazards to the local environment and holistic health.

Among other wastes, E-waste accounts for one of the most rapidly increasing solid waste in the world with possible adversities due to its toxic contents (Ma et al. 2022). However, E-waste contains highly valued materials which is a source of modest income for many. As per reports, one ton of E-waste invariably contains an economic value of $2292.94 in which the content of gold varies appreciably from 79.86 to 3694.51 mg per kg, and around 39 g of gold could be obtained from one ton of printed circuit boards (Huang et al. 2022).

E-waste has been majorly placed under six groups which include: standard equipment that is large, smaller equipment, equipment used in temperature exchanges, TV screens and monitors, information exchange devices that are smaller and electronic lamps. The following countries typically contribute to E-waste majorly include China, the USA, India, Japan, and Brazil. As the proportional rate of production of E-waste increases, which is about 3–5% for this current generation, the aggregate amount of E-waste generated globally in the year 2019 accounted for 53.6 million tons and has been estimated to be about 74.7 million tons by the year 2030 (Van Yken et al. 2021) (Fig. 5.1).

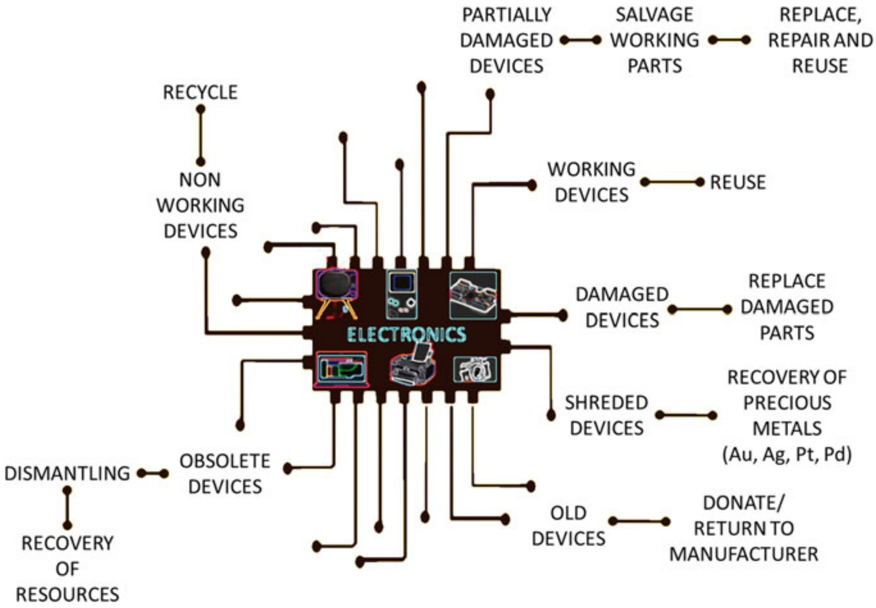



**Fig. 5.1** Sustainable approaches in managing E-waste

## 5.2 Electronic Waste Composition and Its Impact on the Environment

E-waste is composed of diverse and varying mixtures of diverse materials falling into hazardous or non-hazardous categories, viz. metals, including valuable ones, such as silver, gold, aluminum, copper, cadmium, lead, zinc, and nickel; plastics; rare earth elements (REEs); glasses; metalloids, viz. antimony; polychlorinated biphenyl; other additives, etc. (Purchase et al. 2020).

E-waste can be broadly classified under ferrous or non-ferrous materials, plastic components, glasses, woods or plywoods, printed circuit boards, ceramic, and rubber parts, including other items under the Indian scenario (Naik and Khan 2020).

Heavy metals from electronic devices pose a risk to the surrounding environment. The effective concentration of cobalt and lead have been reported to be on the higher side from the fishes of lower trophic level (Steinhausen et al. 2022).

Rare earth elements comprise an essential component of electronic equipment, fertilizers, contrasting agents used in modern medicines, to prepare materials that are fluorescent, etc., that are constantly used in the modern world. Since E-waste inevitably contains strong concentrations of REE, unsafe handling of the dreary waste undoubtedly has the evident potential for higher contamination of the local environment through leaching of the polluted soil and groundwater (Brewer et al. 2022).

**Table 5.1** Some of the constituents of electronic waste (Cui and Jørgen Roven 2011; Needhidasan et al. 2014; Salhofer 2017)

| S. No. | Constituents | Component of |
|---|---|---|
| 1 | Lead | Batteries, cathode ray tubes (CRTs), liquid crystal displays (LCDs), printed circuit boards, printed wiring boards, etc. |
| 2 | Mercury | Batteries, switches, backlighting lamps, thermostats, sensors, relays, printed circuit boards, measuring equipment, gas discharge lamps, medical equipment, cell phones, CRT monitors, television sets, LCDs, etc. |
| 3 | Cadmium | Batteries, printed circuit boards, CRTs, infrared detectors, semiconductors, etc. |
| 4 | Copper | Printed circuit boards, computers, cell phones, printing devices, SAT receivers, etc. |
| 5 | Chlorofluorocarbon | Foam, refrigerating equipment, air-conditioned equipment, etc. |
| 6 | Chromium VI | Decorative hardener, corrosion protection, etc. |
| 7 | Metals | Washing machine, dishwashers, printed circuit boards, etc. |
| 8 | Glass | Florescent tubes, CRT monitors |
| 9 | Plastics | Most of the electronic panels, computer moldings, cablings |
| 10 | Chlorinated biphenyls | Batteries, capacitors, toner cartridges of printers, circuit boards, LCDs, etc. |

Polycyclic aromatic hydrocarbons (PAHs) are one of the integral components of electronic circuit boards. There are investigative reports of increased concentrations of PAHs from human hair, human milk, and urine sampled from people residing near E-waste disposal sites. Local emissions due to the burning of electronic boards typically comprise various PAHs. Derivatives of PAHs have been reliably identified as key indicators for routine analysis (Ma et al. 2022).

Halogenated flame retardants (HFR) constitute essential components of E-waste some of which include polybrominated diphenyl ethers, polybrominated biphenyls, hexabromocyclododecanes, and other alternatives of HFR. Zheng et al. (2012) have reported that eggs obtained from E-waste sites have been found to be contaminated with HFR, polybrominated biphenyls, dechlorane plus, etc. Consumption of contaminated eggs has resulted in an increase in daily intake of HFRs (Table 5.1).

## 5.3 Conventional Methods of E-waste Management

E-waste management in developed countries invariably involves properly recycling and successful recovery of valuable items from the waste or exporting the waste to developing countries. However, in developing countries management of E-waste comprises manual dismantling of waste materials, chipping, burning, melting, dissolution using acids, and successful recovery of valuable metals such as gold, silver, and copper (Purchase et al. 2020). As per Naik and Khan (2020), the following methods are typically employed for the adaptive reuse and recovery of valuable items from E-waste during the recycling process:

a. Dismantling of parts comprising hazardous substances such as chlorofluorocarbons and mercury switches. During this process, valuable parts of the waste like copper from cable, steel, iron, and other valuable metals that are conveniently accessible are typically obtained.
b. Shredding of the waste to segregate ferrous and non-ferrous substances as well as plastics.
c. Usable electronic devices or their essential parts are reused after refurbishing.
d. Recovery of ferrous, non-ferrous, and valuable metals through different recovery processes.
e. The considerable non-recovered portion of the waste is either treated or disposed of in landfills based on its composition. Mercury is recycled or contained in underground landfills, and PCBs are incinerated or stored in underground storage.

## 5.4 Challenges in Managing E-waste

Managing E-waste invariably comes with many problems and hurdles. In some of the countries where the rules regarding the recycling of waste are stringent, the cost of recycling such waste is higher than the revenue that is generated from the materials recovered. Hence, the waste ends up in developing countries with lenient or less stringent rules. However, the working conditions of the people and the environmental conditions are very poor in such regions (Greenpeace International 2008). E-waste has been linked with various health-related issues such as birth defects, pulmonary disorders, neurological disorders as well as cancer which are prevalent in countries that have a poor infrastructure for the management and proper disposal of the waste (Needhidasan et al. 2014).

A wide range of effective techniques and treatments utilized for the separation of plastics and metals have been reported by researchers. Manual salvaging of key parts from gadgets could involve dangerous processes like open burning or acid leaching. Density, electrostatic and magnetic separations are mainly physical processes in which the metal fraction of E-waste is separated from non-metals. The possible release of toxins or dioxin from the dust is one of the major issues in the physical separation process (Islam et al. 2021).

PCBs are laden with valuable metals and are an important source of income. However, as per studies, electronic wastes are disassembled manually for the possible recovery of solder and electronic chips by heating PCBs and extraction of metals through the process of burning with limited concern for toxic chemicals. The income generated during the complex process is very insignificant when compared with the environment and health issues associated with the process of burning plastics and release of toxic gases into the atmosphere as well as contamination of landfills, adjacent water bodies, and soil with heavy metals when the non-extractable parts are carelessly dumped (Osibanjo 2009; Bhutta et al. 2011).

As reported by Van Yken et al. (2021) combination of materials such as plastics, glass, and other items in E-waste complicates enough the processing of such materials. Hydrometallurgical, pyrometallurgical, or a combination of both techniques are generally employed for processing. Estimated expenditure in the prevalent hydrometallurgical method is considerably lower with simpler technological requirements and requires very less intervention for the processing of gaseous emissions that are released during the process but have a higher energy requirement during the process. The active process also releases a large number of organic acids that require downstream processing. The pyrometallurgical method undoubtedly has a lesser energy requirement to operate as it can utilize the energy generated after the combustion of the components of the waste or the energy can be used to generate electricity but the process has higher emissions. An effective combination of processes can be utilized for the extraction of metals. Apart from environmental challenges, geographical barriers also hamper the transportation of bulky waste yet insignificant in economic terms. Innovative technology related to preprocessing of the waste could be improvised to reduce the size of transported wastes but it could again increase the cost of preprocessing, thereby decreasing the net income from the discarded items.

## 5.5 Bioremediation of E-waste

Gradual build-up of E-waste has posed to represent a daunting environmental challenge that undoubtedly requires proper mitigation. The operational requirement of proper techniques and innovative technologies for the successful recovery of valuable metals with a profitable approach is of prime importance for the sustainable management of waste. Among many techniques, bioleaching is being considered for the successful extraction of valuable metals due to its sustainable methods compared to other traditional ones (Baniasadi et al. 2019). Innovative technologies related to the bioremediation of polluted soils contaminated with heavy metals have satisfactorily accomplished tremendous improvisation in the context of its efficient system due to the lower cost and environmentally friendly nature along with carefully restoring the ecological balance of the contaminated soil (Li et al. 2022).

### *5.5.1 Phytoremediation*

Out of many possible approaches to mitigate E-waste, phytoremediation involves the effective use of distinctive flora for the remediation of contaminants and hazardous substances from the apparent waste. Conventional methods of effective treatment are usually costly, inefficient, time taking, and environmentally unviable. Phytoremediation is cheaper, environmentally conducive, and uses green technology for the remediation process. Some of the plants typically utilize roots, stems, and leaves for the up-taking of metals, translocating, and bioaccumulation, respectively (Khan et al. 2019).

The effective use of native plants in remediation has been recognized to be comparatively safer for the environment, less expensive, and ease to cultivate when compared with non-native plants. In one of the published studies, it was observed that a native plant *Chromolaena odorata* was comparatively better with the toleration and degradation of polycyclic aromatic hydrocarbons and thrived better when compared with a reference plant (Futughe et al. 2020).

Aquatic plants, *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), and *Lemna minor* (duckweed) have been reported to be efficient accumulators of heavy metals with possible use as remediators of water polluted with heavy metals (Ali et al. 2020).

In one such study, *Eucalyptus globulus* was utilized as a potential plant for the possible accumulation of metals under the influence of direct and alternating current. It was carefully observed that the plants were able to accumulate metals irrespective of the application of different types of current. Further, direct current with medium voltage was found to be better suited for efficient decontamination, leaching, and consumption of energy during the remediation of soils contaminated with metals (Luo et al. 2018).

In another academic study, the duckweed plant (*L. minor*) was used to properly assess the phytoextraction potential for various metals from the leachates of a local landfill. It was observed that the plant was able to significantly reduce the elevated concentration of heavy metals with the highest removal efficiency of copper at more than 70%. The plant could be considered as an alternative for the sustainable remediation of wastewater contaminants (Daud et al. 2018).

### *5.5.2 Microbial Remediation*

The intended use of specific microorganisms for the purpose of leaching metals and their successful extraction from E-waste has been considered an ecologically sustainable alternative to the effective management of E-waste. Bioleaching involves the application of organisms in the transformation of hazardous materials to the environment into non-hazardous forms along with the extraction of precious metals (Narayanasamy et al. 2022). Diverse species of microorganisms have been recognized to be potential candidates for bioleaching of different types of metals such as lead, copper, and cadmium from E-waste. Some of the beneficial microorganisms that have been found to be useful are *Paenibacillus* sp., *Acidithiobacillus ferrooxidans*, *Sulfobacillus thermosulfidooxidans*, *Acidithiobacillus thiooxidans*, and fungal species include *Aspergillus niger*, *Penicillium simplicissimum*, etc., that typically utilize various methods, viz. bioaccumulation, metal complexation, various redox reactions, etc., during the process (Dahiya et al. 2022). The application of microorganisms is undoubtedly gaining considerable attention in the recycling of metals when compared with other recycling techniques due to its green technological advancement and its applicability in circular bioeconomy because of its environmentally sustainable methods (Srivastava et al. 2020). Some of the preferred methods employed for the extraction of metals and microbial remediation as detailed by Jiang et al. (2019) and Islam et al. (2021) include:

a. Bioleaching, mobilization,
b. Bio-absorption, bio-adsorption,
c. Biotransformation,
d. Bioaccumulation, and
e. Biomineralization.

Bio-metallurgy is the application of beneficial microorganisms for the immobilization and mobilization of gold from numerous sources. Some of the fungal strains are able to secrete cyanide responsible for the mobilization of gold through leaching and the release of gold during the degradation of cyanide complexes. Other methods listed above are utilized by some species of fungi for the recovery of gold from E-waste which makes them a suitable candidate for biomining (Bindschedler et al. 2017).

Bioleaching involves the gradual conversion of precious metals from solid to soluble forms that can be extracted easily. Some of the beneficial microorganisms, viz. *Thiobacillus* sp., species belonging to *Pseudomonas* and *Bacillus* genera, and some of the fungal species, i.e., *Aspergillus* sp. and *Penicillium* sp., are categorized as major groups of microorganisms involved in the process of bioleaching (Needhidasan et al. 2014).

Some of the specific microorganisms associated with the plants at the rhizosphere, such as rhizobacteria, have been helpful in promoting plant growth as well as solubilization and absorption of metals from the sites contaminated with heavy metals thereby helping with the phytoremediation of the contaminated soils (Sinha et al. 2022).

Organic acids produced by microorganisms such as *A. niger* have been found to be a suitable candidate for extraction of lithium from used lithium-ion batteries (Bahaloo-Horeh et al. 2018). In another study, the use of bacterium *Chromobacterium violaceum* for the extraction of metals from sim cards has been suggested (Sahni et al. 2016). Niu et al. (2015) have reported a suitable model for the bioleaching of metals from the powder of used batteries at the pulp density of 10% using a different mixture of bacterial species. In one of the studies, bioleaching of gallium from semiconductor was studied using different strains of bacteria in which *Cellulosimicrobium funkei* was found to be the most promising one (Maneesuwannarat et al. 2016). Marra et al. (2018) have reported that *A. thiooxidans* was a prospective candidate for bioleaching of base metals and rare earth elements (REE) from Waste Electrical and Electronic Equipment (WEEE), wherein REE such as Europium, Cerium, Neodymium, Lanthanum, and Yttrium were immobilized with high efficiency.

Indigenous microorganisms were responsible for the biodegradation of bromine from Polybrominated diphenyl ethers (PBDE) at the sites containing E-waste (Huang et al. 2019) (Table 5.2).

## 5.6 Prospective of Bio-engineered Microorganisms in E-waste Management

Indigenous and native microorganisms have been recognized to be suitable candidates for the bioleaching of valuable metals and REEs from numerous sites. However, it has been carefully observed that the bioleaching potential of bioengineered microorganisms increases significantly. In one such study, Tay et al. (2013) reported that a specific strain of *C. violaceum* that had been metabolically engineered was able to secrete cyanide in higher quantities than produced by a wild strain of the same bacteria, therefore enhancing the recovery rate of gold at double the amount. Isolation of better strains of cyanogenic microorganisms and optimization studies related to the conditions for bioleaching of metals would pave the way forward for sustainable extraction of metals on a commercial scale (Faramarzi et al. 2020). The development of cyanogenic microorganisms using modern biotechnology with better efficiency in the successful recovery of precious metals typically presents a better approach. A recovery process involving the extensive use of a possible combination of multiple approaches along with microbiology would be better suited for the extraction of metals (Bharathi et al. 2022).

## 5.7 Future Scopes and Prospects

Most of the electronic items that are currently used end up in landfills more often due to their design which has no room for upgradation or repair for them to be reused. Lack of complete awareness related to E-waste among the masses results in the improper disposal of such devices, thereby resulting in the release of hazardous substances in the environment. The industries related to information technology sector generates the highest amount of E-waste. However, prominent companies like IBM and HP are properly implementing policies for the reduction of E-waste by either developing a computer that can be recycled and reused or chips that can be cleaned to reduce E-waste. Microbial strains with better efficiency are being investigated or developed for efficient bioremediation of the waste (Absalon et al. 2012). The use of bioengineered microorganisms with better biodegradation potential in biofilms could enhance their functionality in managing waste. The possible use of metagenomic approaches to accurately detect and correctly identify various desired functionalities of microbial communities could be efficiently utilized for developing improved strains that could be used for bioremediation (Sharma et al. 2021).

**Table 5.2** Potential microorganisms responsible for the bioremediation of E-waste and contaminated soils

| S. No. | Microorganism/s | Properties | References |
|---|---|---|---|
| 1 | Consortia of *Frankia* sp. | Bioleaching of gold and silver from E-waste printed circuit boards | Narayanasamy et al. (2022) |
| 2 | *Pleurotus florida* and *Pseudomonas* sp. | Biosorption and bioleaching of iron and copper from E-waste printed circuit boards with the production of laccase enzyme | Kaur et al. (2022) |
| 3 | *Frankia* sp. | Detection of bph operon from the organism responsible for the degradation of biphenyls and polychlorinated biphenyls which are main components of soils contaminated with E-waste analyzed through non-culturable methods | Jiang et al. (2018) |
| 4 | *Leptospirillum* sp. | Bioleaching of copper, zinc, and nickel from unpulverized waste cell phone printed circuit boards | Thacker et al. (2022) |
| 5 | *Penicillium simplicissimum* | Bioleaching of copper, nickel, and aluminum from computer printed circuit boards | Esmaeili et al. (2022) |
| 6 | *Aspergillus niger* or *Penicillium simplicissimum* | Recovery of zinc, nickel, and copper from mobile phone printed circuit boards | Arshadi et al. (2022) |
| 7 | *Sulfobacillus thermosulfidooxidans* | Bioleaching of copper, nickel, and zinc from waste printed circuit boards | Ilyas et al. (2022) |
| 8 | *Pseudomonas aeruginosa* | Recovery of gold from printed circuit boards | Merli et al. (2022) |
| 9 | Marine fungi belonging to the family of Dipodascaceae, Microascaceae, Gymnoascaceae, and Trichocomaceae | Bioleaching of metals from E-waste such as iron, copper, palladium, silver, platinum, and gold | Galasso et al. (2022) |
| 10 | *Acidiphilium multivorum* and *Leptospirillum ferriphilum* | Bioleaching of silver, gold, and other 15 rare earth elements from electronic scraps (e-scraps) | García-Balboa et al. (2022) |

## 5.8 Conclusion

Managing E-waste is of prime importance in this generation as the waste is growing at an alarming rate across the globe. E-waste is a complex stream of waste that involves economic, technological, social, environmental, political, and legal factors in managing the waste that varies between different regions. Most of the developed countries have developed efficient policies for tackling the menace of E-waste. However, the situation in developing countries remains the same due to limitations in various fields such as the lack of proper infrastructure, limited technological resources, and very little awareness about the potential hazard of E-waste among the masses. The processing of E-waste in developing countries is unsafe for health as well as hazardous to the environment. Formulation and adaptation of better policies and availability of proper resources and infrastructure are the need of the hour for proper management of E-waste. Various recycling techniques such as hydrometallurgy, pyrometallurgy, and biohydrometallurgy are being utilized for the processing of E-waste. Recycling the waste significantly reduces the environmental pollution released after the product is discarded as well as the energy that is utilized during the making of a new product. However, as all the waste cannot be recycled, bioremediation of the E-waste is preferably a better solution for managing E-waste sustainably. Improvisation of techniques and use of efficient microorganisms could be useful in the extraction of REE as well as base metals from E-waste as well as the decomposition of toxic contents without hampering the environment. The sustainable approach to the management of the waste through bioremediation could be beneficial for the generation of decent income thus contributing to a circular bioeconomy.

## References

Absalon C, Ymele-Leki P, Watnick PI (2012) The bacterial biofilm matrix as a platform for protein delivery. mBio 3:2–6. https://doi.org/10.1128/mBio.00127-12

Alblooshi BGKM, Ahmad SZ, Hussain M, Singh SK (2022) Sustainable management of electronic waste: empirical evidences from a stakeholders' perspective. Bus Strateg Environ 31:1856–1874. https://doi.org/10.1002/bse.2987

Ali S, Abbas Z, Rizwan M et al (2020) Application of floating aquatic plants in phytoremediation of heavy metals polluted water: a review. Sustainability 12:1927. https://doi.org/10.3390/su12051927

Arshadi M, Esmaeili A, Yaghmaei S, Arab B (2022) Evaluation of *Aspergillus niger* and *Penicillium simplicissimum* for their ability to leach Zn–Ni–Cu from waste mobile phone printed circuit boards. J Mater Cycles Waste Manag 24:83–96. https://doi.org/10.1007/s10163-021-01299-0

Bahaloo-Horeh N, Mousavi SM, Baniasadi M (2018) Use of adapted metal tolerant *Aspergillus niger* to enhance bioleaching efficiency of valuable metals from spent lithium-ion mobile phone batteries. J Clean Prod 197:1546–1557. https://doi.org/10.1016/j.jclepro.2018.06.299

Baniasadi M, Vakilchap F, Bahaloo-Horeh N et al (2019) Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J Ind Eng Chem 76:75–90. https://doi.org/10.1016/j.jiec.2019.03.047

Bharathi SD, Dilshani A, Rishivanthi S et al (2022) Resource recycling, recovery, and xenobiotic remediation from E-wastes through biofilm technology: a review. Appl Biochem Biotechnol. https://doi.org/10.1007/s12010-022-04055-8

Bhutta MKS, Omar A, Yang X (2011) Electronic waste: a growing concern in today's environment. Econ Res Int 2011:1–8. https://doi.org/10.1155/2011/474230

Bindschedler S, Vu Bouquet TQT, Job D et al (2017) Fungal biorecovery of gold from E-waste. In: Sariaslani S, Gadd GM (eds) Advances in applied microbiology. Academic Press, pp 53–81

Brewer A, Dror I, Berkowitz B (2022) Electronic waste as a source of rare earth element pollution: leaching, transport in porous media, and the effects of nanoparticles. Chemosphere 287:132217. https://doi.org/10.1016/j.chemosphere.2021.132217

Cui J, Jørgen Roven H (2011) Electronic waste. In: Letcher TM, Vallero DABT-W (eds) Waste. Elsevier, Boston, pp 281–296

Dahiya D, Sharma H, Rai AK, Nigam PS (2022) Application of biological systems and processes employing microbes and algae to Reduce, Recycle, Reuse (3Rs) for the sustainability of circular bioeconomy. AIMS Microbiol 8:83–102. https://doi.org/10.3934/microbiol.2022008

Daud MK, Ali S, Abbas Z et al (2018) Potential of duckweed (*Lemna minor*) for the phytoremediation of landfill leachate. J Chem 2018:1–9. https://doi.org/10.1155/2018/3951540

Esmaeili A, Arshadi M, Yaghmaei S (2022) Simultaneous leaching of Cu, Al, and Ni from computer printed circuit boards using *Penicillium simplicissimum*. Resour Conserv Recycl 177:105976. https://doi.org/10.1016/j.resconrec.2021.105976

Faramarzi MA, Mogharabi-Manzari M, Brandl H (2020) Bioleaching of metals from wastes and low-grade sources by HCN-forming microorganisms. Hydrometallurgy 191:105228. https://doi.org/10.1016/j.hydromet.2019.105228

Forti V, Baldé CP, Kuehr R, Bel G (2020) The global E-waste monitor 2020: quantities, flows, and the circular economy potential

Futughe AE, Purchase D, Jones H (2020) Phytoremediation using native plants. In: Shmaefsky BR (ed). Springer International Publishing, Cham, pp 285–327

Galasso C, Lekube X, Cancio I et al (2022) Marine fungi as potential eco-sustainable resource for precious metals recovery from electronic waste. Waste Biomass Valorization 13:967–976. https://doi.org/10.1007/s12649-021-01587-8

García-Balboa C, Martínez-Alesón García P, López-Rodas V et al (2022) Microbial biominers: sequential bioleaching and biouptake of metals from electronic scraps. MicrobiologyOpen 11. https://doi.org/10.1002/mbo3.1265

Greenpeace International (2008) Poisoning the poor electronic waste in Ghana: creating toxic free future. Amsterdam, The Netherlands

Hicks C, Dietmar R, Eugster M (2005) The recycling and disposal of electrical and electronic waste in China—legislative and market responses. Environ Impact Assess Rev 25:459–471. https://doi.org/10.1016/j.eiar.2005.04.007

Huang C, Zeng Y, Luo X et al (2019) In situ microbial degradation of PBDEs in sediments from an E-waste site as revealed by positive matrix factorization and compound-specific stable carbon isotope analysis. Environ Sci Technol 53:1928–1936. https://doi.org/10.1021/acs.est.8b06110

Huang T, Zhu J, Huang X et al (2022) Assessment of precious metals positioning in waste printed circuit boards and the economic benefits of recycling. Waste Manag 139:105–115. https://doi.org/10.1016/j.wasman.2021.12.030

Ilyas S, Srivastava RR, Kim H, Ilyas N (2022) Biotechnological recycling of hazardous waste PCBs using *Sulfobacillus thermosulfidooxidans* through pretreatment of toxicant metals: process optimization and kinetic studies. Chemosphere 286:131978. https://doi.org/10.1016/j.chemosphere.2021.131978

Islam A, Swaraz AM, Teo SH et al (2021) Advances in physiochemical and biotechnological approaches for sustainable metal recovery from e-waste: a critical review. J Clean Prod 323:129015. https://doi.org/10.1016/j.jclepro.2021.129015

Jiang L, Luo C, Zhang D et al (2018) Biphenyl-metabolizing microbial community and a functional operon revealed in E-waste-contaminated soil. Environ Sci Technol 52:8558–8567. https://doi.org/10.1021/acs.est.7b06647

Jiang B, Adebayo A, Jia J et al (2019) Impacts of heavy metals and soil properties at a Nigerian e-waste site on soil microbial community. J Hazard Mater 362:187–195. https://doi.org/10.1016/j.jhazmat.2018.08.060

Kaur P, Sharma S, Albarakaty FM et al (2022) Biosorption and bioleaching of heavy metals from electronic waste varied with microbial genera. Sustainability 14

Khan MA, Ullah N, Khan T et al (2019) Phytoremediation of electronic waste: a mechanistic overview and role of plant secondary metabolites. In: Hashmi MZ, Varma A (eds) Electronic waste pollution. Springer International Publishing, Cham, pp 233–252

Li X, Wu Y, Tan Z (2022) An overview on bioremediation technologies for soil pollution in E-waste dismantling areas. J Environ Chem Eng 10:107839. https://doi.org/10.1016/j.jece.2022.107839

Luo J, Wu J, Huo S et al (2018) A real scale phytoremediation of multi-metal contaminated e-waste recycling site with *Eucalyptus globulus* assisted by electrical fields. Chemosphere 201:262–268. https://doi.org/10.1016/j.chemosphere.2018.03.018

Ma S, Lin M, Tang J et al (2022) Occurrence and fate of polycyclic aromatic hydrocarbons from electronic waste dismantling activities: a critical review from environmental pollution to human health. J Hazard Mater 424:127683. https://doi.org/10.1016/j.jhazmat.2021.127683

Maneesuwannarat S, Vangnai AS, Yamashita M, Thiravetyan P (2016) Bioleaching of gallium from gallium arsenide by *Cellulosimicrobium funkei* and its application to semiconductor/electronic wastes. Process Saf Environ Prot 99:80–87. https://doi.org/10.1016/j.psep.2015.10.008

Marra A, Cesaro A, Rene ER et al (2018) Bioleaching of metals from WEEE shredding dust. J Environ Manage 210:180–190. https://doi.org/10.1016/j.jenvman.2017.12.066

Merli G, Becci A, Amato A (2022) Recovery of precious metals from printed circuit boards by cyanogenic bacteria: optimization of cyanide production by statistical analysis. J Environ Chem Eng 10:107495. https://doi.org/10.1016/j.jece.2022.107495

Naik NS, Khan A (2020) E-waste management with respect to Indian scenario. Int J Eng Res Technol 9:652–656

Narayanasamy M, Dhanasekaran D, Thajuddin N (2022) *Frankia* consortium extracts high-value metals from e-waste. Environ Technol Innov 28:102564. https://doi.org/10.1016/j.eti.2022.102564

Needhidasan S, Samuel M, Chidambaram R (2014) Electronic waste—an emerging threat to the environment of urban India. J Environ Health Sci Eng 12:1–9. https://doi.org/10.1186/2052-336X-12-36

Niu Z, Huang Q, Wang J et al (2015) Metallic ions catalysis for improving bioleaching yield of Zn and Mn from spent Zn-Mn batteries at high pulp density of 10%. J Hazard Mater 298:170–177. https://doi.org/10.1016/j.jhazmat.2015.05.038

Osibanjo O (2009) Electronic waste: a major challenge to sustainable development in Africa. Basel Convention Regional Coordinating Centre for Africa, pp 1–7

Pinto V (2008) E-waste hazard: the impending challenge. Indian J Occup Environ Med 12:65. https://doi.org/10.4103/0019-5278.43263

Purchase D, Abbasi G, Bisschop L et al (2020) Global occurrence, chemical properties, and ecological impacts of e-wastes (IUPAC technical report). Pure Appl Chem 92:1733–1767. https://doi.org/10.1515/pac-2019-0502

Sahni A, Kumar A, Kumar S (2016) Chemo-biohydrometallurgy—a hybrid technology to recover metals from obsolete mobile SIM cards. Environ Nanotechnol Monit Manag 6:130–133. https://doi.org/10.1016/j.enmm.2016.09.003

Salhofer S (2017) E-waste collection and treatment options: a comparison of approaches in Europe, China and Vietnam. In: Maletz R, Dornack C, Ziyang L (eds) The handbook of environmental chemistry, vol 63. Springer International Publishing, Cham, pp 227–227

Sharma P, Kumar S, Pandey A (2021) Bioremediated techniques for remediation of metal pollutants using metagenomics approaches: a review. J Environ Chem Eng 9:105684. https://doi.org/10.1016/j.jece.2021.105684
Sinha D, Dey S, Singh A (2022) Role of rhizobacteria in phytoremediation of metal-impacted sites. In: Malik JA (ed) Microbial and biotechnological interventions in bioremediation and phytoremediation. Springer International Publishing, Cham, pp 297–336
Srivastava RR, Ilyas S, Kim H et al (2020) Biotechnological recycling of critical metals from waste printed circuit boards. J Chem Technol Biotechnol 95:2796–2810. https://doi.org/10.1002/jctb.6469
Steinhausen SL, Agyeman N, Turrero P et al (2022) Heavy metals in fish nearby electronic waste may threaten consumer's health. Examples from Accra, Ghana. Mar Pollut Bull 175:113162. https://doi.org/10.1016/j.marpolbul.2021.113162
Tay SB, Natarajan G, Rahim MNBA et al (2013) Enhancing gold recovery from electronic waste via lixiviant metabolic engineering in *Chromobacterium violaceum*. Sci Rep 3:2236. https://doi.org/10.1038/srep02236
Thacker SC, Nayak NS, Tipre DR, Dave SR (2022) Multi-metal mining from waste cell phone printed circuit boards using lixiviant produced by a consortium of acidophilic iron oxidizers. Environ Eng Sci 39:287–295. https://doi.org/10.1089/ees.2020.0389
Van Yken J, Boxall NJ, Cheng KY et al (2021) E-waste recycling and resource recovery: a review on technologies, barriers and enablers with a focus on Oceania. Metals (Basel) 11. https://doi.org/10.3390/met11081313
Zheng X-B, Wu J-P, Luo X-J et al (2012) Halogenated flame retardants in home-produced eggs from an electronic waste recycling region in South China: levels, composition profiles, and human dietary exposure assessment. Environ Int 45:122–128. https://doi.org/10.1016/j.envint.2012.04.006

# Chapter 6
# Challenges and Approaches in E-waste Management

**Nazrin Ullah**

**Abstract** E-wastes comprising of discarded electrical and electronic goods that approaches their end of useful life are a global environmental issue of recent times. E-wastes generally are the unused electrical or electronic equipments that contain non-ferrous and valuable metals, alloys, glass, ceramics, organic polymers with toxic content, etc., and also materials that need to be disposed or recycled. So, the large-scale generation of e-wastes serves as an environmental hazard as well as a business opportunity due to presence of over 60% useful metals like iron, copper, gold, etc. But the management of the e-wastes has become a burgeoning and challenging issue due to population growth, increasing demand of electronic products, and changing lifestyle of people around the world.

**Keywords** E-waste · Bioleaching · Biosorption · Bioaccumulation · Biotransformation · Biomineralization

## 6.1 Introduction

As per current data, the growth of e-wastes is almost three times that of municipal solid waste globally (Status report 2010; Abdelbasir et al. 2018). In China, India, and Africa, e-wastes such as leaded glass, circuit boards, and mercury lamps are received in the name of free trade from the developed countries that again leads to recycling and management problems there (Williams 2005). Significant proportions of these e-wastes are then dismantled, reused, and recycled with inappropriate strategies which lead to a heavy toll on families and communities of e-waste management workers. Due to lack of social awareness towards the hazardous nature of these e-wastes and more emphasis on financial gains, e-waste management has become a more tedious task in this digital world (Kumar et al. 2008). Guiyu in the Guangdong province, China is widely considered as the e-waste capital of the world. In India, e-waste market is mostly unorganized and presence of unregistered and unauthorized

N. Ullah (✉)
Department of Environmental Science, Tezpur University, Tezpur, India
e-mail: nazrinullah@gmail.com; nazrin@tezu.ernet.in

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_6

**Table 6.1** Classification of e-wastes

| Types of e-waste | Appliances |
|---|---|
| Type 1 | Major appliances (refrigerators, washing machines, dryers, etc.) |
| Type 2 | Small appliances (vacuum cleaners, irons, blenders, fryers, etc.) |
| Type 3 | Computer and telecommunication appliances (laptops, PCs, telephones, mobile phones, etc.) |
| Type 4 | Consumer electronics (video and audio equipments) |
| Type 5 | Lighting devices (incandescent light bulbs, fluorescent tubes, gas discharge lamps, etc.) |
| Type 6 | Electrical and electronic tools (drills, saws, gardening devices, etc.) |
| Type 7 | Toys, leisure (electronic toys, models, sports equipment, etc.) |
| Type 8 | Medical devices (all medical equipments with the exception of implants) |
| Type 9 | Monitoring devices (detectors, thermostats, laboratory equipment, etc.) |
| Type 10 | Vending machines |

*Source* https://en.m.wikipedia.org

companies, and changing lifestyle of the soaring population makes the generation of e-wastes unsustainable (Widmer et al. 2005). According to Global E-waste Statistics Partnership (GESP), e-wastes grew by 21% in five years up to 2019, when 53.6 million metric tonnes of e-waste were generated. This growth will continue as long as the use of computers, mobile phones, and other electronics continue to expand. As per recent GESP estimates, only 17.4% of e-waste produced in 2019 reached proper disposal or recycling facilities, and the remaining were illegally dumped. It is also predicted that global e-waste will escalate up to 74 million tonnes by 2030, driven by factors like fervent pace of technological change and increase use of electrical or electronic goods, transboundary movement of e-wastes, replaceable market in developed countries, and product obsolescence rates. Various physical, chemical, and biological methods are in trend for disposal; recycling; and management of e-waste, but adoption of more sustainable approaches is the need of the hour. E-wastes are of various types which are listed under Table 6.1.

These various types of e-wastes lead to a lot of environmental problems such as pollution of ground water, acidification of soil, and degradation of ecosystems which can be minimized by converting them into useful raw materials using eco-friendly technologies (Shinu and Needhidasan 2020).

## 6.2 Components of E-wastes

E-wastes comprise of diverse components such as growing range of obsolete electronic, electrical, and telecommunication devices like computers, servers, main frames, monitors, TVs, cellular phones and pagers, calculators, etc. It also consists of recording devices such as DVDs, CDs, floppies, and electronic compounds such as chips, processors, and printed circuit boards. Various precious metals such as gold, platinum, copper, rare earth elements, and even plastics are present in discarded waste electrical and electronic goods. Various hazardous substances are present in electronic scraps such as polychlorinated biphenyls (PCBs) in condensers, transformers; chlorofluorocarbon (CFC) in insulation foam, freezers, etc., that deplete the ozone layer; polycyclic aromatic hydrocarbons (PAHs) in combustion products, cadmium in plastics, batteries; indium and strontium in smart phone touch screens, etc., that need to be extracted or safely disposed (Morf et al. 2007; Robinson 2009). The heavy metals and various toxic fumes present in the e-wastes affect the soil, air, and water directly by releasing carcinogens, acids, etc., and indirectly by biomagnification in the food chains (Sankhla et al. 2016).

## 6.3 Effects of E-waste and Its Improper Management

E-wastes are an amalgam of hazardous as well as valuable materials which need to be managed properly. Improper reprocessing or disposal practices lead to irreversible impact on environment and human health (UNEP 2010; Balde et al. 2015). The hazardous contaminants present in e-wastes are recognized as poisonous, explosive, corrosive, flammable, ecotoxic, and mutagenic for living organisms (Tripathi 2011). Deposition of heavy metals of e-wastes in human tissues poses risk to various body organs (Li et al. 2011), increase concentration of micro-nucleated bi-nucleated cells, DNA damage in occupational workers in the recycling sites, effects in infants and neonatal and multiple chronic disorders (Alluri et al. 2007; Tchounwou et al. 2012; Wuana and Okieimen 2011). Children are at more risk to the toxic metals (cadmium, lead, etc.) present in e-wastes due to different entry routes in their body such as through mouth, hands, breastfeeding, and placental exposures (Kiddee et al. 2013). Again, e-wastes deployed in landfills pollute groundwater by producing contaminated leachates, acids, and sludge from melting computer chips causes acidification of soil, lead used as a soldering agent, and in cathode ray tube (CRT), monitor causes impaired cognitive function, behavioural disturbances, and lower IQ in people (Sankhla et al. 2016). As these wastes are related to various heavy metals and carcinogens, different types of diseases of skin, respiratory, endocrine systems can occur which can be prevented by proper management approaches and scientific disposal of e-wastes and implementation of existing policies and guidelines.

In 2016, Asia recorded the highest quantity of e-waste generated of about 18.2 million tonnes (Mt) followed by Europe with 12.3 Mt, America with 2.2 Mt, and Oceania produces about 0.7 Mt. Oceania is the leading e-waste producer per inhabitant with 6% collection rate, followed by Europe with 35%, America with 17%, and Africa's collection rate information is very little (Balde et al. 2017).

## 6.4 Constraints in E-waste Management

According to UNEP (2007), the major constraints in e-waste management are (Awasthi et al. 2016; Kumar and Rawat 2018):

(a) Surplus generation of e-wastes
(b) Changing lifestyle of the people
(c) Unsustainable consumption of electronic products
(d) High component complexity and associated toxicity of e-wastes
(e) Requirement of secondary data
(f) Bulk consumption of electrical and electronic equipments (EEE) by the Govt Departments and public establishments
(g) More focus on financial gains from e-wastes
(h) Inappropriate reprocessing or disposal practices in developing countries that cause secondary pollution.

## 6.5 Global Perspectives on E-wastes

The proliferated use of personal computers (PCs), smart phones, and entertainment electronics is growing rapidly throughout the world in the recent decades. An estimated 50 Mt of e-wastes are generated globally each year (Schwarzer et al. 2005). In 1994, about 7 million tonnes of PCs reached the end of their useful life which rose to 100 million PCs in 2004. This increase in quantity of e-wastes represent rapidly decreasing average lifespan of the e-products; USA leads the world by producing 3 million tonnes of e-waste each year, and Switzerland is the first country in having organized e-waste management system by implementing extended producer responsibility (EPR) and advance recycling fee (ARF) paradigms. But the problem of e-waste management has become more serious in the developing countries like China, India, and other Asian developing nations due to their tremendous consumption of EEE and as they have become dumping grounds of e-wastes for the first world countries (Bertram et al. 2002). India is also not lagging behind in e-waste generation that is growing at 15%, and according to a Central Pollution Control Board (CPCB) report, 65 cities in India generate more than 60–70% of total e-waste in addition to import of e-waste from developed countries (Hazardous wastes rules 1989/2000/2002). Basel Convention that developed a framework for the control of transboundary movement of e-wastes is a good step taken by United nations Environment Programme (UNEP) in this regard (Johri 2008; Khetriwal et al. 2005), and Basel ban amendment to this convention will be an added advantage. Implementation of some paradigms by particular countries such as National Electronics Action Plan initiated by US Environment Protection Agency, EPR and ARF by Switzerland Government and European Union's (EU) WEEE directive of August, 2004 that makes it compulsory for the manufacturers, and importers in EU to take back their discarded electronic products from consumers to ensure environmentally safe disposal are the steps related to e-waste management (Widmer et al. 2005).

## 6.6 Management of E-waste

Management of e-wastes is increasingly in focus due to continuous growth of e-waste generation, their hazardous nature, presence of precious metals in them, changing lifestyle of the soaring population, and export of e-wastes from developed to industrializing countries which lack proper strategies for reprocessing, etc. These developing countries like India, China, etc., are facing immense problem in dealing with these e-wastes due to practise of inappropriate management techniques (Sthiannopkao and Wong 2013) and due to disposal of 90% of e-waste in landfills and casual recycling of 5% e-waste in Middle-East and North African countries (WAMDA 2018). Various challenges in management of e-waste are varying composition of e-waste, inappropriate recycling and disposal practices, lack of awareness, etc. Numerous strategies such as pyrometallurgy, hydrometallurgy, and mechanical are employed to recover valuable metals from e-waste, but high processing cost and toxicity of the metals present restrict their application (Thakur et al. 2019). In the light of sustainability practices and environment protection, biological approaches such as bioremediation and bioleaching are more promising options.

Bioremediation is an eco-friendly and cost-effective process that utilizes micro-organisms and plants to degrade and stabilize the pollutants (Sharma et al. 2012). It can be considered as an alternative to incineration process, use of catalytic barriers, and absorbents to convert the pollutants into harmless substances (Park and Fray 2009). However, bioremediation, bioleaching, and other biological processes are somewhat sluggish processes. So, onsite bioremediation assisted with bioaugmentation using blended fungi and use of genetically engineered microbes for bioremedation should be developed that can help to fasten up the removal of heavy metals from e-wastes contaminated soil (Hassan et al. 2021). Some of the bioremediation strategies used in recent times for sustainable e-waste management are as follows:

- Bioleaching
- Biosorption
- Bioaccumulation
- Biotransformation
- Biomineralization.

### *6.6.1 Bioleaching*

It is an eco-friendly and economically feasible process of management that found its application in mobilization of metals from e-wastes. There are two types of bioleaching process such as direct (using micro-organisms) and indirect (using metabolic compounds). The types of micro-organisms used for the bioleaching process are chemolithotrophic bacteria (e.g. *Acidithiobacillus ferrooxidans*, *Leptospirillum ferriphilum*, etc.) that release $Fe^{3+}$ to reduce the valuable metals from e-wastes and cynogenic bacteria (e.g. *Chromobacterium violaceum*, *Pseudomonas* spp., etc.) that extract metals from e-wastes by releasing cyanide and also heterotrophic fungi (e.g. *Aspergillus niger*, *Penicillium chrysogenum*) (Narayanasamy et al. 2018; Thakur et al. 2019). This technique is also used in case of extraction of valuable metals such as indium and strontium which present in smartphone touch screens under optimal conditions of pH, solid content, elemental sulphur, etc., using adapted *A. ferrooxidans* (Pourhossein et al. 2021). Bioleaching carried out using acid leads to increased process cost and unsustainability of the process; pH adjustment is also not a necessary requirement rather it reduces the efficiency of the process. For instance: The maximum extraction efficiency of copper and nickel from e-wastes with pH adjustment is about 90% and 88%, respectively, whilst without pH adjustment, the maximum leaching efficiency for copper and nickel obtained was 100% and 92% (Arshadi and Yaghmaei 2020). Again, it was found in a study that bioleaching approach is more effective when mixed culture of micro-organisms such as *A. ferrooxidans* and *Acidithiobacillus thiooxidans* are used for the recovery of precious metals such as copper, zinc, nickel, and aluminium from the discarded printed circuit boards (PCBs) than individual pure culture of these micro-organisms (Arslan 2021) where otherwise two-step bioleaching process under organic acid forming conditions must be taken into account to extract the precious metals from printed circuit boards with maximum efficiency (Narayanasamy et al. 2018). The maintenance of optimum conditions such as initial pH, glycine concentration, and temperature and pulp density is also important factors to maximize precious metal dissolution from e-wastes (Kumar et al. 2018). In some cases, bacterial strains are obtained from abandoned mines for bioleaching of metals from waste PCBs that constitute major portion of e-wastes under optimum conditions such as at initial pH of 9, a pulp density of 10 g/l, a temperature of 10 °C, and a glycine concentration of 5 g/l (Kumar et al. 2021). Some moderately thermophilic and heterotrophic bacteria are also exploited for leaching of metals from scrap that comprises *Sulfobacillus thermosulfidooxidans* (Ilyas et al. 2007).

### *6.6.2 Biosorption*

It is an eco-friendly and cost-effective alternative for removal of heavy metals from e-wastes by using abundant natural materials like microbial biomass, agro wastes, biopolymers, etc., due to the presence of metal binding functional groups in them (Kanamarlapudi et al. 2018). This process is, however, influenced by various process parameters such as pH, temperature, initial concentration of the metal ions, biosorbent dose, and speed of agitation. It can be considered as an economical process as the biosorbent can be regenerated and reused after removal of the heavy metals. It is a reversible rapid process that is involved in binding of ions onto the functional groups present on the surface of the biosorbent in aqueous solutions by means of various interactions (Davis et al. 2003). Biosorption can remove contaminants even in dilute concentrations with high efficiency along with advantages of simple operation, no additional nutrient requirement, low quantity of sludge generation, regeneration of biosorbent, a single stage process, etc. (Chojnacka 2010). In this process, biosorbents such as the dead and live micro-organisms are first suspended in the solution that contains the biosorbate (the metal ions). At the equilibrium stage, the metal-enriched biosorbent could be separated after incubation for a particular time-interval (Chojnacka 2009). The types of biosorbents selected for biosorption process are based on their capacities to bind/uptake metal ions with greater affinities. The biosorbents selected for a process include any kind of plant, animal, or microbial biomass and their derivatives; industrial and agricultural wastes, etc., that have special characteristics such as high affinity for metals, low cost, availability, and possibility of reuse (Macek and Mackova 2011). The application of micro-organisms or biologically origin materials as biosorbents for heavy metal removal is becoming an attractive technology in the recent decades due to high surface to volume ratio; large availability, removal of metals over broad range of pH and temperature; rapid kinetics of adsorption and desorption and low cost (Abbas et al. 2014).

### 6.6.3 Bioaccumulation

It is a process of sequestration of toxic metals inside the body of microbes from the surrounding environment which can replace chemical-based processes in the future. The heavy metals accumulate to alarming concentrations in the organisms such as bacteria and fungi owing to their excellent metal-binding properties. Various organisms are found to accumulate particular toxic metals inside their body for instance: *Vibrio harveyi* has the ability to accumulate cadmium; *Bacillus circulans*, *Bacillus megaterium*, *Deinococcus radiodurans*, and *Micrococcus luteus* can accumulate chromium and uranium metals; and fungal strains such as *A. niger*, *Dipodascaceae*, and *Monodictys pelagic* are reported for bioaccumulation of lead, platinum, and chromium from electronic scrap (Patel and Kasture 2014). In a study, it was also found that *Bacillus licheniformis* is able to remove copper (71.3%) and lead (70.1%); Pb (65.76%) can also be bioaccumulated by *Aspergillus flavus* and zinc (74.1%) by *Pseudomonas aeruginosa* (Akintokun et al. 2017). Marine fungi that inhabit highly contaminated marine sediments are also successful to sequester and bioleach metals especially platinum (31–62%) from discarded e-wastes depending upon the fungal strains and metals considered (Galasso et al. 2022). Bioaccumulation of toxic metals is also done by fishes that are of great concern as it not only affects the fish population, but humans are also posed to danger due to consumption of contaminated fish. The fishes accumulate the toxic metals from water by diffusion via skin and gills as well as oral consumption which results from inability of the fish to metabolize the heavy metals. So, there is need of proper awareness of the danger of improper disposal of heavy metals that ultimately affects human beings and the ecosystem (Nussey et al. 2000; Oguzie 2003).

### 6.6.4 Biotransformation

It is a process of change of chemical properties of the toxic metals obtained from e-waste through addition or removal of electrons (Karigar and Rao 2011). It is carried out in two ways as follows: (1) direct-enzymatic reduction mechanism and (2) indirect reduction mechanism (Tabak et al. 2005). The micro-organisms can play the role of detoxification of heavy metals obtained from e-waste contaminated soil and biotransform them into harmless forms. For instance: *Rhodobacter sphaeroides* and *Rhodium marinum* can eradicate metals such as zinc, copper, lead, and cadmium from the polluted water through biotransformation. Various kinds of plastics such as polyethylene and polystyrene being used for packing that eventually contaminate our environment are converted into harmless forms (biotransformation) by advanced mechanisms using different strains of bacteria (Kathiresan 2003).

### 6.6.5 Biomineralization

It is a process in which toxic metals ions combine with the anions from microbes to form minerals (Patel and Kasture 2014). It can be carried out in two ways as follows: biological induced mineralization (BIM) and biological-controlled mineralization (BCM). In the former case, minerals are formed at a definite site inside or on the cell, whilst in BIM, minerals are formed extracellularly (Ahmed et al. 2019).

## 6.7 Conclusion

Other bioremediation strategies such as phytoremediation (removal of toxic metals such as mercury using metal accumulating plants like cultivated tobacco, swamp lily, etc.) and vermi-remediation technologies (biotransformation of toxic metals into harmless compounds using earthworms) can also be referred for extraction of toxic metals from e-wastes economically and in an eco-friendly way to protect human beings and environment.

## References

Abbas SH, Ismail IM, Mostafa TM, Sulaymon AH (2014) Biosorption of heavy metals: a review. J Chem Sci Technol 3(4):74–102

Abdelbasir SM, El-Sheltawy CT, Abdo DM (2018) Green processes for electronic waste recycling: a review. J Sustain Metall 4:295–311

Ahmed T, Liaqat I, Murtaza R, Rasheed A (2019) Bioremediation approaches for E-waste management: a step towards sustainable environment. Springer Nature Switzerland AG

Akintokun AK, Ontunde OO, Shintu OB, Okeyode IC, Taiwo MO (2017) Bioaccumulation of heavy metals using selected organisms isolated from electronic waste dumpsite of two south-western states in Nigeria. Appl Environ Res 39(2):29–40

Alluri HK, Ronda SR, Settalluri VS, Bondili JS, Suryenarayana V, Venkateswan P (2007) Biosorption: an eco-friendly alternative for heavy metal removal. Afr J Biotechnol 6:2924–2931

Arshadi M, Yaghmaei S (2020) Advances in bioleaching of copper and nickel from electronic waste using *Acidithiobacillus ferrooxidans*: evaluating daily pH adjustment. Chem Pap 74:2211–2227

Arslan V (2021) Bacterial leaching of copper, zinc, nickel and aluminium from discarded printed circuit boards using acidophilic bacteria. J Mater Cycles Waste Manage 23:2005–2015

Awasthi AK, Zeng X, Li J (2016) Integrated bioleaching of copper metal from waste printed circuit board—a comprehensive review of approaches and challenges. Environ Sci Pollut Res 23:21141–21156

Balde CP, Wang F, Kuehr R, Huisman J (2015) The global e-waste monitor-2014. UN University, IAS-SCYCLE, Bonn, Germany

Balde CP, Forti V, Gray V, Kuehr R, Stegmann P (2017) The global e-waste monitor 2017

Bertram M, Graedel TE, Rechberger H, Spatari S (2002) The contemporary European copper cycle: waste management subsystem. Ecol Econ 42(1–2):43–57

Chojnacka K (2009) Biosorption and bioaccumulation in practice. Nova Science Publishers, UK, p 137

Chojnacka K (2010) Biosorption and bioaccumulation—the prospects for practical applications. Environ Int 36:299–307

Davis TA, Volesky B, Mucci A (2003) A review of the biochemistry of heavy metal biosorption by brown algae. Water Res 37:4311–4330

Galasso C, Lekube X, Cancio I, Dell'Anno A, Brunet C, Sansone C, Tangherlini M (2022) Marine fungi as potential eco-sustainable resource for precious metals recovery from electronic waste. Waste Biomass Valorization 13:967–976

Hassan A, Pariatamby A, Ossai IC, Ahmed A, Muda MA, Wen TZ, Hamid FS (2021) Bioaugmentation-assisted bioremediation and kinetics modeling of heavy metals polluted landfill soil. Int J Environ Sci Technol 19:6729–6754

Hazardous wastes (management and handling) rules, 1989/2000/2002

Ilyas S, Anwar MA, Niazi SB, Ghani MA (2007) Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria. Hydrometallurgy 88:180–188

Johri R (2008) E-waste implications, regulations and management in India and current global best practices. The Energy and Resource Institute

Kanamarlapudi LRK, Chintalpudi VK, Muddada S (2018) Application of biosorption for removal of heavy metals from wastewater. Biosorption. https://doi.org/10.5772/intechopen.77315

Karigar CS, Rao SS (2011) Role of microbial enzymes in the bioremediation of pollutants: a review. Enzyme Res. https://doi.org/10.4061/2011/805187

Kathiresan K (2003) Polythene and plastic-degrading microbes in an Indian mangrove soil. Rev Biol Trop 51:629–633

Khetriwal DS, Kraeuchi P, Schwaninger M (2005) A comparison of electronic waste recycling in Switzerland and in India. J Environ Impact Assess Rev 25:492–504

Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manag. https://doi.org/10.1016/j.wasman.2013.01.006

Kumar S, Rawat S (2018) Future e-waste: standardization for reliable assessment. Gov Inf Q 35(4):S33–S42

Kumar AVA, Hashimi SA, Hilal N (2008) Investigation of kinetics and mechanism involved in the biosorption of heavy metals on activated sludge. Int J Green Energy 5:313–321

Kumar A, Singh H, Kumar S (2018) Bioleaching of gold and silver from waste printed circuit boards by *Pseudomonas balearica* SAE1 isolated from an e-waste recycling facility. Curr Microbiol 75:194–201

Kumar A, Saini HS, Sengor S, Sani RK, Kusnar S (2021) Bioleaching of metals from waste printed circuit boards using bacterial isolates native to abandoned gold mine. BioMetals 34:1043–1058

Li JH, Duan HB, Shi PX (2011) Heavy metal contamination of surface soil in electronic waste dismantling area: site investigation and source-apportionment analysis. Waste Manag Res 29:727–738

Macek T, Mackova M (2011) Potential of biosorption technology. In: Microbial biosorption of metals. Springer, Netherlands, pp 7–17

Morf LS, Tremp J, Gloor R, Schuppisser F, Stengele M, Taverna R (2007) Metals, non-metals and PCB in electrical and electronic waste—actual levels in Switzerland. Waste Manag 27:1306–1316

Narayanasamy M, Dhanasekaran D, Vinothini G, Thajuddin N (2018) Extraction and recovery of precious metals from electronic waste printed circuit boards by bioleaching acidophilic fungi. Int J Environ Sci Technol 15:119–132

Nussey G, Van Vuren JHJ, Du Preez HH (2000) Bioaccumulation of chromium, manganese, nickel and lead in the tissues of the moggel, *Labeo umbratus* (Cyprinidae), from Witbank Dam, Mpumalanga. Water SA 26:269–284

Oguzie FA (2003) Heavy metals in fish, water and effluents of lower Ikpoba river in Benin City, Nigeria. Pak J Sci Ind Res 46:156–160

Park YJ, Fray DJ (2009) Recovery of high purity precious metals from printed circuit boards. J Hazard Mater 164:1152–1158

Patel S, Kasture A (2014) E-waste management using biological system—overview. Int J Curr Microbiol Appl Sci 3:495–504

Pourhossein F, Rezaei O, Mousavi SM, Beolchini F (2021) Bioleaching of critical metals from waste OLED touch screens using adapted acidophilic bacteria. J Environ Health Sci Eng 19:893–906

Robinson HB (2009) E-waste: an assessment of global production and environmental impacts. Sci Total Environ 408:183–191

Sankhla MS, Kumari M, Nandan M, Mohrih S (2016) Effect of electronic waste on environmental and human health—a review. J Environ Sci Toxicol Food Technol 10(9):98–104

Schwarzer S, Bono AD et al (2005) E-waste, the hidden side of IT equipment's manufacturing and use. In: Environment alert bulletin (UNEP early warning on emerging environmental threats), no 5

Sharma P, Fulekar MH, Pathak B (2012) E-waste—a challenge for tomorrow. Res J Recent Sci 1(3):86–93

Shinu NT, Needhidasan S (2020) An experimental study of replacing conventional coarse aggregate with E-waste plastic for M40 grade concrete using river sand. Mater Today Proc 22(3):633–638

Status report on e-waste management in Sri Lanka (2010) Central Environment Authority

Sthiannopkao S, Wong MH (2013) Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci Total Environ 463–464:1147–1153

Tabak M, Clark DS, Hatchett SP, Key MH, Lasinski BF, Snavely RA, Wilks SC, Town RPJ (2005) Review of progress in fast ignition. Phys Plasmas 12:057305

Tchounwou PB, Yedjou CG, Patlolla AK, Sultan DJ (2012) Heavy metals toxicity and the environment. In: Molecular, clinical and environmental toxicology, vol 101, pp 133–164. Springer, Basel

Thakur P, Kumar A, Kumar S (2019) Bioremediation and management of e-waste

Tripathi BD (2011) A short-term study on toxic effects of distillery sludge amendment on microbiological and enzymatic properties of agricultural soil in a tropical city. J Earth Sci Clim Change 2:106

UNEP (2010) E-waste vol I: inventory assessment manual, vol 1, pp 145–162

WAMDA (2018) The Middle East and its e-waste problems. https://www.wamda.com/2018/10/middle-east-e-waste-problem. Accessed 22 Jan 2019

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Böni H, Schnellmann M (2005) Global perspectives on e-waste. Environ Impact Assess Rev 25(5):436–458. The gadget scrap heap: electronic waste, June 2007, pp 44–48. www.ChemistryWorld.org

Williams E (2005) International activities on e-waste and guidelines for future work. In: Proceedings of the third workshop on material cycles and waste management in Asia, Tsukuba, Japan, Dec 2004

Wuana RA, Okieimen FE (2011) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecol 1–20

# Chapter 7
# Bioremediation: A Sustainable Way for E-waste Management

**Hemant Dasila, Damini Maithani, Pragati Srivastava, and Manisha Kabdwal**

**Abstract** Electronic waste (E-waste) describes discarded electronic devices. E-waste at present days becomes a prime concern around the globe and poses a serious threat to community health wise on a large scale. Chemical properties of E-waste are different as compared to other household and municipal waste due to presence of complex component that require advance technical tool for its scientifically disposal. Improper management practices of E-waste cause release of toxic compounds which adversely affect air, water, and soil quality. Growing industrialization causes mishandling of toxic compounds which present in E-waste such as polyaromatic hydrocarbon (PAH), xenobiotic, heavy metal, and insecticides. Therefore, their effective management is very crucial for environmental sustainability and human health.

**Keywords** Electronic waste · Leaching · Biotransformation

## 7.1 Introduction

E-waste comprises of variety of emerging electronic goods such as audio system, mobile phones, air-conditioners (AC), freezers, and like expendable personal computers disposed by people (Patel and Kasture 2014). Average E-waste production is around 30–60 Mt which is significantly higher than the 20–50 Mt/year during 2008 (Robinson 2009). E-waste as already mentioned comprises of complex compound

H. Dasila (✉)
Department of Microbiology, Eternal University, Baru Sahib, Sirmaur, Himachal Pradesh 173101, India
e-mail: hemantdasila4@gmail.com

D. Maithani
School of Biotechnology, IFTM University, Moradabad 244102, India

P. Srivastava
Department of Microbiology, College of Basic Sciences and Humanities, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar 263145, India

M. Kabdwal
Patanjali Research Institute, Haridwar, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_7

**Table 7.1** Classification of E-waste based on their nature with their respective source of accumulation

| Types of E-wastes | Examples | Source |
|---|---|---|
| Persistence organic pollutant (POP) | Brominated, polychlorinated biphenyl through air | Bimaculate in sea food |
| Polyaromatic hydrocarbon | Acenapthene, anthracene, Benzopyrene, benzofluro anthene, chrysene, phenanthrene | Via air, food |
| Dioxin | Polychlorinated dibenzodioxins | Air, dust, soil, and food |
| Elements | Lead, chromium, mercury, zinc, nickel, lithium | Water and soil |

and contains metal as one of major side product during E-waste generation (UNEP 2007; Song et al. 2014; Balde et al. 2015). Metal from E-waste has been recovered by using biological, chemical, and hybrid modern leaching techniques (Table 7.1). Traditionally, most of the E-waste components are subjected to landfill, and frequency of recycling the E-waste is also very low as there is a limitation of land; thus, importance of E-waste recycling becomes very important. E-waste recovered from urban and rural area differs in their physical and chemical properties. E-waste compromises of both valued and hazardous material, and thus, their separation becomes very necessary. One of the most important examples of valuable item is metal which is present in complex form in E-waste. Base metal recovery and other important valuable material can be recycled but it is not cost effective (Esteve-Nunez et al. 2001).

Nations are facing some serious problem in handling E-waste that is either locally manage or imported (Nnorom and Osibanjo 2008). It has been observed that most of the developed nations (U.S.A, Germany, etc.) transport their E-waste to developing countries (Pakistan, China, India, Vietnam, Ghana, etc.), and there comes a problems in most of these developing countries inappropriate E-waste management practices which are employed. Around 90% of E-waste is been disposed to landfill, and only about 4–5% is been recycled (WAMDA 2018).

## 7.2 E-waste Composition

Electronic waste (E-waste) at majority depends entirely upon nature and persistence nature of electronic fragment. Telecommunication and information technology (IT) scraps compromise majority of valued metals (Tripathi 2011; Tanskanen 2013). A typical mobile at an average has more than 40 components which include costly material such as silver (Ag), palladium (Pa), and gold (Au) along metals like lithium (Li), antimony (An), cobalt (Co), and indium (In). Some remnants in the form of plastic, ceramics, etc. (Izatt et al. 2012). In normal PC, around 6 kg of iron is used.

AC and refrigerators consist of chlorofluorocarbon (CFC), and this released CFCs in landfill contribute to majority of stratosphere ozone depletion (Scheutz et al. 2004).

### *7.2.1 Organic Part of Composition*

Electronic component of gadgets composed of organic component part too having different fibres of polymeric nature (Alaee et al. 2003). Amongst them, some chlorinated and brominated derive organic compounds which later can be analyzed by different technique. The plastic part of electronic gadgets contains 30% of flame (Bientinesi and Petarca 2009). Halogenated plastic was released from E-waste which is very difficult to handle and were subjected to dehalogenation process.

## 7.3 Different Strategies for E-waste Bioremediation

Different methods of leaching have been employed to encounter huge E-waste product formation, and these are discussed below.

### *7.3.1 Chemical Leaching*

Chemical leaching involves the use of cyanide, thiourea, thiosulfate, and halide leaching, and chemical leaching method is one of the most commonly used methods employed for recovery of metals from E-waste. A solution used in the chemical method includes hydrochloric acid, sulphuric acid, mixture of sulphuric acid, and nitric acid with alkali and acid used for metal recovery. Ethylene diamine tetra acetate (EDTA) amongst potent chelating agent and being used for the metal recovery too from ore was recovered from E-waste. The most common limiting factors that regulate chemical leaching method include release of toxic gases, high-energy consumptions, and its cost.

### *7.3.2 Biological Leaching*

Use of biological active agent and natural agent for leaching purpose against E-waste scrap is called microbial leaching. These active agents possess the great potential to transform metals. Many studies have also been reported where precious metals have been recovered, and most common metal recovered from biological leaching is gold (Faramarzi et al. 2004; Brandl 2008). *Chromobacterium violaceum*, one of the microorganisms, found to be efficient in mobilization of gold (Au) from E-waste. In addition to *C. violaceum*, some *Pseudomonas* strain also found to be associated with extraction of gold from waste electronic goods (Pham and Ting 2009). Microorganisms involve the mobilization of metals via formation of various oxides ($FeSiO_4$, $FeCr_2O_4$, $Fe_3O_4$), hydroxides (OH), $Mn_3O_3(OH)_6$, and sulphides ($FeS_2$, $MoS_2$, $AS_2S_3$, $CuFeS_2$, $Cu_2S$, $Fe_7S_8$, $MnS_2$, PbS, ZnS) (Ilyas and Lee 2015). Other microorganisms that are involved in bioleaching of heavy metals are *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, and *Sulfolobus* sp. (Mishra and Rhee 2010), and these microorganisms are reported to show bioleaching (Lee and Pandey 2012). *A. ferrooxidans* and *A. thiooxidans* use $Fe^{+2}$ and reduced sulphur as energy source and $CO_2$ as carbon source for reduction of heavy metals (Brandl et al. 2001). At present, three groups of bacteria include autotrophs (*Thiobacillus* sp.), heterotrophs (*Pseudomonas* sp.), and heterotrophic fungi (*Aspergillus* and *Penicillium* sp.) (Schinner and Burgstaller 1989; Pant et al. 2012).

Some important chemical reactions involved in metal oxidations

(i) Oxidation

$$Fe^{2+} + O_2 + H^+ \rightarrow Fe^{3+} + H_2O$$

$Fe^{3+}$ formed in this reaction later utilized by *A. ferrooxidans* to oxidize Cu

$$Cu^0 + Fe^{3+} \rightarrow Fe^{2+} + Cu^{2+}$$

(ii) Direct mechanism of leaching involves bioleaching of pyrite

$$2FeS_2 + 7O_2 + 2H_2O + 2H_2SO_4 - 2FeSO_4 + 2H_2SO_4$$

$$4FeS_2 + O_2 + 2H_2SO_4 - 2Fe(SO_4)_3 + 2H_2O$$

For Cu, bioleaching process account for almost 10% of cu metal extraction. *A. ferrooxidans* is also employed for copper recovery via bioleaching or biomining method which involves oxidation of iron and sulphur mineral and electron released during this oxidation process later utilized by electron acceptor NADH (Levicán et al. 2002; Yarzábal et al. 2002; Brasseur et al. 2004; Bruscella et al. 2007; Valdés et al. 2008).

Genome analysis of *A. ferrooxidans* identifies the importance of electron transport chain which involves in oxidation of ferrous ion. Two transcription units such as pet I and rus DNA sequence are play important role in oxidation reaction when identify by bioinformatic tools (Valdés et al. 2008). pet I sequence is part of pet I operon (pet A, B, and C) which encodes the subunit of cytochrome bc1 complex (Levicán et al. 2002). Rus operon includes gene cyc2, cyc1, hyp, coxB, coxC, and coxD. Rus operon encodes two types of cytochrome (Cyc 1 and Cyc 2) of cytochrome oxidase (CoxBACD) and rusticyanin (Appia-Ayme et al. 1999). All

**Table 7.2** Advantages and disadvantages of biological and chemical leaching process

| | Biological leaching | Chemical leaching |
|---|---|---|
| Advantage | Inexpensive | More efficient |
| | Environmental friendly | Mineral yield is high |
| | No requirement of high temperature and pressure | Demand of energy input is high |
| | Ideal process for low grade sulphide ore | Process is operated at much controlled way |
| Disadvantage | Process is slow | Expensive process |
| | Low yield of mineral | Not good for environment |
| | Sometimes, control of process is not optimized | Potential threat for acid leak accident |
| | High risk of contamination | |

these molecular and computational biological evidences proposed that *A. ferrooxidans* is one of the potential biological agents to be used in industrial bioleaching (Valdés et al. 2008). Advantage and disadvantage of chemical and biological leaching have been mentioned in Table 7.2.

### *7.3.3 Biotransformation*

Biotransformation involves the biochemical modification one or mixture of chemical compounds which transform toxic substance to less toxic one via oxidation and reduction cycle. Biotransformation process can be done on whole cells or their purified enzyme product. Biotransformation approaches involve the use of microorganisms natural metabolic potential to destroy or accumulate toxic complexes from E-waste from radionuclides, pharmaceuticals constituents, etc. (Karigar and Rao 2011). *Rhodobacter marinum* and *Rhodobacter sphaeroides* possess the potential to eradicate toxic metal like copper, lead, zinc, and cadmium from various polluted water via biotransformation process. Two main mechanisms that are involved in biotransformation are (i) direct enzyme reduction and (ii) indirect enzyme reduction (Tabak et al. 2005).

Polyaromatic hydrocarbons are one of the most diverse hydrocarbons, and due to its persistence in nature, they causes mutagenicity. Some aquatic bacterial species are known to biotransform PAHs via slight modification in their biodegradation pathway, and most common examples of these bacteria are *Cycloclasticus spirillensus*, *Lutibacterium anuloederans*, and *Neptunomonas naphthovorans* (Chung and King 2001).

There are different types of category of plastic that are being used in market for packaging, fishing, and transport services, these include poly vinyl chloride, polystyrene, polyethylene terephthalate, polypropylene, etc., and all these plastics are known to bioaccumulate in an environment that eventually result in contamination of environment.

### *7.3.4 Biosorption*

Biosorption is adsorption phenomenon, and this process is used to bind solvable pollutant (toxic metal) on cellular surface. The ability of microorganisms (bacteria and fungi) to reduce heavy metal ion or radionuclide has gain attention in bioadsorption process and further used their ability at large scale in industry (Volesky et al. 1993). Biosorption for E-waste bioremediation varies with ability metabolism of microorganisms.

There are direct and indirect types of mechanisms that are involved in microorganisms metabolism and in direct mechanism physiochemical interaction occur between functional group present in bacterial cell surface against metal of interest that results in its bio-adsorption. Microbial cell wall consists of lipid, carbohydrates, and protein, and all these macromolecules have surface area to interact with metal (Ahalya et al. 2003). These interactions led to the transportation of toxic material after bioadsorption via altering cell permeability.

### *7.3.5 Consortia or Mixed Culture Mediated E-waste Bioremediation*

Consortia or mixed cultures of microorganisms are more efficient in carrying out bioleaching process from E-waste than single culture. *A. ferrooxidans* and *A. thiooxidans* in mixed culture were found to be potentially good in extracting metals like copper (Cu), zinc (Zn), nickel (Ni), and lead (Pb) from PCB scrap (Liang et al. 2010; Pant et al. 2012). Combination of *Aspergillus niger* and *Penicillium simplicissimum* was associated with extraction of copper and nickel from E-waste (Brandl et al. 2001; Mulligan and Kamali 2003). Mixed culture of bacteria (*Bacillus circulans* and *Bacillus mucilaginosus*) and fungi (*Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans*) was found to be associated with extraction of Al from its ore (Groudev 1987; Brandl et al. 2001; Solisio and Lodi 2002). Amongst bacteria, consortia made of combination using *Gallionella* sp., *Acidithiobacillus* sp., and *Leptospirillum* sp. used for bioleaching of metals from their natural source, e.g. acid mine drainage (Xiang et al. 2010).

## 7.4 Factors Influencing Leaching Purpose

Different factors affect bioleaching purpose such as temperature, redox potential, pH, mass transfer, nutrient availability, and gases like carbon dioxide ($CO_2$) and water potential. Bioleaching environment includes population density, microbial diversity, spatial distribution of microorganisms, and metal tolerance (Brandl 2008). *T. ferrooxidans* mediated oxidation of sphalerite influenced by source of energy, microbial cell, particle size, and temperature (Ballester et al. 1990). Presence of surface active agent, organic compounds, and organic solvents inhibits oxidation of pyrite by *T. ferrooxidans* (Bacelar-Nicolau and Johnson 1999). Some heavy metals like copper (Cu), uranium (U), nickel (Ni), and thorium (Th) also affect leaching process by interfering with metabolic pathway of microorganisms (Leduc et al. 1997). Biocides from industry like tetra-n-butyltin, 5,5b-dichlorophenylmethane (dichlorophen), isothiazolinones, 2,2b-dihydroxy, and isothiazolinones reported to decrease leaching rate manganese oxide by heterotrophic microorganisms (Arief and Madgwick 1992).

## 7.5 Impact of E-waste on Environment and Human Health

Over the past few decades, spectacular advances in technology and the changing lifestyles of people accelerated the manufacture of electrical and electronic equipment (EEE) at an exponential rate (Rautela et al. 2020). Rapid technical evolutions in EEE, especially in mobiles, and their widespread expansion in usage have significantly increased the number of devices that are quickly out of date and abandoned, leading to substantial waste electrical and electronic equipment generation (WEEE, or E-waste). E-waste has adverse impacts both on environment and on human health, which is increasingly becoming a global concern. The world produced 48.5 million tonnes of electronic waste in 2018, according to a UN report (https://tcocertified.com/news/global-e-waste-reaches-record-high-says-new-un-report). Unfortunately, only 20% of this E-waste is recycled. Without taking any decisive action, this trend will lead to the production of 120 million tonnes of electronic scrap by 2050, causing irreparable damage to the ecosystem.

The Organization for Economic Co-operation and Development (OECD) defines electronic waste as an electrical device that has reached the end of its useful life. Therefore, apart from mobile phones, there are numerous types of other E-waste. Electronic devices like refrigerators, freezers, computers, telecommunications equipment, solar panels, TVs, monitors, LED bulbs, and vending machines have the potential to generate a significant amount of E-waste.

Toxic heavy metals such as Pb, Hg, and Cr (VI), as well as BFRs such as polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), and brominated flame retardants (BFRs), pollute the environment with electronic debris (Schurter 2019). In developing countries, E-waste is dumped in unhygienic or unmanaged locations. These E-waste disposal activities are commonly carried out in

Pakistan, India, the Philippines, Nigeria, and China. E-waste pollutants are airborne like dust or fumes, which dominate human exposure pathways through inhalation, ingestion, and skin absorption (Mielke and Reagan 1998). These potentially have genotoxic effects and a negative impact on human health.

### 7.5.1 Impact on Human Health

There are reports which suggests that there is potential effect on human health and the environment through the USE-LCIA model. They discovered that Hg, followed by lead and chromium, is the most potent carcinogen and non-carcinogen in mobile phone plastic. Sb, Cd, Hg, As, Pb, and Be were the next most notable eco-toxicity risks, followed by Cr. India's pilot study in the Delhi NCR region revealed that all 63 of the workers were working in an E-waste rubbish yard without any safety because recycling processes are still in their infancy (Kowsar et al. 2010). Even gloves and appropriate tools were not accessible. Other developing and underdeveloped nations are experiencing a more alarming situation. An occupational and environmental health officer of the Ghana Health Service remarked the following during in-depth interviews for a brief case study in Ghana: "The practice of burning electrical and electronic waste endangers the lives of all others living in close proximity who inhale the fumes" (Agyei-Mensah et al. 2012). Including workers, people living near to E-waste processing facilities are exposed to genotoxic compounds discharged and transported via several natural pathways (Awasthi et al. 2018). Various studies have assessed the average daily doses (ADD) of heavy metals, including through direct ingestion (ADDing), absorption through the skin (ADDderm), and inhalation (ADDinh) (Fang et al. 2013; Xue et al. 2012). The levels of heavy metals (particularly Cr, Cu, Cd, and Pb) were found to be higher in mechanical workplaces than in manual dismantling sectors, and the mechanical operation is thought to produce more contaminated particles and dust. According to reports, children in these locations are eight times more vulnerable to these toxins. Along with heavy metals, individuals living near E-waste recycling facilities are frequently exposed to polychlorinated biphenyls (PCBs) through both dietary (meat, seafood, drinking water, etc.) and non-dietary (inhalation and cutaneous exposure) routes (Meng et al. 2014). It was found that poor E-waste recycling can cause high rates of miscarriage, birth defects, and cancer clusters amongst workers (Keirsten and Michael 1999). Pregnant women living in E-waste recycling areas struggle to protect themselves from heavy metals and organic pollution from E-waste, increasing the likelihood of premature births, reduced birth weights and infant lengths, spontaneous abortions, stillbirths, Apgar scores, and neonatal behavioural neurological assessment (NBNA) scores (Song and Li 2015). According to research, it was observed that poor E-waste recycling has been linked to increased incidence of miscarriage, birth deformities, and cancer clusters amongst workers (Keirsten and Michael 1999). Premature births, spontaneous abortions, stillbirths, reduced infant weights and lengths, Apgar scores, and neonatal behavioural neurological assessment (NBNA) are all more likely to occur in pregnant women living near E-waste recycling areas because they are unable to protect themselves from the heavy metals and organic pollution from E-waste (Song and Li 2015). It was also found that pregnant women exposed to E-waste chemicals had negative effects and ran the risk of their unborn children developing infectious and allergy illnesses (Potera 2000). Children living near E-waste sites are more susceptible to exposure of persistent organic pollutants like PCBs, PBDE, and dioxin. It was observed that children's serum sample has significantly rise in toxic chemicals along with disturbed thyroid stimulating hormone (TSH) (Han et al. 2011). Furthermore, the adverse effects of exposure to chromium, nickel, and manganese were also quite evident, especially in children's (Zheng et al. 2013) reduced forced vital capacity (FVC) of the lungs. Another study demonstrated (Bi et al. 2007) that blood lead levels (BLLs) and the serum concentrations of PBDEs and organo-chlorine pesticides (OCPs) were significantly higher amongst children inhabiting near E-waste zones in Guiyu than those in the children from controlled sites (Burns et al. 2009) focussed on E-waste recycling enterprises in Russia and discovered that boys who were fed local cuisine or who were breastfed by women who worked in this industry had greater levels of dioxin and PCBs in their blood than other boys.

Recently, molecular studies were conducted to investigate these manifestations related to the exposure of E-waste. Women exposed to an E-waste location showed significant S100P protein downregulation, enhanced MT expression, and elevated placental cadmium levels (Zhang et al. 2011). Additionally, as compared to the surrounding healthy area, significant disparities in lymphocyte DNA damage were found in neonates residing in the E-waste recycling region (Li et al. 2008).

As a response to this serious issue, responsible authorities developed a various tool that show definite promise in dealing with it. To assess the risk of human exposure to hazardous E-waste, various guidelines U.S. EPA (Shi et al. 2019) and a scientific health risk assessment model were developed and made available, which can predict the seriousness of the situation so that actions can be taken at the right time. The U.S. EPA has developed a health risk assessment methodology aiming to calculate the hazard quotients (HQ) for each non-carcinogenic heavy metal (Xue et al. 2012). Nevertheless, the ultimate responsibility lies with the end users to operate electrical and electronic equipment in a responsible and controlled manner (EEE).

## 7.6 Future Strategies for Minimizing E-waste

Electronic and electrical equipment are nearly vital in the age of information and communication technologies. Due to the rapid advancement of technology, many of these gadgets become outdated within a few years after their creation. These elements contribute to the surge in demand brought on by the rising spending power of people around the world, and they also causes large amounts of E-waste to be produced (Ahirwar and Tripathi 2021).

E-waste management has become indispensable issue in reducing environmental problems. E-waste is the management of non-operational and unwanted electrical and electronic products. We must make wise choices in order to have sustainable operations because the manufacturing, usage, and disposal of electrical and electronic devices are involved (Ghosh et al. 2022). One has to make crucial choices in this matter to step towards sustainable E-waste management scenarios. Keshavarz-Ghorabaee et al. (2022) developed a special methodology with the goal of finding a long-term solution for managing E-waste. The problem is referred to as an multi-criteria decision-making (MCDM) problem, and the scheme is the key to the solution, which must be verified in the light of many sustainability criteria. To deal with the evaluation process, an expanded fuzzy simultaneous evaluation of criteria and alternatives (SECA) integrated with simple multi-attribute rating technique (SMART) is presented.

The α-cut strategy is used to evaluate criteria and alternatives whilst taking into account various degrees of uncertainty. The suggested methodology aids in the review process by including subjective and objective data, the insights of other experts, and the unreliability of the data. Chen et al. (2021) proposed artificial intelligence-based E-waste management for environmental planning. Three major strategies such as life cycle assessment (LCA), multi-criteria analysis (MCA), and extended producer responsibility (EPR) were considered.

The Ministry of Environment Korea produced a set of guidelines for Cambodian E-waste management with certain guiding principles, as follows Xavier et al. (2021):

- Prior to disposal, reuse as much of the E-waste as feasible.
- Reduce E-waste at the source, such as with consumers, dealers, and those who repair and disassemble devices, rather than keeping or discarding electronic and electric equipment, repair it.
- E-waste should be recycled before being disposed of.
- It should be managed throughout its life cycle according to environmentally sound principles, including during the generation process, storage, transportation, treatment, and disposal.
- Locate, create, and run a secure disposal facility for hazardous garbage, including E-waste, from a few designated urban locations.
- Tying up with national and international laws, regulations, conventions, and protocols.

Pan et al. (2022) described future research agendas on circular economy practices in the waste electrical and electronic equipment (WEEE) industry. The main activities related to the circular economy (CE) that involves turning electrical and electronic equipment EEE into waste electrical and electronic equipment (WEEE) were the target of the study. The actions include (1) putting materials to good use, such as recycling and recovering E-waste and its components; (2) extending the lifespan of E-waste and its components through reuse; (3) limited use of E-waste via refuse, rethink, and decrease.

## 7.7 Conclusion

E-waste disposal and its management are very crucial and needed to be done in a very precise manner as E-waste not only damages environment but it also effects human health. Lack of knowledge and awareness about E-waste disposal can cause serious health issue especially to children. Bioremediation of E-waste using biological active microorganisms now becomes one of the prominent tool to encounter E-waste disposal issue. Bioremediation mediated E-waste disposal process not only eco-friendly but also cost effective . However, proper implication of E-waste polices that are regulated by government should be done.

## References


Agyei-Mensah S, Oteng-Ababio M (2012) Perceptions of health and environmental impacts of e-waste management in Ghana. Intl J Environ Health Res 22(6):500–517

Ahalya N, Ramachandra T, Kanamadi R (2003) Biosorption of heavy metals. Res J Chem Environ 7:71–79

Ahirwar R, Tripathi AK (2021) E-waste management: a review of recycling process, environmental and occupational health hazards, and potential solutions. Environ Nanotechnol Monit Manag 15:100409

Alaee M, Arias P, Sjödin A, Bergman Å (2003) An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environ Int 29(6):683–689

Appia-Ayme C, Guiliani N, Ratouchniak J, Bonnefoy V (1999) Characterization of an operon encoding two c-type cytochromes, an aa(3)-type cytochrome oxidase, and rusticyanin in *Thiobacillus ferrooxidans* ATCC 33020. Appl Environ Microbiol 65(11):4781–4787

Arief YY, Madgwick JC (1992) The effect of biocides on microaerobic bacterial biodegradation of manganese oxide. Biorecovery 2(2):95–106

Awasthi AK, Wang M, Awasthi MK, Wang Z, Li J (2018) Environmental pollution and human body burden from improper recycling of e-waste in China: a short-review. Environ Pollut 243:1310–1316. https://doi.org/10.1016/j.envpol.2018.08.037

Bacelar-Nicolau P, Johnson DB (1999) Leaching of pyrite by acidophilic heterotrophic iron-oxidizing bacteria in pure and mixed cultures. Appl Environ Microbiol 65(2):585–590

Balde CP, Wang F, Kuehr R, Huisman J (2015) The global e-waste monitor—2014. United Nations University, IAS—SCYCLE, Bonn, Germany

Ballester A, Gonzalez F, Blazquez ML, Mier JL (1990) The influence of various ions in the bioleaching of metal sulphides. Hydrometallurgy 23(2–3):221–235

Bi X, Thomas GO, Jones KG, Qu W, Sheng G, Martin FL, Fu J (2007) Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China. Environ Sci Technol 41(16):5647–5653

Bientinesi M, Petarca L (2009) Comparative environmental analysis of waste brominated plastic thermal treatments. Waste Manag 29(3):1095–1102

Brandl H (2008) Microbial leaching of metals. In: Biotechnology set, 2nd edn, pp 191–224

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59(2):319–326

Brasseur G, Levicán G, Bonnefoy V, Holmes D, Jedlicki E, Lemesle-Meunier D (2004) Apparent redundancy of electron transfer pathways via bc1 complexes and terminal oxidases in the extremophilic chemolithoautotrophic *Acidithiobacillus ferrooxidans*. Biochim Biophys Acta (BBA)-Bioenergy 1656(2):114–126

Bruscella P, Appia-Ayme C, Levicán G, Ratouchniak J, Jedlicki E, Holmes DS, Bonnefoy V (2007) Differential expression of two bc1 complexes in the strict acidophilic chemolithoautotrophic bacterium *Acidithiobacillus ferrooxidans* suggests a model for their respective roles in iron or sulfur oxidation. Microbiology 153(1):102–110

Burns JS, Williams PL, Sergeyev O, Korrick S, Lee MM, Revich B, Hauser R (2009) Predictors of serum dioxins and PCBs among peripubertal Russian boys. Environ Health Perspect 117(10):1593–1599. https://doi.org/10.1289/ehp.0800223

Chen D, Liu R, Lin Q, Ma S, Li G, Yu Y, An T (2021) Volatile organic compounds in an e-waste dismantling region: from spatial-seasonal variation to human health impact. Chemosphere 275:130022

Chung WK, King GM (2001) Isolation, characterization, and polyaromatic hydrocarbon degradation potential of aerobic bacteria from marine macrofaunal burrow sediments and description of *Lutibacterium anuloederans* gen. nov., sp. nov., and *Cycloclasticus spirillensus* sp. nov. Appl Environ Microbiol 67:5585–5592

Esteve-Nunez A, Caballero A, Ramos JL (2001) Biological degradation of 2,4,6-trinitrotoluene. Microbiol Mol Biol Rev 65:335–352

Fang W, Yang Y, Xu Z (2013) PM10 and PM2.5 and health risk assessment for heavy metals in a typical factory for cathode ray tube television recycling. Environ Sci Technol 47(21):12469–12476. https://doi.org/10.1021/es4026613

Faramarzi MA, Stagars M, Pensini E, Krebs W, Brandl H (2004) Metal solubilization from metal-containing solid materials by cyanogenic *Chromobacterium violaceum*. J Biotechnol 113(1):321–326

Ghosh BK, Mekhilef S, Ahmad S, Ghosh SK (2022) A review on global emissions by E-products based waste: technical management for reduced effects and achieving sustainable development goals. Sustainability 14(7):4036

Groudev SN (1987) Use of heterotrophic microorganisms in mineral biotechnology. Acta Biotechnol 7(4) 299–306

Han G, Ding G, Lou X, Wang X, Han J, Shen H, Du L (2011) Correlations of PCBs, DIOXIN, and PBDE with TSH in children's blood in areas of computer E-waste recycling. Biomed Environ Sci 24(2):112–116. https://doi.org/10.3967/0895-3988.2011.02.004

Ilyas S, Lee JC (2015) Hybrid leaching: an emerging trend in bioprocessing of secondary resources. In: Microbiology for minerals, metals, materials and the environment. CRC Press, pp 359–382

Izatt NE, Izatt SR, Bruening RL (2012) Green procedure for the selective recovery of precious, specialty, and toxic metals from electronic wastes. In: Electronics goes green 2012+ (EGG). IEEE, pp 1–6

Karigar CS, Rao SS (2011) Role of microbial enzymes in the bioremediation of pollutants: a review. Enzyme Res. https://doi.org/10.4061/2011/805187

Keirsten S, Michael P (1999) A report on poison PCs and toxic TVs, silicon valley toxic coalition

Keshavarz-Ghorabaee M, Amiri M, Zavadskas EK, Turskis Z, Antucheviciene J (2022) A fuzzy simultaneous evaluation of criteria and alternatives (F-SECA) for sustainable E-waste scenario management. Sustainability 14(16):10371

Kowsar R, Hashia H, Khan F (2010) e-Waste and its health impacts. 88 10(4) (Ver 1.0) (2010)

Leduc LG, Ferroni GD, and Trevors JT (1997) Resistance to heavy metals in different strains of Thiobacillus ferrooxidans. World J Microbiol Biotechnol 13:453–455

Lee JC, Pandey BD (2012) Bio-processing of solid wastes and secondary resources for metal extraction—a review. Waste Manag 32(1):3–18

Levicán G, Bruscella P, Guacunano M, Inostroza C, Bonnefoy V, Holmes DS, Jedlicki E (2002) Characterization of the petI and res operons of *Acidithiobacillus ferrooxidans*. J Bacteriol 184(5):1498–1501

Li Y, Xu X, Liu J, Wu K, Gu C, Shao G, Huo X (2008) The hazard of chromium exposure to neonates in Guiyu of China. Sci Total Environ 403(1–3):99–104. https://doi.org/10.1016/j.scitotenv.2008.05.033

Liang G, Mo Y, Zhou Q (2010) Novel strategies of bioleaching metals from printed circuit boards (PCBs) in mixed cultivation of two acidophiles. Enzyme Microb Technol 47(7):322–326

Meng M, Li B, Shao J, Wang T, He B, Shi J (2014) Accumulation of total mercury and methylmercury in rice plants collected from different mining areas in China. Environ Pollut 184:179–186. https://doi.org/10.1016/j.envpol.2013.08.030

Mielke HW, Reagan PL (1998) Soil is an important pathway of human lead exposure. Environ Health Perspect 106:217–229

Mishra D, Rhee YH (2010) Current research trends of microbiological leaching for metal recovery from industrial wastes. In: Current research, technology and education topics in applied microbiology and microbial biotechnology, vol 2, pp 1289–1292

Mulligan CN, Kamali M (2003) Bioleaching of copper and other metals from low-grade oxidized mining ores by Aspergillus niger. J Chem Technol Biotechnol Int Res Proc Environ Clean Technol 78(5):497–503

Nnorom IC, Osibanjo O (2008) Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour Conserv Recycl 52:843–858

Pan X, Wong CW, Li C (2022) Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: a systematic review and future research agendas. J Clean Prod 132671

Pant D, Joshi D, Upreti MK, Kotnala RK (2012) Chemical and biological extraction of metals present in E-waste: a hybrid technology. Waste Manag 32(5):979–990

Patel S, Kasture A (2014) E (electronic) waste management using biological systems—overview. Int J Curr Microbiol Appl Sci 3:495–504

Pham VA, Ting YP (2009) Gold bioleaching of electronic waste by cyanogenic bacteria and its enhancement with bio-oxidation. In: Advanced materials research, vol 71. Trans Tech Publications, pp 661–664

Potera C (2000) Exposure now, sickness later: early exposure to PCBs and dioxins may increase some childhood diseases. Environ Health Perspect 108(12):574–575

Rautela M, Gopalakrishnan S, Gopalakrishnan K, Deng Y (2020) Ultrasonic guided waves based identification of elastic properties using 1d-convolutional neural networks. In: International Conference on Prognostics and Health Management (ICPHM), pp 1–7. IEEE

Robinson HB (2009) E-waste: an assessment of global production and environmental impacts. Sci Total Environ 408:183–191

Scheutz C, Mosbaek H, Kjeldsen P (2004) Attenuation of methane and volatile organic compounds in landfill soil covers. J Environ Qual 33:61–71

Schinner F, Burgstaller W (1989) Extraction of zinc from industrial waste by a *Penicillium* sp. Appl Environ Microbiol 55(5):1153–1156

Schurter (2019) China RoHS. https://www.schurter.com/safe-easy/Environment/ChinaROHS

Shi J, Xiang L, Luan H, Wei Y, Ren H, Chen P (2019) The health concern of polychlorinated biphenyls (PCBs) in a notorious e-waste recycling site. Ecotoxicol Environ Saf 186:109817. https://doi.org/10.1016/j.ecoenv.2019.109817

Solisio C, Lodi A (2002) Bioleaching of zinc and aluminium from industrial waste sludges by means of *Thiobacillus ferrooxidans*. Waste Manag 22(6):667–675

Song Q, Li J (2015) A review on human health consequences of metals exposure to e-waste in China. Environ Pollut 196:450–461. https://doi.org/10.1016/j.envpol.2014.11.004

Song X, Liu M, Wu D, Qi L, Ye C, Jiao J, Hu F (2014) Heavy metal and nutrient changes during vermicomposting animal manure spiked with mushroom residues. Waste Manag 34:1977–1983

Tabak M, Clark DS, Hatchett SP, Key MH, Lasinski BF, Snavely RA, Wilks SC, Town RPJ (2005) Review of progress in fast ignition. Phys Plasmas 12:057305

Tanskanen P (2013) Management and recycling of electronic waste. Acta Mater 61:1001–1011

Tripathi BD (2011) A short-term study on toxic effects of distillery sludge amendment on microbiological and enzymatic properties of agricultural soil in a tropical city. J Earth Sci Clim Change 2:106

United Nations Environment Program (UNEP) (2007) E-waste vol I: inventory assessment manual. United Nations Environment Programme Division of Technology, Industry and Economics, International Environmental Technology Centre, Osaka/Shiga

Valdés J, Pedroso I, Quatrini R, Dodson RJ, Tettelin H, Blake R, Eisen JA, Holmes DS (2008) *Acidithiobacillus ferrooxidans* metabolism: from genome sequence to industrial applications. BMC Genom 9(1):597

Volesky B, May H, Holan ZR (1993) Cadmium biosorption by *Saccharomyces cerevisiae.* Biotechnol Bioeng 41:826–829

WAMDA (2018) The Middle East and its e-waste problems. https://www.wamda.com/2018/10/middle-east-e-waste-problem

Xavier LH, Giese EC, Ribeiro-Duthie AC, Lins FAF (2021) Sustainability and the circular economy: a theoretical approach focused on e-waste urban mining. Resour Policy 74:101467

Xiang Y, Wu P, Zhu N, Zhang T, Liu W, Wu J, Li P (2010) Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. J Hazard Mater 184(1):812–818

Xue M, Yang Y, Ruan J, Xu Z (2012) Assessment of noise and heavy metals (Cr, Cu, Cd, Pb) in the ambience of the production line for recycling waste printed circuit boards. Environ Sci Technol 46(1):494–499. https://doi.org/10.1021/es202513b

Yarzábal A, Brasseur G, Ratouchniak J, Lund K, Lemesle-Meunier D, DeMoss JA, Bonnefoy V (2002) The high-molecular-weight cytochrome c Cyc2 of *Acidithiobacillus ferrooxidans* is an outer membrane protein. J Bacteriol 184(1):313–317

Zhang Q, Zhou T, Xu X, Guo Y, Zhao Z, Zhu M, Huo X (2011) Downregulation of placental S100P is associated with cadmium exposure in Guiyu, an e-waste recycling town in China. Sci Total Environ 410–411:53–58. https://doi.org/10.1016/j.scitotenv.2011.09.032

Zheng G, Xu X, Li B, Wu K, Yekeen TA, Huo X (2013) Association between lung function in school children and exposure to three transition metals from an e-waste recycling area. J Expo Sci Environ Epidemiol 23(1):67–72. https://doi.org/10.1038/jes.2012.84

# Chapter 8
# Role of Bacteria for the Recovery of Precious Metals from E-waste

**Dipika Jaspal, Smita Jadhav, and Prashant Mahajan**

**Abstract** Electronic waste (e-waste) is the fast-growing waste produced all over the world, which is estimated to be 20–50 million tons. Printed circuit boards (PCBs) and other electronic equipments are the major contributors to e-waste encompassing a higher concentration of precious metallic elements like copper (Cu), silver (Ag), and gold (Au) as well as it contains hazardous and toxic materials. To avoid the dangerous effect of these substances on living beings and the environment, various methods have been applied, particularly the use of bacteria to recover metals from e-waste, as a sustainable approach toward the environment. The current chapter focuses on precious metals leaching from PCBs (e-waste) by various bacteria reflecting a feasible and alternative technique to the existing conventional methods for e-waste recycling. In the recovery of precious metals, various researchers have mentioned the vital role played by pH. A massive portion of the valuable metals is estimated to exist in e-waste. Generally, one metric ton of e-waste consists of 160–210 kg of Cu and 80–1500 g Au which is much higher related to that existing in its ore. Bacterial remediation is environmentally feasible, energy-efficient, cost-effective, and reduces secondary pollution. Bacterial leaching exhibites a potential industrial applicability in reclaiming e-waste.

**Keywords** E-waste · Bacteria · Precious metals · Recovery

D. Jaspal (✉)
Department of Applied Science, Symbiosis Institute of Technology (SIT), Symbiosis International (Deemed University) (SIU), Gram: Lavale, Tal: Mulshi, Pune, Maharashtra 412115, India
e-mail: dipikaj@sitpune.edu.in

S. Jadhav
Bharati Vidyapeeth's College of Engineering for Women, Pune, Maharashtra 411043, India

P. Mahajan
Symbiosis Institute of Technology (SIT), Symbiosis International (Deemed University) (SIU), Gram: Lavale, Tal: Mulshi, Pune, Maharashtra 412115, India

Department of Engineering Sciences, AISSMS Institute of Information Technology, Savitribai Phule Pune University, Pune, Maharashtra 411001, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_8

## 8.1 Introduction

E-waste (electronic waste) generation is a universal concern that entails emergency management. This is not a common waste but is a vital scrap that comprises of substantial quantities of metal resources. The e-waste streams move at a faster pace than the streams of municipal waste, causing concern worldwide necessitating immediate management (Akbari and Ahmadi 2019). According to the United Nations, India generates 2 million tons of e-waste and is the world's fifth largest producer of e-waste, generating about 44 million tons of e-waste, containing approximately 70% heavy metals and 40% toxic lead (Pandit 2016). By 2017, 64 million tons of e-waste was produced as stated by the solving the e-waste problem initiative (StEP) (Alam et al. 2018). There are numerous terminologies for e-waste; however, simply e-waste refers to any damaged or discarded electrical and electronic waste (Dave et al. 2018). E-waste encompasses all electronic devices such as televisions, computers, laptops, cell phones, chargers, adaptors, and so on. It is envisaged that e-waste produced from outdated processors would raise by 500%, and from the scrap, cellular phones would be approximately 18 times higher in the year 2020 related to the year 2007 (Abdelbasir et al. 2018). PCBs are an essential component of the generated e-waste, containing a lot of precious elements. It contains Cu 10–20%, iron (Fe) 1–4%, nickel (Ni) 1–3%, lead (Pb) 1–5%, and precious metals such as Ag, Au, and platinum (Pt) 0.3–0.4%, making them a potential secondary metal resource (Priya and Hait 2018). Another e-waste, cellular phone, contains over 40 elements, including base metals such as tin (Sn) and Cu in addition to precious metals such as Au, Ag, and palladium (Pd). In a computer PCB, Cu accounts for approximately 50%, which is substantially more than contained in the ore (Ashiq et al. 2020). PCBs are toxic and hazardous due to the presence of flame retardants and heavy metals (Priya and Hait 2018). E-waste comprises of metal elements such as Ag, Au, Cu, Ni, Fe, Pb, Sn, and cadmium (Cd) (He et al. 2015). Metallic elements, like Ag, Cu, and Au, are extremely valuable and could be recovered for new applications. Noxious elements like mercury (Hg), chromium (Cr), Pb, and arsenic (As) are present as major components in majority of the e-wastes. Computer monitors and televisions cathode ray tubes (CRTs) contain barium (Ba), zinc (Zn), Cu, and Pb, along with rare earth metals. As a result, most countries have made landfill disposal of cathode ray tubes illegal. As a result of the existence of lethal components such as polybrominated diphenyl ethers, Pb, Cd, Hg, and beryllium (Be), the disposal of e-waste has raised environmental and health concerns (Khanna et al. 2014).

Common methods of e-waste disposal include landfilling, burning, and incineration. Toxic gases such as dioxins and furans are released during heavy metal recovery using pyrometallurgical and hydrometallurgical methods, affecting the environment and public health. Pyrometallurgy is an energy-intensive process that requires smelting at temperatures ranging from 300 to 900 °C, and when implemented to waste electrical and electronic equipment (WEEE) may result in the release of poisonous fumes of dioxin and furan, owing to the occurrence of brominated flame retardants (Baniasadi et al. 2019; Amato et al. 2020). Correspondingly, by employing lethal organic solutions such as $H_2SO_4$, $HNO_3$, HCl, and $H_2O_2$, hydrometallurgy systems endanger natural aquatic resources and necessitate sophisticated wastewater treatment techniques (Xiang et al. 2010).

There are several methods which are used for the recovery of precious metals from e-waste. Cost-effective treatment methods to recover precious metals and remove hazardous materials from e-wastes such as electrical and electronic equipment are required for a circular economy approach (Xia et al. 2018; Chandane et al. 2020). Bioleaching is a novel and environmentally friendly method of recovering metals from e-waste. Microorganisms use this process to get soluble metal compounds from insoluble metal compounds (Chang et al. 2019). Bioleaching is a practically pioneering and viable approach that can be sound a substitute for traditional e-waste reutilizing techniques. It makes use of microbes' natural ability to change metals (which exist in solid form in e-waste) to a dissolved state (Narayanasamy et al. 2018). The method substantially cuts the cost and energy, required for the recovery of precious metals (Pakostova et al. 2018). Iron and sulfur-oxidizing chemo lithotrophic acidophiles like *Acidithiobacillus*, *Leptospirullum*, and *Ferrobacillus*, as well as heterotrophs like *Chromobacterium*, *Pseudomonas*, *Sulfolobus Anum*, and *Bacillus*, are commonly used in bioleaching (Priya and Hait 2017). Several chemo lithotrophic bacteria such as cyanogenic bacteria (*Chromobacterium violaceum*), *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*), fungi (e.g., *Aspergillus niger* besides *Penicillium simplicissimum*) (Ilyas et al. 2010; Brandl et al. 2001; Pradhan and Kumar 2012; Fonti et al. 2016) has been used for the recovery of metals from e-waste. Bacteria use methods like redoxolysis, acidolysis, and complexolysis to liquefy metals from the e-scrap during the bioleaching process. Cyanogenic bacteria (e.g., *Bacillus megaterium*, *C. violaceum*, *Pseudomonas fluorescens*, and *Pseudomonas aeruginosa*) yield HCN as a subordinate metabolite forming dissolvable metal-cyanide complexes from metal-comprising objects/scraps like low-quality ore and e-waste (Natarajan and Ting 2015).

## 8.2 Metals in E-waste

In computer PCBs and mobile phone-PCBs, Cu is generally a major component along with other metals. In accordance with chemical composition, e-waste contains several precious metals, metalloids, and radioactive elements. It includes As, Be, Ba, Cu, Cr, Cd, Fe, Pb, Ni, Hg, Sn, Zn, aluminum (Al), antimony (Sb), lithium (Li), europium (Eu), manganese (Mn), silica (Si), selenium (Se), yttrium (Y), etc. Precious metals comprise Ag, Au, Pd, In, Pt, etc. Americium (Am), a radioactive element, also found in the e-scrap (Widmer et al. 2005; Gaidajis et al. 2010). Waste PCBs (WPCBs) contain mostly polymers and porcelains, with 28–30% of their content comprising of metallic elements like Cu 10–20%; Pb 1–5%; Ni 1–3% and valuable metallic elements such as Ag, Au, and Pt 0.3–0.4% (Sarvar et al. 2015). It is approximated that more than 320 tons of Au and more than 7500 tons of Ag are used to manufacture mobile phones, computers, tablets, and other electronic equipment per annum worldwide. The urban prospecting of e-waste containing Ag and Au may generate income of about 21 billion dollars annually, however, presently only 15% of these precious metals are recovered (Mor et al. 2021).

## 8.3 Recovery of Precious Metals from E-waste

Numerous commercial universal techniques such as hydrometallurgy or pyrometallurgy exist for recovering e-waste (Pradhan and Kumar 2012). For example, Dowa Eco-System issued innovative metallurgic techniques to recover up to 22 metallic elements. At Rönnskär, in a leaching plant, Boliden recovered 223 ktons Cu, 34 ktons Zn clinker, 27 ktons Pb, 483 tons Ag, and 11 tons Au in 2021 from the e-waste (Boliden Rönnskär 2021). Furthermore, e-waste from the electronic and electrical manufacturing trades and metal reclaim plants further increases these wastes with the use or generation of bottom ash/fly ash, rechargeable batteries, emission control catalysts, and heavy metal-comprising sludge. In spite of technology eagerness, hydrometallurgy and pyrometallurgy are extensively applied in industry and become challenging for environmental sustainability. The pyrometallurgy process is carried out at a high temperature, and when applied to waste electrical and electronic equipment, it might release toxic gases, like dioxin and furan owing to the existence of brominated flame retardants (Baniasadi et al. 2021). In the hydrometallurgical processes, the usage of chemicals for metal dissolution, mostly sulfuric, hydrochloric, nitric acid, or/and hydrogen peroxide, poses a threat of pollution and acidification, for which advanced wastewater treatment methods are essential. For Au recovery, cyanide is used as a bleaching agent with the resultant production of polluted wastewater.

Sannigrahi and Suthindhiran in their study addressed the degradation of waste PCBs (WPCBs) (resistors and diode) with the bacterial strain of *Magnetospirillum* sp. RJS5 (KM289194), *Magnetospirillum* sp. RJS7, *Magnetospirillum* sp. RJS2 (KJ570852), (KT693285) *Magnetospirillum* sp. RJS6 (KT266803), and *Magnetospirillum gryphiswaldense* (MSR-1). The e-WPCBs were crushed to decrease dimensions, and the samples were analyzed using a particle size analyzer and X-ray powder diffraction (XRD). Heavy metals like Cd, Cu, Ni, Pb, and Zn were determined in diodes from e-waste, whereas As, Cr, Cu, Pb, Ag, Zn, and silicon (Si) were observed from resistors. The samples were exposed to the different bacterial strains separately and with consortia for 12 days (Sannigrahi and Suthindhiran 2019). The isolation of RJS6, RJS2, MSR-1 and with the recovery of Pb 100%, Cd 97%, and Ni 99% from the diode was observed respectively as revealed by atomic absorption spectroscopic (AAS) analysis. Likewise from the resistor, substantial recovery was apparent with RJS2 (Cu-89%) and RJS6 (Zn-88%). The comprehensive recovery of Cd (80%) and Pb (66%) was greater from the treated diode. Also, 45% Cu and 40% Pb were retrieved from resistors. MAG2 correspondingly revealed improved retrieval of Ni (22%) from the resistor and Pb (57%) from the diode. XRF and scanning electron microscope energy-dispersive X-ray spectroscopy (SEM–EDS) analysis established that RJS2 and RJS6 were the key strains in the recovery of metal (Sannigrahi and Suthindhiran 2019).

Pyrite [5–50 g/L pyrite concentrate (PyC)] was explored as a source of sulfur and iron in a novel technique. A rise from 24 to 84% in Cu extraction was evident considering PyC concentration 50 g/L, with almost 62% decrease in the consumption of acid. The bioleaching rate of Cu enhanced with an increase in 10–50% v/v of the inoculum (Bas et al. 2013).

The impact of regular pH alteration on the bioleaching effectiveness of e-waste by *A. ferrooxidans* was studied by Arshadi and Yaghmaei (2020). Bacterial characteristics, Ni and Cu leaching efficiency, were studied along with chemical characteristics including Fourier transform infrared spectrometer (FTIR), field emission scanning electron microscopy (FESEM), and X-ray diffraction (XRD). Pulp density was shown to be 1.5% (w/v) with the highest leaching as 88 and 90% for Ni and Cu with adjustment in pH, which changed to 92 and 100% without adjusting pH. This was indicative of the fact that pH adjustments reduced the efficiency (Arshadi and Yaghmaei 2020).

Natural bacterial strains segregated from an abandoned Au mine and *C. violaceum* (MTCC-2656) were used for metal bioleaching from WPCBs. Noxiousness determination and dosage-response investigation of WPCBs exhibited EC50 values of 98.7, 90.8 g/L, and 128.9, for *B. megaterium* SAG1, *Lysinibacillus sphaericus* (*L. sphaericus*) SAG2, and *Bacillus* sp. SAG3, respectively, while, for *C. violaceum*, EC50 was 83.70 g/L. This indicated the feasible process and technical viability of metallic elements bacterial leaching from WPCBs using coalmine isolates. The inducing parameters such as pulp density, pH, precursor molecule (glycine), and temperature were optimized by a one-factor at a time process (OFAT). Appreciable retrieval of metal was observed at a pulp density of 10 g/L, an initial pH of 9.0, at 30 °C, and 5 g/L glycine concentration of, excluding for *L. sphaericus* which offered maximum activity with 8.0 as initial pH. In ideal conditions, the recovery of Au and Cu metals from WPCBs was 73.6 ± 3% and 87.5 ± 8% for *C. violaceum* and 66.6 ± 6% and 72.7 ± 5% for *B. megaterium*, respectively (Kumar et al. 2021).

WECBs comprise more amounts of Cu, Au, and Ag which can be recovered by bacterial leaching from natural ores. Still, the use of the bioleaching process for e-waste is in the initial phase. Annamalai and Gurumurthy investigated the bioleaching competence of *A. ferrooxidans* to extract Cu from PCBs at a laboratory scale by using agitation decanters. The impact of quantity and dimensions of PCBs, initial pH, and capacity of inoculant on Cu suspension rates was estimated. It was observed that the maximum suspension rate of 32.44% was accomplished in one week of bacterial leaching at pH 2 for 1 mm size of the e-waste. The smallest size induced maximum suspension rates, indicative of good bacterial hold due to greater surface area. Similarly, the Cu suspension rates enhanced with the inoculant capacity (Annamalai and Gurumurthy 2019).

Noxiousness tolerance of bacterial strain *Pseudomonas balearica* (*P. balearica*) was evaluated employing crumpled waste computer PCBs per liter (L) of cultivation media, with a particle size of particle size $\leq$ 150 μm. For the e-waste pulp concentration, the EC50 for SAE1 was 325.7 g/L. The suspension of Au and Ag from the e-waste was carried out by two-step bioleaching process. Important aspects such as pulp and glycine concentration, pH, and temperature were optimized to enhance precious metal suspension. The process led to Au (68.5%) and Ag (33.8%) suspension at 30 °C, respectively, at a pH of 9, and 10 g/L and 5 g/L concentration of glycine, respectively. Indigenous e-waste bacterial leaching of Au and Ag's and its investigation to govern e-waste noxiousness tolerance was carried out (Kumar et al. 2018).

E-waste includes several types of different polymers of which the main polymers are acrylonitrile butadiene styrene, polystyrene, and polypropylene. The results of the eradication of low-concentration constituents (for instance plastics and polymers) were analyzed using the shaking table technique. Leaching of Ni and Cu counter to the preliminary trial (Model-1) and pre-treated trial deprived of low-concentration constituents (Model-2) was correlated. The development characteristics and the quantity of bioleaching metals (including pH, Eh, and bacterial count) were observed within 25 days. The investigation of Model-1 exhibited maximum bio-retrieval of Cu 94% and Ni 79% on the 14th day. Whereas, with Model-2, the bio-reclamation of Ni and Cu reduced to 74 and 87%, respectively, on the sixth day. Instrumental investigation including XRD, XRF, FTIR, and FESEM pre- and post-bacterial leaching of both e-waste models established that the process of leaching by bacteria was relatively competent (Arshadi et al. 2019).

A novel approach established on leaching by bacteria, in stages, using a column reactor was explored to recuperate Cu from e-scrap. This method effectively obtained bio-recovery of Cu (80%) in not more than 6 h. A microrespirometer system was offered to assess the harmful effects of the chief metallic elements existing in the leachate on the action of *A. ferrooxidans*. Outcomes demonstrated that noxiousness was dependent upon the alterations among metals, reaction time, and concentration. The concentration of Cu obtained attained throughout PCB bioleaching illustrates that bacterial absorption was not influenced even after 48 h of contact. Though, wherever leachate is collected, noxious concentrations (higher than 0.05 M) can be attained. Ni noxiousness assessments have revealed that, for concentrations more than 1 M, inhibition activity augmented with the interaction period, which is more than 90% after 24 h. Rather, in the case of lesser concentrations (less than 0.1 M), no noteworthy effect was observed on the activity. Metal exposure time was found to be a key factor in bioleaching processes. The consequences of the noxiousness as well emphasize the suitability of completing the biological stage and the biochemical oxidation in dual diverse phases throughout the bioleaching. Iron (II) concentration of more than 0.5 M entirely restricted the activity of *A. ferrooxidans* even after 4 h of interaction. While at lesser concentrations, the inhibitory effect was less, and next to 8 h, the biological action improved because of the usage of iron as a source of energy for bacterial evolution. Approaches established in the current investigation on metallic bacterial leaching, along with the method useful for the tracking movement

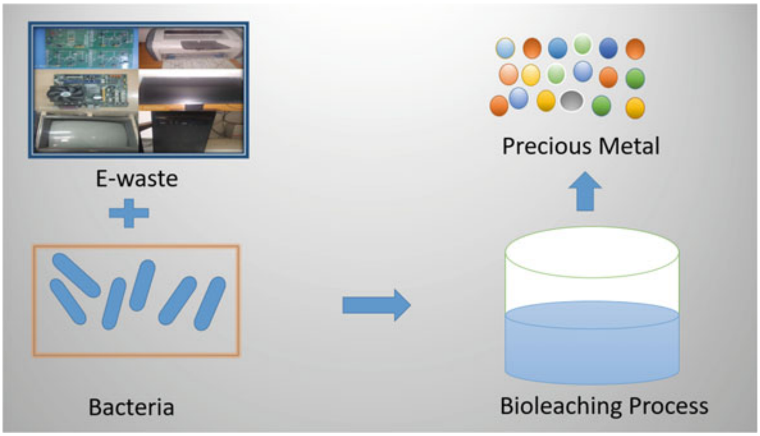



**Fig. 8.1** Bacterial precious metal recovery

of the biological development by microrespirometers, provided imperative data for detecting the boundaries of the modern application. Results further demonstrate the possibility and scope of bioleaching for scaling up at the industrial level (Benzal et al. 2020b). Figure 8.1 depicts the process of bio-recovery of precious metals by bioleaching process.

*C. violaceum*, a nitrile-producing bacteria, was utilized to separate Au from the WPCBs in a culture media through peptone, glycine, and yeast. Au removal efficacy was dependent on several aspects, for instance, base metals, particle dimensions, dissolved oxygen, and sustenance, mainly numerous metallic ions, which may catalyze the metabolism. The dissolved oxygen concentration in every single solution was reduced to a negligible after 24 h lacking of oxygen supplement, which was spent by bacterial respiration and the reaction of Au and nitrile. pH had a slight intensification in place of the generation of $OH^-$. For the source of the oxygen, a household oxygenator was employed to provide the sterilized oxygen for bacteriological respiration, and Au removal efficacy augmented considerably which was higher than in the prior studies (Li et al. 2015).

Pourhossein and his team explored bioleaching process for retrieving Indium (In) and Strontium (Sr) from smartphone touch screens of the type organic light emitting diode. The statistical method of response surface methodology was effectively employed. The impacts of significant variables such as elemental sulfur, solid content, ferrous sulfate, and pH and their contacts on In and Sr retrieval by means of modified *A. ferrooxidans* were assessed. Under optimum conditions, In extraction was noticed, with 200 mg/L concentration in solution. In the case of Sr, a 5% extraction ability was noticed, which, bring about a high Sr concentration in solution, about 3000 mg/L, owing to its high content in the solid (2%) (Pourhossein et al. 2021).

Discarded e-waste from computers altered the pure culture of *A. thiooxidans*, *A. ferrooxidans*. PCBs-adapted mixed cultures of *A. thiooxidans* and *A. ferrooxidans* were utilized for retrieval of the Cu, Zn, Ni, and Al. The impact of pulp density, inoculum bacteria, and initial pH was explored to regulate the optimal conditions in bioleaching experimentations. Optimal investigational environments in mixed culture tests were interpreted as 10% pulp density, 10% inoculum bacteria, initial pH 1.8, leaching time 10 days, initial temperature 30 ± 2 °C, particle size 125 μm, and stirring speed was 180 rpm. Metal recovery ability for Cu, Zn, Ni, and Al under optimal conditions was found to be 94, 89, 88, and 59%, respectively (Arslan 2021).

The retrieval of metallic elements from e-waste was explored with *Aspergillus fumigatus* (*A. fumigatus*) A2DS, a fungal strain, separated from the metal and mining sector wastewater. Cu (57%) and Ni (32%) by the bacterium after the first step leaching at a temperature of 30 °C (agitated for seven days) were leached and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES). The maximum amount of Cu and Ni were retrieved at a pH of 6. The XRD image of e-waste demonstrated 77% of Cu comprising compounds. The XRD investigation of the leachate residue displayed only 23% Euchorite ($AsCu_2H_7O_8$) and approximately 9% other Cu comprising compounds, representing the leaching aspect of the fungus. HPLC investigation of the exhausted medium exhibited the existence of diverse acids like fumaric, succinic, and citric acid. The FTIR spectra revealed the reduction in carboxylic stretching in the leachate formed and subsequently bioleaching, employing an exhausted medium. Inductively coupled plasma atomic emission spectroscopy (ICP-OES) of the leachate acquired via exhausted medium demonstrated that Cu (61%) and Ni (35%) were extracted after one week of cultivation and agitation. *A. fumigatus* A2DS metal absorption and adsorption capacity were determined with instrumental techniques transmission electron microscopy (TEM) and scanning electron microscopy energy dispersive X-ray (SEM–EDX) (Patel and Lakshmi 2021).

Cu bio-recovery from waste cellular phones was analyzed with a two-step bioleaching method. In the process iron (II) ions were oxidized to iron (III) biologically through *A. ferrooxidans* in the first step. Bio-oxidation of iron (II) was nearly accomplished in the first step in 48 sedimentations followed by filtration. No substantial alterations among both isolation approaches were detected in view of the comprehensive method's effectiveness. In both steps, Cu recovery of 95–100% of Cu was obtained in only 48 h with 7.5 g/L of e-waste concentration. To assess low-cost and environmentally approachable systems using leachate solution, to recover the Cu, adherence of Cu (II) with iron was carried out. The Cu residue obtained had a percentage purity of 64.8% (Benzal et al. 2020b).

An attempt to remove heavy metals from the e-waste through metal-resistant actinobacterium *Streptomyces albidofavus* (*S. albidofavus*) TN10 separated from the termite nest was also made. These bacteria were initiated to retrieve several heavy metals (Pb 46%, Fe 42%, Ca 74%, Al 66%, Ni 81%, Cu 68%, Cd 65%, Ag 56%, Zn 82%) in three days under laboratory environment. Inductively coupled plasma mass spectrometry (ICP-MS) was employed to determine the metal content of e-waste after bioleaching. The untreated e-waste and bioleaching residue were exhibited by

XRD, FTIR, and SEM techniques for the functional group and structural changes recognition which confirmed the bioleaching process (Kaliyaraj et al. 2019).

Therefore, biologic lixiviation of metals such as Cu, Ag, and Au was carried out from e-waste of cell phones using species of *Candida orthopsilosis*, *A. niger*, and *Sphingomonas* sp. and their individual consortia. The bacteria were cultivated in an organic medium with an action of 1 M citric acid with an equal quantity of e-waste. All activities were inoculated for 35 days at ambient temperature. The outcomes exhibited that the consortium of *A. niger* MXPE6, *C. orthopsilosis* MXL20, and *Sphingomonas* sp. MXB8 could enhance their dehydrated biomass by 126% and 147%, respectively, in the occurrence of e-waste. The extraction of Ag was carried out by *A. niger* MXPE6, the consortium of *Sphingomonas* sp. MXB8/*C. orthopsilosis* MXL20, and *Sphingomonas* sp. MXB8, while the extraction of Au through a consortium of *A. niger* MX5 and *A. niger* MXPE6 and Cu leached by *A. niger* MX5. Citric acid augmented Cu extraction by 280% compared to treatments inoculated with bacteria (Díaz-Martínez et al. 2019).

Research presented that *Acidiphilium acidophilum* was suitable for extraction of Cu from e-waste which was beneficial in the synthesis of organic–inorganic hybrid (OIH). Egg white was utilized as a polyphenol oxidase (PPO) enzyme source for OIH synthesis. The existence of P, N, and Cu in OIH was confirmed by several investigative systems. The OIH exhibited PPO enzyme activity. The OIH exhibited additional PPO enzyme action associated with egg white. The OIH correspondingly presented the capability for the degradation of phenol. It degraded about 95% phenol in 1 h. Thus, this investigation exhibited augmented Cu recovery from e-waste (Chandane et al. 2020).

Bacterial leaching of valuable metals from e-WPCBs by *A. niger* DDNS1 was investigated. The variation stages initiated at 0.1, 0.5, and 1.0% of fine dust of PCBs with 10% inoculant which was optimized with different aspects like pH, particle dimensions, and pulp concentration, to accomplish maximum retrieval of the precious metals. The contacts of these metallic elements were also interpreted with SEM, EDS, XRD, FTIR, and AAS. The outcomes specified that removal of the valuable metals was attained mostly by the sole organic solvents instigating from *A. niger* DDNS1. The initial pH takes an imperative part in the metals' precipitate formation and mining of precious metals. The two-step bacterial leaching method was tracked for the highest aggregation of metals (Narayanasamy et al. 2018).

*A. ferrooxidans* strain Z1 was utilized in the bioleaching of metal concentrates of WPCBs. The impacts of iron concentration, initial pH, amount of metal concentrates, particle size, and quantity of dose on the bioleaching method were explored to optimize conditions. The outcomes demonstrated that about 92% Cu leaching competence was accomplished in 78 h in a 2-step method; in addition, 85% Al and 95% Zn were extracted after 183 h under the optimal circumstances of initial Fe (II) 9 g/L, initial pH 2.25, amount of metal concentrates 12 g/L. It revealed that metallic elements could be effectively separated from metal concentrates by *A. ferrooxidans* Z1 and the bacterial leaching time span decreased to 81 to 78 h (Yang et al. 2017).

Native isolates *Frankia casuarinae* and *Frankia* sp. were exposed to bacterial leaching of Au and valuable elements allowing e-waste by single and dual-step leaching processes. The existence of organic acid reactive units which were acquired by the leaching of metals was governed by the FTIR spectra and by the acidic pH of the growth medium. The AAS investigations computed the introductory aggregation of metals and their noteworthy growth carried via extracting process. The primary concentration of valuable metallic elements such as Ag, Au, Zn, and Cu found in the e-waste was 0.05, 0.04, 0.1, and 0.35 mg/g, respectively. *Frankia* sp. isolated valuable metallic elements such as Ag, Au, Zn, and Cu (0.14, 0.2, 0.2, and 0.68 mg/g), respectively. *F. casuarinae* isolated precious metals such as Ag, Au, Zn, and Cu (0.15, 0.25, 0.2, and 0.55 mg/g), respectively. The valuable element Au was isolated by *F. casuarinae* than *Frankia* sp. The precious metallic element Cu was substantially raised by *Frankia* sp. than *F. casuarinae*. Greater Au retrieval 75% was attained by *F. casuarinae* and retrieval of Cu around 94% by *Frankia* sp. bacterial leaching of the bio-oxidized e-scrap at 0.2% less pulp concentrations. The outcomes were established via SEM–EDX and XRD investigation (Marappa et al. 2020).

Cu recovery from e-waste was revealed, which involved a consecutive approach of electroextraction and bioleaching particularly to extract Cu. This perspective was offered as per bit of the solution to determine the stimulating intensifying accretion of e-waste, in the environment. In the initial phase, bacterial leaching was verified for diverse pulp concentrations and effectively applied to isolate numerous metallic elements from e-waste by means of the acidophilic bacteria, *A. ferrooxidans*. Accordingly, in a subsequent phase, the system concentrated on the retrieval of Cu from bioleaching by electroextraction. Thin films of Cu were formed, and the outcomes revealed that 75.8% of Cu accessible in e-waste was reclaimed as a fine Cu foil, over with 99% purity, as ascertained by EDX analysis and ICP-OES. This system of Cu extraction, electroextraction, and combination bioleaching established a closed-loop technique of reprocessing that demonstrated the accomplishment of bacterial leaching in the circular economy. Cu foils had the prospective to be reprocessed, to generate valuable and novel Cu-clad laminate for making the multifaceted PCBs for the microchip technology (Baniasadi et al. 2021).

Shredded powder formed in the mechanical disassembling of WEEE and was an enriched source of several premium metallic elements that may be vanished as worthless waste. Investigation of crushed PCBs composition demonstrated the existence of Cu and Ag as well as other metals, viz., Fe, Ni, and Ag. Valuable metal like Au exists in a minimum concentration that is 0.04 mg/g mentioned this scrap as a low quality. Despite the less concentration of Au, e-scrap can be assumed as promising “secondary ore” to retrieve other noble metallic elements like Ag. The bacterial leaching of Ag with *P. balearica* SAE1 could be enhanced by pre-treatment of e-waste using low-cost leachate, i.e., ferric chloride ($FeCl_3$). The dose of $FeCl_3$ leachate was altered to retrieve Cu before the activity of bacterial leaching. Bacterial leaching of Ag was carried out by *P. balearica* SAE1 at pH 9, with 100 mL Luria Broth (LB) medium at 30 °C. The maximum percentage of Cu was retrieved with 1% $FeCl_3$ before bacterial leaching. Dissolution of Ag augmented for processed e-waste (36%) in comparison with unprocessed e-waste PCBs (25%). Cu recovery increased bacterial leaching of Ag, as obtainable cyanide was employed by Ag metal. Thus, this investigation provided a cost-effective fusion technique to augment Ag metal recovery by bacterial species from e-waste (Thakur and Kumar 2021).

Another investigation aimed to check the result of pre-treatment and pulverization of the damaged mobile PCBs (MPCBs) on the microbial leaching of Cu, Zn, and Ni. Pre-processed, crushed, untreated, and non-pulverized MPCBs were utilized throughout the extraction process. The well-conserved acidophilous iron oxidant Leptospiral-controlled consortia were initiated, and it was utilized for bacterial leaching. Greater Zn removal was noted with pulverized MPCBs while unpulverized MPCBs exhibited the removal of Cu and Ni. The base pre-processes demonstrated a beneficial impact on the removal of Cu and Zn while untreated MPCB exhibited higher removal of Ni. Furthermore, when the pH was adjusted at 2.0, the removal ability of Cu enhanced 1.45 times higher during the testing. The results of the method exhibited a twenty-seven, thirty-three, and one eighty-six-fold enhancement in Cu, Zn, and Ni extraction. As Cu is the chief element in any e-scrap, pre-treatment and unpulverized should be advocated method for bacterial leaching (Thacker et al. 2021).

Tay et al. showed the creation of a metabolically engineered strain of *C. violaceum* that developed more than 70% cyanide leachability and retrieve more than double Au from e-scarp related to wild-kind of bacteria. Results confirmed the effectiveness of leachability metabolic engineering in the building of improved leaching bacteria for the retrieving of precious metallic elements from e-waste (Tay et al. 2013).

The waste materials are reprocessed to diminish the unwanted material in landfill and lessen the groundwater, soil, and air pollution as a result of the release of hazardous elements. Reprocessing of waste materials is a substantial concern when it signifies a probable source of precious metals. Waste printed wired boards (PWBs) as a major portion of WEEE comprise many harmful substances, non-metals, and metals. The composite resources from PWBs are metallic elements, ceramic, and polymers. The recovery of Cu from PWBs by leaching methods was investigated using an assorted medium of acidophilous microbes from acid coal mine drainage and the bacteria *A. ferrooxidans*. The experiment of bioleaching was accomplished in shake flasks stirred at 170 rpm with 10% (v/v) inoculant and pulp density of 35 g/L. The concentration of metal was ascertained by energy dispersive X-ray fluorescence (XRF). The results of XRF exhibited that the highest recovery of Cu from PWBs through *A. ferrooxidans* was around 89%, while 92 recovery of Cu was obtained with a mixed culture of bacteria from AMD (Utimura et al. 2017).

A two-step bioleaching process, using *A. ferrooxidans*, was used in ideal conditions (temperature 30 °C, 10 g/L of $Fe^{2+}$ concentration) in two-step bacterial leaching process for nine days, which attained a higher yield as compared to chemical treatment i.e., 94% and 70% of Cu and Zn, respectively. The carbon footprint valuation evidenced the progress benefit, as an effective hydrometallurgical option. The core bioengineering gravity is the high energy demand, which could be resolved through the execution of a heap leaching setup, capable of substantially reducing the required energy. This probability, linked to the high process productivity and the influence of weather alteration, demonstrated the benefit of the bioengineering approach for the implementation of a WEEE, which develops a subordinate source of raw materials, conforming to the circular economy supports (Becci et al. 2020).

The credibility of bacterial leaching of certain metallic elements, viz., Zn, Cu, Ni, and Pb from e-waste of WPCBs from electronic equipment, was estimated by unpolluted media of *A. acidophilum*, a species of acidophilous proteobacteria. Outcomes after the investigation specified that *A. acidophilum* was competent to cultivate in the existence of e-scrap and competently dissolvable ample metallic elements like Cu along with Ni and Zn traces existing in PCB. The highest metal microbial leaching efficiency with 1 g/L pulp density was noticed within 60 days of the leaching period. Bioleaching competence of Cu accomplished within 45 days was about 78% which asymptotically augmented to 79% at 60 days. An analogous asymptotic bioleaching tendency was correspondingly noticed for Zn, Pb, and Ni. These results emphasize the applied viability of employing *A. acidophilum* for the effective progress of bacterial leaching for metallic retrieval from e-waste. Though, leaching time and yield can be unpremeditated by improving several organic and inorganic aspects governing the method (Priya and Hait 2018). Recovery metals and exact figures obtained by various researchers have been presented in Table 8.1.

## 8.4 Advantages and Disadvantages of Using Bacteria for Bioremediation of Electronic Waste

The results congregated from various studies that valuable metals can be recovered from e-waste. Concurrently, it plays a substantial part in environmental contamination by recovering the colossal messes of WPCBs. Thus, suitable handling and recovery of e-waste are essential for environment conservation, economic assistance, and resource recycling. Recovery of hazardous metals by using a hydrometallurgical process is reported highly hazardous owing to its low melting point. Also, precipitation methods for the recovery of metals lead to toxic effects due to the utilization of acids during the leaching process. Several investigators have reported maximum retrieval of metallic elements from e-waste successfully employed by simple, efficient, and cost-effective bioprocess technology using various bacteria.

## 8.5 Challenges and Future Prospects

E-waste bioremediation is a green technology from the environmental conservation perspective. Still, research is restricted in the e-waste bioremediation arena as compared to other methods mostly due to dealing with live streams being tough as related to chemical and mechanical actions. The predominant e-waste dealing

**Table 8.1** Bio-recovery of precious metals from e-waste by several bacteria

| Material | Bacteria used | % Recovery | References |
|---|---|---|---|
| PCBs (diode and resistors) | *Magnetospirillum* sp. RJS5 (KM289194), *Magnetospirillum* sp. RJS2 (KJ570852), *Magnetospirillum* sp. RJS6 (KT266803), *Magnetospirillum* sp. RJS7 (KT693285), and *M. gryphiswaldense* (MSR-1) | MSR-1 Pb (100%), RJS2 Cd (97%), and RJS6 Ni (99%) from diode<br>RJS2 (Cu-89%) and RJS6 (Zn-88%) from resistors | Sannigrahi and Suthindhiran (2019) |
| Scrap TV circuit boards | *Mesophilic bacteria* with the addition of pyrite concentrate | Cu 84% | Bas et al. (2013) |
| Waste PCBs | *A. ferrooxidans* | Cu 100% and Ni 92% | Arshadi and Yaghmaei (2020) |
| Waste PCBs | *C. violaceum* (MTCC-2656) and local bacterial species separated from an deserted Au mine | Cu 87.5 ± 8% and Au 73.6 ± 3% for *C. violaceum* and Cu 72.7 ± 5% and Au 66.6 ± 6% for *B. megaterium* | Kumar et al. (2021) |
| Computer circuit boards | *A. ferrooxidans* | Cu 32.44% | Annamalai and Gurumurthy (2019) |
| Computer circuit boards | Indigenous bacterial strain *P. balearica* SAE1 | 68.5 and 33.8% of Au and Ag | Kumar et al. (2018) |
| Copy machine PCBs (1.03%), computer PCBs (52.83%), mobile phone PCBs (25.47%), CPUs (5.28% %), and fax machines PCBs (13.21%) | *A. ferrooxidans* | Sample 1<br>94 and 79% of Cu and Ni<br>Sample 2<br>Ni and Cu reduced to 74 and 87% | Arshadi et al. (2019) |
| Electronic scrap | *A. ferrooxidans* | Cu 80% | Benzal et al. (2020a) |
| Waste-printed circuit boards | *C. violaceum* | Au 70.6% | Li et al. (2015) |
| Smartphone touch screens (organic light emitting diode) | *A. ferrooxidans* | In and Sr 100% | Pourhossein et al. (2021) |
| PCBs | *A. ferrooxidans*, *A. thiooxidans* | Cu, Ni, Zn, and Al were 94, 89, 88, and 59%, respectively | Arslan (2021) |
| PCBs | Fungal strain *A. fumigatus* A2DS | 61% of Cu and 35% of Ni | Patel and Lakshmi (2021) |
| PCBs | *A. ferrooxidans* | Cu 95–100% | Benzal et al. (2020b) |
| PCBs | Metal-resistant actinobacterium *Streptomyces albidofavus* TN10 | Al 66%, Ca 74%, Cu 68%, Cd 65%, Fe 42%, Ni 81%, Zn 82%, Ag 56%, Pb 46% | Kaliyaraj et al. (2019) |
| PCBs | *A. niger* MXPE6, the consortium of *Sphingomonas* sp. MXB8/*C. orthopsilosis* MXL20 and *Sphingomonas* sp. MXB8<br>*A. niger* MX5 and *A. niger* MXPE6<br>*A. niger* MX5 | 54, 44.2, and 35.8% of Ag<br>0.53% of Au<br>2.8% Cu | Díaz-Martínez et al. (2019) |

(continued)

**Table 8.1** (continued)

| Material | Bacteria used | % Recovery | References |
|---|---|---|---|
| PCBs | *A. acidophilum* (NCIM 5344) (*A. acidophilum*) and hydrogen peroxide ($H_2O_2$) | Cu | Chandane et al. (2020) |
| PCBs | *A. niger* DDNS1 | Precious metals | Narayanasamy et al. (2018) |
| PCBs | *A. ferrooxidans* strain Z1 | 92.57% Cu, 85.24% Al, and 95.18% Zn | Yang et al. (2017) |
| PCBs | *Frankia* sp. DDNSF-01 and *F. casuarinae* DDNSF-02 | Au 75% was obtained for *F. casuarinae* and Cu 94% recovery by *Frankia* sp. | Marappa et al. (2020) |
| PCBs | *A. ferrooxidans* | Cu 75.8% | Baniasadi et al. (2021) |
| PCBs | *P. balearica* SAE1 | Cu 95% | Thakur and Kumar (2021) |
| PCBs | *C. violaceum*, *Pseudomonas aeruginosa*, and *Pseudomonas fluorescens* | Au 30%<br>Cu 95% | Natarajan and Ting (2015) |
| Mobile printed circuit boards | *Leptospirillum*-dominated consortium | Cu, Zn, and Ni | Thacker et al. (2021) |
| Electronic waste | *C. violaceum* | Au 30% | Tay et al. (2013) |
| PCBs | *Acidithiobacillus ferrivorans* and *A. thiooxidans* | Au 44%<br>Cu 98% | Işıldar et al. (2016) |
| PCBs | *C. violaceum*, *Pseudomonas fluorescens*, and *Acidithiobacillus ferrivorans* | Au 55%<br>Cu 85% | Pham and Ting (2009) |

approaches are still detrimental and noxious to humans in addition to the biotic and abiotic environments. Several methods for metal leaching from e-waste are established and have been employed. These methods can approach a minor quantity of e-waste, and the bacteria utilized in the method failed to persist feasible for an extended period as a result of the noxiousness of e-waste. Thus, there is a vital need to concentrate on the development of process optimization, better strain, and scale-up of the existing method for e-waste treatment and management. Accordingly, the field stipulation directs toward various interdisciplinary subjects such as metallurgy, microbiology, biotechnology, and engineering.

## References

Abdelbasir SM, El-Sheltawy CT, Abdo DM (2018) Green processes for electronic waste recycling: a review. J Sustain Metall 4:295–311. https://doi.org/10.1007/s40831-018-0175-3

Akbari S, Ahmadi A (2019) Recovery of copper from a mixture of printed circuit boards (PCBs) and sulphidic tailings using bioleaching and solvent extraction processes. Chem Eng Process Process Intensif 142:107584. https://doi.org/10.1016/j.cep.2019.107584

Alam ZF, Riego AJV, Samson JHRP et al (2018) The assessment of the genotoxicity of e-waste leachates from e-waste dumpsites in metro manila, Philippines. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-018-1719-6

Amato A, Becci A, Beolchini F (2020) Sustainable recovery of Cu, Fe and Zn from end-of-life printed circuit boards. Resour Conserv Recycl 158:104792

Annamalai M, Gurumurthy K (2019) Enhanced bioleaching of copper from circuit boards of computer waste by *Acidithiobacillus ferrooxidans*. Environ Chem Lett 17:1873–1879. https://doi.org/10.1007/s10311-019-00911-y

Arshadi M, Yaghmaei S (2020) Advances in bioleaching of copper and nickel from electronic waste using *Acidithiobacillus ferrooxidans*: evaluating daily pH adjustment. Chem Pap 74:2211–2227. https://doi.org/10.1007/s11696-020-01055-y

Arshadi M, Yaghmaei S, Mousavi SM (2019) Study of plastics elimination in bioleaching of electronic waste using *Acidithiobacillus ferrooxidans*. Int J Environ Sci Technol 16:7113–7126. https://doi.org/10.1007/s13762-018-2120-1

Arslan V (2021) Bacterial leaching of copper, zinc, nickel and aluminum from discarded printed circuit boards using acidophilic bacteria. J Mater Cycles Waste Manag 23:2005–2015. https://doi.org/10.1007/s10163-021-01274-9

Ashiq A, Cooray A, Srivatsa SC et al (2020) Electrochemical enhanced metal extraction from E-waste. In: Prasad MNV, Vithanage M, Borthakur A (eds) Handbook of electronic waste management. Butterworth-Heinemann, pp 119–139 (chapter 6). https://doi.org/10.1016/B978-0-12-817030-4.00004-8

Baniasadi M, Graves JE, Ray DA et al (2021) Closed-loop recycling of copper from waste printed circuit boards using bioleaching and electrowinning processes. Waste Biomass Valoriz 12:3125–3136. https://doi.org/10.1007/s12649-020-01128-9

Baniasadi M, Vakilchap F, Bahaloo-Horeh et al (2019) Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J Ind Eng Chem 76:75–90

Bas AD, Deveci H, Yazici EY (2013) Bioleaching of copper from low grade scrap TV circuit boards using mesophilic bacteria. Hydrometallurgy 138:65–70. https://doi.org/10.1016/j.hydromet.2013.06.015

Becci A, Amato A, Fonti V et al (2020) An innovative biotechnology for metal recovery from printed circuit boards. Resour Conserv Recycl 153:104549

Benzal E, Cano A, Solé M et al (2020a) Copper recovery from PCBs by *Acidithiobacillus ferrooxidans*: toxicity of bioleached metals on biological activity. Waste Biomass Valoriz 11:5483–5492. https://doi.org/10.1007/s12649-020-01036-y

Benzal E, Solé M, Lao C et al (2020b) Elemental copper recovery from e-wastes mediated with a two-step bioleaching process. Waste Biomass Valoriz 11:5457–5465. https://doi.org/10.1007/s12649-020-01040-2

Boliden Rönnskär—Boliden. https://www.boliden.com/operations/smelters/boliden-ronnskar. Accessed 18 Aug 2022

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59(2):319–326

Chandane P, Jori C, Chaudhari H et al (2020) Bioleaching of copper from large printed circuit boards for synthesis of organic–inorganic hybrid. Environ Sci Pollut Res 27:5797–5808. https://doi.org/10.1007/s11356-019-07244-x

Chang CY, Chen SY, Klipkhayai P et al (2019) Bioleaching of heavy metals from harbor sediment using sulfur-oxidizing microflora acclimated from native sediment and exogenous soil. Environ Sci Pollut Res 26:6818–28. https://doi.org/10.1007/s11356-019-04137-x

Dave S, Sodha AB, Tipre DR (2018) Microbial technology for metal recovery from e-waste printed circuit boards. J Bacteriol Mycol 6:241–247. https://doi.org/10.15406/jbmoa.2018.06.00212

Díaz-Martínez ME, Argumedo-Delira R, Sánchez-Viveros G et al (2019) Microbial bioleaching of Ag, Au and Cu from printed circuit boards of mobile phones. Curr Microbiol 76:536–544. https://doi.org/10.1007/s00284-019-01646-3

Fonti V, Dell'Anno A, Beolchini F (2016) Does bioleaching represent a biotechnological strategy for remediation of contaminated sediments? Sci Total Environ 563:302–319

Gaidajis G, Angelakoglou K, Aktsoglou D (2010) E-waste: environmental problems and current management. J Eng Sci Technol Rev 3:193–199

He JF, Duan CL, He YQ et al (2015) Recovery of valuable metal concentrate from waste printed circuit boards by a physical beneficiation technology. Int J Environ Sci Technol 2(8):2603–2612. https://doi.org/10.1007/s13762-014-0664-2

Ilyas S, Ruan C, Bhatti H et al (2010) Column bioleaching of metals from electronic scrap. Hydrometallurgy 101:135–140

Işıldar A, van de Vossenberg J, Rene ER et al (2016) Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). Waste Manag 57:149–157. https://doi.org/10.1016/j.wasman.2015.11.033

Kaliyaraj D, Rajendran M, Angamuthu V et al (2019) Bioleaching of heavy metals from printed circuit board (PCB) by *Streptomyces albidoflavus* TN10 isolated from insect nest. Biores Bioprocess 6:47. https://doi.org/10.1186/s40643-019-0283-3

Khanna R, Cayumil R, Mukherjee P et al (2014) A novel recycling approach for transforming waste printed circuit boards into a material resource. Procedia Environ Sci 21:42–54

Kumar A, Saini HS, Kumar S (2018) Bioleaching of gold and silver from waste printed circuit boards by *Pseudomonas balearica* SAE1 isolated from an e-waste recycling facility. Curr Microbiol 75:194–201. https://doi.org/10.1007/s00284-017-1365-0

Kumar A, Saini HS, Şengör S et al (2021) Bioleaching of metals from waste printed circuit boards using bacterial isolates native to abandoned gold mine. Biometals 34(5):1043–1058. https://doi.org/10.1007/s10534-021-00326-9

Li J, Liang C, Ma C (2015) Bioleaching of gold from waste printed circuit boards by *Chromobacterium violaceum*. J Mater Cycles Waste Manag 17:529–539. https://doi.org/10.1007/s10163-014-0276-4

Marappa N, Ramachandran L, Dharumadurai D et al (2020) Recovery of gold and other precious metal resources from environmental polluted e-waste printed circuit board by bioleaching *Frankia*. Int J Environ Res 14:165–176. https://doi.org/10.1007/s41742-020-00254-5

Mor RS, Sangwan KS, Singh S et al (2021) E-waste management for environmental sustainability: an exploratory study. Procedia CIRP 98:193–198. https://doi.org/10.1016/j.procir.2021.01.029

Narayanasamy M, Dhanasekaran D, Vinothini G et al (2018) Extraction and recovery of precious metals from electronic waste printed circuit boards by bioleaching acidophilic fungi. Int J Environ Sci Technol 15:119–132. https://doi.org/10.1007/s13762-017-1372-5

Natarajan G, Ting YP (2015) Gold biorecovery from e-waste: an improved strategy through spent medium leaching with pH modification. Chemosphere 136:232–238. https://doi.org/10.1016/j.chemosphere.2015.05.046

Pakostova E, Grail BM, Johnson DB (2018) Bio-processing of a saline, calcareous copper sulfide ore by sequential leaching. Hydrometallurgy 179:36–43

Pandit V (2016) India's e-waste growing at 30% annually. The Hindu Business Line. https://www.thehindubusinessline.com/info-tech/indias-ewaste-growing-at-30-annually/article8686442.ece. Accessed 29 Sept 2018

Patel F, Lakshmi B (2021) Bioleaching of copper and nickel from mobile phone printed circuit board using *Aspergillus fumigatus* A2DS. Braz J Microbiol 52:1475–1487. https://doi.org/10.1007/s42770-021-00526-y

Pham VA, Ting YP (2009) Gold bioleaching of electronic waste by cyanogenic bacteria and its enhancement with bio-oxidation. AMR 661:71–73. https://doi.org/10.4028/www.scientific.net/amr.71-73.661

Pourhossein F, Rezaei O, Mousavi SM et al (2021) Bioleaching of critical metals from waste OLED touch screens using adapted acidophilic bacteria. J Environ Health Sci Eng 19:893–906. https://doi.org/10.1007/s40201-021-00657-2

Pradhan JK, Kumar S (2012) Metals bioleaching from electronic waste by *Chromobacterium violaceum* and *Pseudomonads* sp. Waste Manag Res 30(11):1151–1159

Priya A, Hait S (2017) Comparative assessment of metallurgical recovery of metals from electronic waste with special emphasis on bioleaching. Environ Sci Pollut Res 24:6989–7008

Priya A, Hait S (2018) Feasibility of bioleaching of selected metals from electronic waste by *Acidiphilium acidophilum*. Waste Biomass Valoriz 9:871–877. https://doi.org/10.1007/s12649-017-9833-0

Sannigrahi S, Suthindhiran K (2019) Metal recovery from printed circuit boards by magnetotactic bacteria. Hydrometallurgy 187:113–124. https://doi.org/10.1016/j.hydromet.2019.05.007

Sarvar M, Salarirad MM, Shabani MA (2015) Characterization and mechanical separation of metals from computer printed circuit boards (PCBs) based on mineral processing methods. Waste Manag 45:246–257

Tay S, Natarajan G, Rahim M et al (2013) Enhancing gold recovery from electronic waste via lixiviant metabolic engineering in *Chromobacterium violaceum*. Sci Rep 3:2236. https://doi.org/10.1038/srep02236

Thacker SC, Nayak NS, Tipre DR et al (2021) Impact of pulverization, pretreatment and pH regulation on microbial extraction of metals from waste mobile phone printed circuit boards. Appl Biochem Microbiol 57:675–682. https://doi.org/10.1134/S0003683821050173

Thakur P, Kumar S (2021) Pretreatment of low-grade shredded dust e-waste to enhance silver recovery through biocyanidation by *Pseudomonas balearica* SAE1. 3 Biotech 11:454. https://doi.org/10.1007/s13205-021-02977-4

Utimura SK, Rosario CGA, Botelho AB et al (2017) Bioleaching process for metal recovery from waste materials. In: Energy technology. Springer, Cham, pp 283–290

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D et al (2005) Global perspectives on e-waste. Environ Impact Assess Rev 25:436–458. https://doi.org/10.1016/j.eiar.2005.04.001

Xia M, Bao P, Liu A et al (2018) Bioleaching of low-grade waste printed circuit boards by mixed fungal culture and its community structure analysis. Resour Conserv Recycl 136:267–275. https://doi.org/10.1016/j.resconrec.2018.05.001

Xiang Y, Wu P, Zhu N et al (2010) Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. J Hazard Mater 184:812–818

Yang C, Zhu N, Shen W et al (2017) Bioleaching of copper from metal concentrates of waste printed circuit boards by a newly isolated *Acidithiobacillus ferrooxidans* strain Z1. J Mater Cycles Waste Manag 19:247–255. https://doi.org/10.1007/s10163-015-0414-7

# Chapter 9
# Importance of Microorganisms in Metal Recovery from E-waste

**Parth Chaudhary, Manu Pant, Somya Sinha, and Kumud Pant**

**Abstract** E-waste is defined as electronic or electrical items that have been discarded or wasted. It contains many precious metals that could be extracted. Bioleaching is the process by which microbial activity causes an insoluble metal to become available or soluble, and this technique is used for extraction of precious metals from e-waste as the other techniques like pyrometallurgy and hydrometallurgy have certain drawbacks. Many bacteria, fungi, and algae, such as *Acidithiobacillus ferrooxidans*, *Chromobacterium violaceum*, *Frankia*, *Sphingomonas*, *Cladosporium* sp., and many more are used in bioleaching wherein appropriate bioleaching process begins with shredding, which is followed by sorting and analysis to identify the desirable components to be removed and is finished with the activity of bacteria that create lixiviants to extract pure metals. Different microbes are used in different ways for each metal to aid in extraction. Bioleaching has advantages for the economy and the environment, but there are also biosafety concerns, hence the compiled knowledge of the said is required.

**Keywords** Bioleaching · Precious metals · E-waste · Microorganisms · Printed circuit board

## 9.1 Introduction

When an electronic gadget is discarded, it is termed as electronic trash (e-waste). If improperly disposed of, e-waste can be a serious hazard to both human health as well as to the environment (Arslan 2021). The printed circuit boards (PCBs), known as "artificial ore," are one such discard containing a high number of precious polymers, namely bromine, glass, ceramics, and a significant quantity of metals (Priya and Hait 2018). Precious metals like Au, Ag, Cu, etc., are a major part of

P. Chaudhary · S. Sinha · K. Pant (✉)
Department of Biotechnology, Graphic Era Deemed to be University, Dehradun, India
e-mail: kumud.pant@geu.ac.in

M. Pant
Department of Life Sciences, Graphic Era Deemed to be University, Dehradun, India

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_9

metals present in PCBs. The extraction of these heavy precious metals through mining involves techniques such as hydrometallurgy and pyrometallurgy that have many disadvantages including pollution control measures and environmental degradation. Bioleaching, the use of microorganisms for extraction of heavy metals, is dependent on the activity of microorganisms that can replenish the leaching agent as well that are responsible for metal extraction (Pennesi et al. 2019). Moreover, it is an environment friendly and cost-effective method therefore of great importance in today's context. Bioleaching of precious metals has been discussed elsewhere in the chapter.

## 9.2 E-waste

E-waste is characterized as dumped or trashed electronic or electrical items.

### *9.2.1 Sources of E-waste*

The printed circuit board (PCB) in computers, mobile phones, and other electronic appliances incorporates a large group of e-waste materials. The LCD, OLED, and other display materials that use metals and components also account for e-waste.

### *9.2.2 Composition of E-waste*

The PCBs are approximately 3% of the equipment and have both metallic and non-metallic parts. The non-metallic parts generally comprise of polymers, plastics, bromine, glass, and ceramics while the metallic part has copper as the major element and aluminum, nickel, iron, tin, and lead with precious metals like gold and silver in trace amounts (Díaz-Martínez et al. 2019; Işıldar et al. 2016; Madrigal-Arias et al. 2015; Arshadi and Mousavi 2015). Even in trace amounts, these precious metals are needed to be extracted from the e-waste due to their lesser abundance in nature along with difficult extraction through mining.

The OLEDs used in smartphone touch screens have emissive and conductive layers present in between two electrodes. The anode is made up of indium-tin-oxide (ITO) (Pourhossein et al. 2021). Indium being a perilous and precious metal found in minuscule quantity (0.24 ppm) in earth and around 250 ppm used in smart displays (Díaz-Martínez et al. 2019; Pourhossein et al. 2021; Benzal et al. 2020). Another crucial metal found in display screens is Strontium which is used in form of carbonates and accounts for more than 2000 ppm (Işıldar et al. 2016; Pourhossein et al. 2021).

## 9.3 Recovery of Precious Metals from E-waste

The methods being used for the recovery of precious metals from e-waste in recent times are as follows:

- Pyrometallurgy
- Hydrometallurgy
- Biohydrometallurgy.

### *9.3.1 Pyrometallurgy and Hydrometallurgy*

*In pyrometallurgy*, the waste material is exposed to a high temperature above 1200°.

*In hydrometallurgy*, acids like $H_2SO_4$, $HNO_3$, and HCL and alkalis like $H_2O_2$ and NAOH are, respectively, used in acid and alkali leaching.

These techniques are recently being applied in the extraction of metals from electronic waste. However, they have certain drawbacks, including environmental degradation, large volumes of waste material, expensive costs, etc., and to overcome these problems, an eco-friendly technique is developed called biohydrometallurgy (Arslan 2021).

### *9.3.2 Biohydrometallurgy*

Biohydrometallurgy involves use of overlapping areas of biology and hydrometallurgy for the extraction of metals. The relations between biological activities of microbes with metals present in minerals and their dissolved forms are an important factor that accounts for the use of biohydrometallurgy (Işıldar et al. 2016). The biomining technique known as *bioleaching* is based on biohydrometallurgy.

## 9.4 Bioleaching

The conversion of an insoluble metal to an available or soluble form due to activity of microbes is bioleaching. Bioleaching of precious metals, namely as Au, Ag, Cu, Zn, Pb, and other heavy metals by microorganisms in a feasible, cost-effective, and environmentally friendly manner is discussed further in this chapter.

### 9.4.1 Microorganisms Involved in Bioleaching of Precious Metals

The bioleaching of metals from e-waste has been carried out using a range of bacterial and fungus cultures. Bacteria like *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Leptospirillum ferrooxidans*, as well as fungus like *Aspergillus niger* and *Penicillium simplicissimum*, are frequently utilized because of their ability to convert the insoluble form of metal present in e-waste into soluble metal forms, especially from oxides to sulfates (Arslan 2021).

The poor cyanogenic potential of lixiviant-producing bacteria like *Chromobacterium violaceum* has prevented extensive commercial usage of this bioleaching microbes, but the fabrication of metabolically-engineered *C. violaceum* strains has enhanced the potential of bioleaching of precious metals (Tay et al. 2013).

For bioleaching, leading to bioremediation of heavy metals from contaminated e-waste, another organism is a bacterium belonging to genus *Frankia*, a symbiote of actinorhizal plants. *Frankia* strains may thrive and survive high amounts of micrometal elements such as As, Co, Cu, Mo, Se, B, Ni, Zn, Cd, Hg, Cr, and Pb in e-waste contaminated and discarded wasteland (Arshadi and Mousavi 2015).

Recently, the use of algae for e-waste management has also been observed, therefore attempts being made to optimize the process.

### 9.4.2 Mechanism of Bioleaching

For the extraction of valuable metals, the e-waste containing metals must first be crushed and shredded into incredibly tiny particles. When dealing with PCBs, the capacitors and microprocessors are removed, and just the board is divided for destruction. Following the shredding, fine particles in the form of powder with a size range of 0.1–1 mm are sieved so as to prepare for further steps (Benzal et al. 2020). By using hydraulic sorting, the metallic component of the PCB powder could be separated from the non-metallic components, such as plastics that might be harmful to the bioleaching process, leaving metal concentrations (Yang et al. 2017; Natarajan and Ting 2014). The resulting solution was then evaluated using an inductively coupled plasma optical emission spectrometer (ICP-OES), which revealed the presence of strontium and indium in the smart phone touch screen (SPTS) powder with a particle size of less than 100 m (Pourhossein et al. 2021). Metals in e-waste can be converted from their insoluble form to soluble form either by direct or by indirect bioleaching (Table 9.1). There are certain methods used in commercial and industrial large-scale bioleaching processes for extraction of metals from ores that are listed below:

- Heap leaching
- Slope/dump leaching
- In situ leaching.

**Table 9.1** Direct and indirect bioleaching

| Direct bioleaching | Indirect bioleaching |
|---|---|
| Direct contact between bacteria and sulfide molecules | A lixiviant is produced by bacteria that oxidize sulfides |
| Enzymes help in disjunction of metal from its ore. It is the bacteria that further aids in metal extraction | Ore is oxidized and separated from metal by leaching agents that do it via oxidation process |
| Direct bioleaching can be understood by Eq. (1) $MeS + 2O_2 \xrightarrow{\text{Bacteria}} MeSO_4$ (Metal Sulfate) (1) | Indirect bioleaching explained by Eqs. (2) and (3) $MeS + Fe_2(SO_4) \rightarrow M_eSO_4 + 2FeSO_4 + S^0$ (2) $2S^0 + 3O_2 + H_2 \xrightarrow{\text{Bacteria}} 2H_2SO_4$ (3) |
| The bacteria tether to particular location on the mineral crystal and solubilize the metal through electrochemical interplay | It is the heightened pace of reoxidation of minerals that aids in leaching of metals by bacteria |
| Less preferred | More preferred |
| One step method | Two step method |

## 9.4.3 Precious Metals and Their Bioleaching

### 9.4.3.1 Gold (Au)

- *Acidithiobacillus ferrivorans*, *A. thiooxidans*, *Pseudomonas fluorescens*, and *Pseudomonas putida* leach 44% of gold from PCB in mobile phones and PCs (Madrigal-Arias et al. 2015).
- In a feeding medium with 50 g/L of glucose and pH 4.4, the *A. niger* strains MXPE6 and MX7, which have been discovered to be $AuCl_3$ tolerant, successfully leached and recovered 87% of the gold from the PCB of mobile phones (Arshadi and Mousavi 2015).
- *Bacillus megaterium* is another bacterium that can leach Au from PCB-treated computers, recovering up to 63% Au (Natarajan and Ting 2014).
- *C. violaceum*, a bacterium, has the potential of generating cyanide when cultivated in nutrient media supplemented with glycine and is capable of recovering Au from electronic waste up to 63% from mobile phone PCB (Huerta-Rosas et al. 2020).
- Wild-type *C. violaceum* produces cyanide from medium supplemented with glycine at short intervals. It is generally seen during the early growth phase of its life cycle. The reliance on cell density is quorum-regulated and was probably designed in tandem with the defense mechanism of niche colonization. By adjusting the organism's lixiviant metabolic process, cyanide generation may be detached from quorum control and its volume raised (Tay et al. 2013).
- The modified *C. violaceum* strains pBAD and pTAC improve the recovery of priceless Au from ESM (Tay et al. 2013).

- *Frankia casuarinae*, a soil actinomycete, was found to leach gold by 75% (Marappa et al. 2020).

#### 9.4.3.2 Silver (Ag)

- The consortium of *Sphingomonas* sp. MXB8/*Corthopsilosis* MXL20 and *Sphingomonas* sp. MXB8 exhibits the maximum silver leaching ability. The leaching of almost 98% of Ag and other metals from solder residues for 60 h is attributed to its citric acid production ability (Işıldar et al. 2016).
- *Pseudomonas balearica* SAE1 can leach Ag (33%) from PCB pulp when cultivated in medium containing glycine that stimulates cyanide generation (Díaz-Martínez et al. 2019).
- *Frankia* sp. was also found to leach silver to a great extent (Marappa et al. 2020).
- It was observed that leaching of silver with *Cladosporium* sp. A and B and *Penicillium chrysogenum* via the combined biotic-abiotic process was about 67%, 40%, and 53%, respectively, whereas in the control which is un inoculated, it was about 26% (Saidan et al. 2012).
- Fungus *Verticillium* sp. and bacteria *Lactobacillus fermentum* form silver nanoparticles that remain bound by the cell surface (Saidan et al. 2012).
- *P. chrysogenum* and *Cladosporium* sp. Strains are more effective in leaching silver and manganese because of their higher silver tolerance (Saidan et al. 2012).

#### 9.4.3.3 Copper (Cu)

- Copper is one of the abundant metals in the PCBs, and its extraction is affected by organic acid formation by microbes like bacteria, to quite an extent. Other organism like heterotrophic fungi is also successful in leaching of copper (Cu) in e-waster at an ideal pH of 2.0 and even less in comparison with sulfuric acid leaching, created by the bacterium *Acidithiobacillus* (Ilyas et al. 2013).
- In the case of Cu, citric acid boosts leaching by 280% when compared to *A. niger* MX5 bioleaching. Acids have been used for leaching metals from e-waste like printed circuit boards (PCBs) for quite some time. In case of PCB, for example, $H_2SO_4$ could extract 100% of Cu, and the efficacy of the leaching process was found to rely on the concentration of the material utilized (Díaz-Martínez et al. 2019).
- Bioleaching of metal content from e-waste in a column reactor utilizing a consortium of *Sulfobacillus thermosulfidooxidans* could recover 85% Cu in 16 days (Chen et al. 2015).
- Using a sizable column and a pure culture of *A. ferrooxidans*, Chen et al. were successful in extracting 95% of the copper from the e-scraps in 28 days (Wang et al. 2009).
- Performing column bioleaching along with stirring of waste and iron renovation, results showed 80% extraction of Cu in 6 h (Benzal et al. 2020).

- Mixed cultures of *A. ferrooxidans* and *A. thiooxidans* demonstrated higher copper solubilizing capacities than pure cultures of both individually, from PCBs (Becci et al. 2020).
- Under ideal conditions, the bioleaching process (two-step) could improve the efficiency of leaching copper.
- With *Frankia casuarinae* and also other species, 94% Cu could be leached successfully in bioleaching process (Marappa et al. 2020).

#### 9.4.3.4 Nickel (Ni)

- Ni demonstrated more than 60% dissolving effectiveness in a culture of *A. thiooxidans* at optimal pH. However, in a combined culture of *A. ferrooxidans* and *A. thiooxidans*, Ni dissolution was 77% (Arslan 2021).

#### 9.4.3.5 Indium (In) and Strontium (Sr)

In research done by Pourhossein et al. in 2020, the central composite design (CCD) in response surface methodology (RSM) was deployed for deducing combination of various parameters or variables for optimum metal recovery (Pourhossein et al. 2021). The CCD considered composition of medium as an important aspect for metal leaching from SPTS by *A. ferrooxidans*. The optimum biorecovery was established to be ferrous sulfate (Conc. 13 g/L), sulfur (Conc. 5.63 g/L), solid content (3 g/L), and opening pH (1.1). Through this parametric and experimental setup, indium was fully recovered, whereas only 5% strontium was leached.

The images of few microorganisms used in bioleaching are shown in Fig. 9.1.

### *9.4.4 Role of Algae in E-waste Management*

- *Ascophyllum nodosum*, a brown alga or cold water sea weed, has been tested for biosorption and hence recovery of Indium. This biosorption potential was observed both in single (In) and two-metal ion system (In-Fe); therefore, its commercialization value is required to be explored further (Pennesi et al. 2019).
- In process optimization done by Noura El-Ahmady El-Naggar and Nashwa H. Rabei, both Nickel ($Ni^{2+}$) ions and methylene blue were biosorbed and hence removed from waste industrial water using *Gracilaria* seaweed biomass. The percentage of recovery was 97.53 and 94.86 for Nickel ($II^{+}$) ions, respectively (El-Naggar and Rabei 2020).
- A green microalgae *Chlorella vulgaris* in both living and dried forms have been used in an optimized procedural setup for recovery of precious metals viz neodymium (Nd) and silver (Ag) from e-waste stream (Tunali and Yenigun 2021).

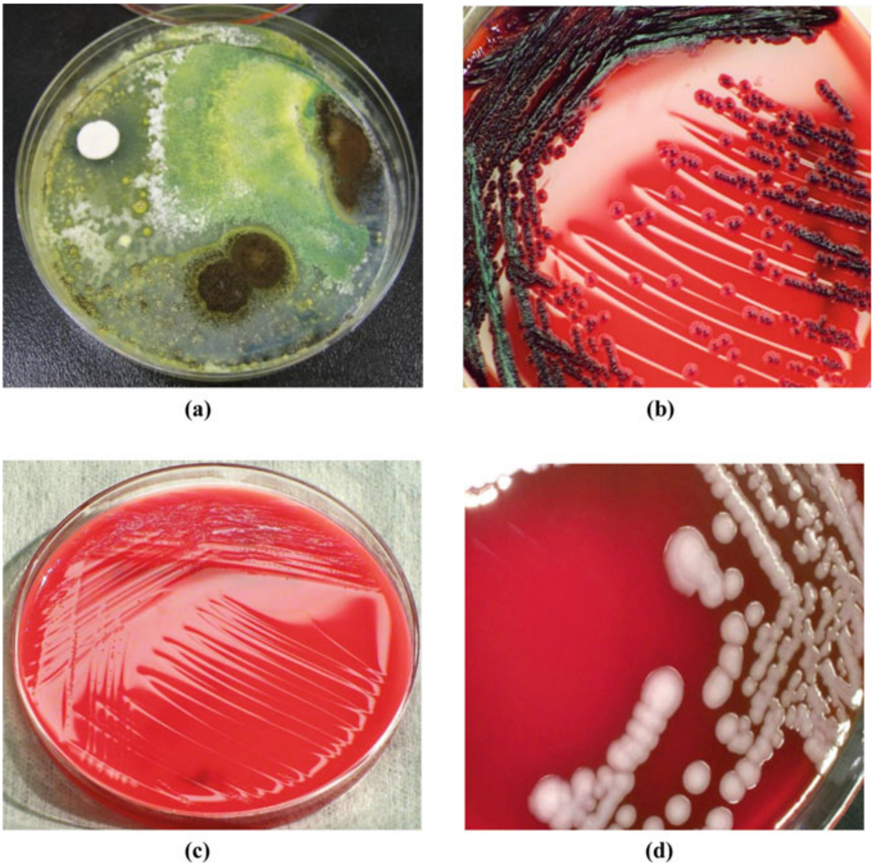



**Fig. 9.1** Images of microorganisms obtained from Public Image Health Library (PHIL) at Centers for Disease Control and Prevention (CDC). **a** Black colonies are of fungus *Aspergillus niger* (Chew and Marianni 2012). **b** *Chromobacterium violaceum* bacteria on blood agar (Moore et al. 2010a). **c** Colonies of *Pseudomonas fluorescens* bacteria on blood agar (Moore et al. 2010b). **d** *Bacillus megaterium* bacteria on sheep agar (Parker 2014)

- In an exclusive experimentation, extremophile red algae *Galdieria sulfuraria* have been used to remove and recover rare earth elements, namely yttrium, cerium, europium, and terbium using two different strains SAG 107.79 and ACUF 427 with varying pH range from 2.5 to 5.5. The metal yielding ability was found to vary with pH content (Iovinella et al. 2022). The above experimentations open up prospective of further research in algal bioleaching so that cost-effective and efficient metal recovery can be planned from this yet untapped natural resource.

### *9.4.5 Benefits of Bioleaching*

- Economical: Due to requirement of fewer professionals/competent workers for handling sophisticated chemical facilities, bioleaching is often simpler and hence less expensive to operate and maintain than other procedures.
- Environmentally friendly: The procedure is less harmful to the environment than traditional extraction methods. Because reducing sulfur dioxide emissions during smelting is costly, this might convert into profit for the corporation. Because the bacteria involved develop organically, little landscape damage occurs, and the mine and surrounding region may be kept relatively intact. Because bacteria flourish in mining settings, they are easily cultured and recycled.
- For ores with very tiny amount of metal(s), bioleaching can be a very helpful procedure in metal recovery.
- It can be utilized to partially replace the considerable crushing and grinding those results in prohibitive costs and energy usage in a traditional method.

### *9.4.6 Demerits of Bioleaching*

- Economical: In comparison with smelting, the bacterial leaching process is quite sluggish. This results in lower profits as well as a major delay in the cash flow needed to build new facilities.
- Toxic substances are occasionally created throughout the procedure. The generated sulfuric acid and $H^+$ ions can escape into the water (both ground and surface), acidifying it and in-turn harming the environment.
- The fresh water causes dilution of the solution, thereby causing ion precipitation and “yellow boy” pollution. Given that the procedure might result in a breach of biosafety, a bioleaching system must be properly constructed.
- Unlike other approaches, bioheap leaching cannot be halted fast since leaching continues with rains and natural bacteria.

## References

Arshadi M, Mousavi SM (2015) Enhancement of simultaneous gold and copper extraction from computer printed circuit boards using *Bacillus megaterium*. Biores Technol 175:315–324

Arslan V (2021) Bacterial leaching of copper, zinc, nickel and aluminum from discarded printed circuit boards using acidophilic bacteria. J Mater Cycles Waste Manag 23(5):2005–2015

Becci A, Amato A, Fonti V et al (2020) An innovative biotechnology for metal recovery from printed circuit boards. Resour Conserv Recycl 153:104549

Benzal E, Cano A, Solé M, Lao-Luque C, Gamisans X, Dorado AD (2020) Copper recovery from PCBs by *Acidithiobacillus ferrooxidans*: toxicity of bioleached metals on biological activity. Waste Biomass Valoriz 11(10):5483–5492

Chen S, Yang Y, Liu C et al (2015) Column bioleaching copper and its kinetics of waste printed circuit boards (WPCBs) by *Acidithiobacillus ferrooxidans*. Chemosphere 141:162–168

Chew G, Marianni L (2012) *Aspergillus niger* (Image ID 20863). Public Image Health Library (PHIL) at Centre for Disease Control and Prevention (CDC). Accessed 26 Nov 2022

Díaz-Martínez ME, Argumedo-Delira R, Sánchez-Viveros G, Alarcón A, Mendoza-López M (2019) Microbial bioleaching of Ag, Au and Cu from printed circuit boards of mobile phones. Curr Microbiol 76(5):536–544

El-Naggar NE-A, Rabei NH (2020) Bioprocessing optimization for efficient simultaneous removal of methylene blue and nickel by Gracilaria seaweed biomass. Sci Rep 10:17439. https://www.nature.com/articles/s41598-020-74389-y

Huerta-Rosas B, Cano-Rodríguez I, Gamiño-Arroyo Z et al (2020) Aerobic processes for bioleaching manganese and silver using microorganisms indigenous to mine tailings. World J Microbiol Biotechnol 36(8):1–16

Ilyas S, Lee JC, Chi RA et al (2013) Bioleaching of metals from electronic scrap and its potential for commercial exploitation. Hydrometallurgy 131:138–143

Iovinella M et al (2022) Bioremoval of Yttrium (III), Cerium (III), Europium (III), and Terbium (III) from single and quaternary aqueous solutions using the extremophile *Galdieria sulphuraria* (Galdieriaceae, Rhodophyta). Plants 11:1376. https://doi.org/10.3390/plants11101376

Işıldar A, van de Vossenberg J, Rene ER, van Hullebusch ED, Lens PN (2016) Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). Waste Manag 57:149–157

Madrigal-Arias JE, Argumedo-Delira R, Alarcón A, Mendoza-López M, García-Barradas O, Cruz-Sánchez JS, Jiménez-Fernández M (2015) Bioleaching of gold, copper and nickel from waste cellular phone PCBs and computer goldfinger motherboards by two *Aspergillus niger* strains. Braz J Microbiol 46:707–713

Marappa N, Ramachandran L, Dharumadurai D, Nooruddin T (2020) Recovery of gold and other precious metal resources from environmental polluted E-waste printed circuit board by bioleaching *Frankia*. Int J Environ Res 14(2):165–176

Moore A, Parker T, Marsh A (2010a) *Chromobacterium violaceum* (Image ID 12434). Public Image Health Library (PHIL) at Centre for Disease Control and Prevention (CDC). Accessed 26 Nov 2022

Moore A, Parker T, Marsh A (2010b) *Pseudomonas fluorescens* (Image ID 12457). Public Image Health Library (PHIL) at Centre for Disease Control and Prevention (CDC). Accessed 26 Nov 2022

Natarajan G, Ting YP (2014) Pretreatment of e-waste and mutation of alkali-tolerant cyanogenic bacteria promote gold biorecovery. Biores Technol 152:80–85

Parker T (2014) *Bacillus megaterium* (Image ID 17104). Public Image Health Library (PHIL) at Centre for Disease Control and Prevention (CDC). Accessed 26 Nov 2022

Pennesi C et al (2019) Adsorption of Indium by waste biomass of brown alga *Ascophyllum nodosum*. Sci Rep 9:16763. https://www.nature.com/articles/s41598-019-53172-8

Pourhossein F, Rezaei O, Mousavi SM, Beolchini F (2021) Bioleaching of critical metals from waste OLED touch screens using adapted acidophilic bacteria. J Environ Health Sci Eng 19(1):893–906

Priya A, Hait S (2018) Extraction of metals from high grade waste printed circuit board by conventional and hybrid bioleaching using *Acidithiobacillus ferrooxidans*. Hydrometallurgy 177:132–139

Saidan M, Brown B, Valix M (2012) Leaching of electronic waste using biometabolised acids. Chin J Chem Eng 20(3):530–534

Tay SB, Natarajan G, Rahim MNBA, Tan HT, Chung MCM, Ting YP, Yew WS (2013) Enhancing gold recovery from electronic waste via lixiviant metabolic engineering in *Chromobacterium violaceum*. Sci Rep 3(1):1–7

Tunali M, Yenigun O (2021) Biosorption of $Ag^+$ and $Nd^{3+}$ from single- and multi-metal solutions ($Ag^+$, $Nd^{3+}$, and $Au^{3+}$) by using living and dried microalgae. J Mater Cycles Waste Manag 23(4). https://doi.org/10.1007/s10163-020-01168-2

Wang J, Bai J, Xu J et al (2009) Bioleaching of metals from printed wire boards by *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* and their mixture. J Hazard Mater 172(2–3):1100–1105

Yang C, Zhu N, Shen W, Zhang T, Wu P (2017) Bioleaching of copper from metal concentrates of waste printed circuit boards by a newly isolated *Acidithiobacillus ferrooxidans* strain Z1. J Mater Cycles Waste Manag 19(1):247–255

# Chapter 10
# Bioleaching: A Sustainable Resource Recovery Strategy for Urban Mining of E-waste

**Geeta Bhandari, Sanjay Gupta, Parul Chaudhary, Shalu Chaudhary, and Saurabh Gangola**

**Abstract** The continuous and prodigious consumer requirement of electrical and electronic equipment along with their expedited product obsolescence rate owing to the fast advancements in technology has resulted in rise in generation of waste electrical and electronic equipment across the globe. Majority of e-waste contains complex mixture of heavy metals, plastics, refractory oxides, halogens and combustible substances that impose several health hazard and environmental challenges. E-waste also consists of various valuable metals and thus its recycling is not merely significant for waste management but also for the recovering of these valuable metals. Currently, conventional hydrometallurgical and pyrometallurgical methods are being employed for extraction of metals, but the high cost and toxic intermediates are the limitations of these methods. Biotechnological methods are exclusively exploited for metal recovery and are emerging as sustainable and environment-friendly methods. Bioleaching involves microbes for facilitating leaching of minerals and is more economical in comparison with conventional metallurgic treatments owing to lower operational and energy demand. Thus, this chapter provides a comprehensive insight into biological methods of extraction of valuable metals from e-waste. In addition, advanced and hybrid recycling technologies that are being studied are also discussed.

**Keywords** Bioleaching · E-waste · Metal revcover · Microbial leaching

G. Bhandari (✉) · S. Gupta · S. Chaudhary
Department of Biosciences, Himalayan School of Biosciences, Swami Rama Himalayan University, Dehradun 248016, India
e-mail: geet33n@gmail.com

P. Chaudhary
Department of Microbiology, College of Basic Sciences and Humanities, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263145, India

S. Gangola
School of Agriculture, Graphic Era Hill University, Bhimtal Campus, Uttarakhand 263136, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_10

## 10.1 Introduction

In the recent times, urbanisation and advancements in technology has resulted in extensive demand of electrical and electronic appliances including; automatic teller machines, computers, coffee machines, mobile phones, printers, photocopiers, refrigerators, television, telecommunication servers and washing machines (Garlapati 2016; Rene et al. 2021). This extensively enhanced need for these appliances across the global has caused production of immense quantity of electronic waste (e-waste) throughout the world (Cole et al. 2019). Electronic waste is considered as waste generated from electrical and electronic equipment (WEEE) and is a combination of ceramics, plastics, metals and composites (Karimi-Maleh et al. 2021). Globally, the generation rate of e-waste has been reported to 52.2 million tons per years and is expected to increase at the rate of 2.5 million tons annually (Yaashikaa et al. 2022). Several reports have also projected that the absolute volume of e-waste will increase to 74 million tons in 2030. Additionally, with advances in technology and marketable consumer design, the market life of various electric appliances has shortened considerably. Thus, developing and underdeveloped nations face huge challenge of managing this huge amount of e-waste owing to deficiency of proper management technologies (Nnorom and Osibanjo 2008). It has also been found that majority of countries dispose the large volumes of e-waste without any proper treatment into the landfills, open aquatic systems and agricultural land (Islam et al. 2020). A large amount of hazardous metals (Cd, Hg, Pb, Cr) present in e-waste can add up to increasing the level of toxicity in different ecosystems (Qu et al. 2019; Bhandari and Bhatt 2020). Long-term persistence of e-waste in the different ecosystems can enhance the possibility of exposure to hazardous substances and thus affecting human health through the soil and groundwater contamination and transport of contaminants through food web (Fig. 10.1).

Moreover, the toxic nature and detrimental implications on the ecosystem and human health, the financial returns from e-waste drive the need to recycle valuable metals from e-waste. In addition, considering the fact that most of the raw materials of electronic appliances are non-renewable, resource depletion, especially the growing concerns about the economic grades of ores, leads to the need to recover valuable metal resources in the e-waste. It has become electronic. Interest in scrap metal recycling continues to grow. Bioleaching is a potential technique for resource recovering of metals from e-waste. This technique employs indigenous microorganisms and their metabolites to extract valuable metals from waste such as spent catalysts and e-waste (Ivanus 2010; Mishra et al. 2008). Bioleaching of waste is a highly potent recycling strategy owing to its eco-friendly, sustainable and lower operational and energy costs.

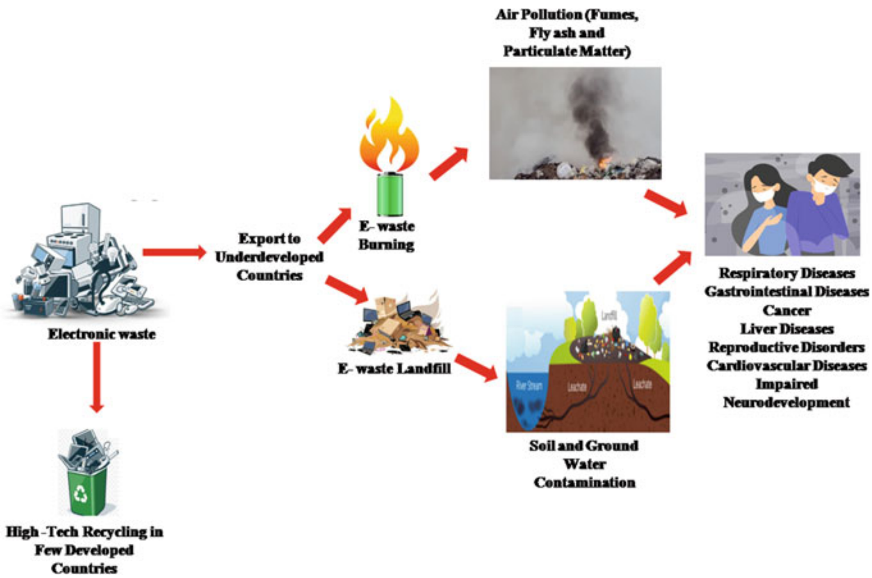



**Fig. 10.1** Pathways of transport of electronic waste and their impact on environment and human health

## 10.2 E-waste Composition

The sources of e-waste production are divided into two categories on the basis of usage, supply and demand: white goods (large household devices; air conditioners, dryers, freezers, ovens washing machines and refrigerators), grey goods (information and communication devices; CD-ROM, computers, disk driver, keyboards, LCD, mouse, typewriter, telephones, fax machine, modem and pager) and brown goods (audio or video devices; audio appliances, camera, mobile phone, recording, appliances, TV and projector) (Saini and Taneja 2012). These electronic appliances consist of various toxic compounds and thus can cause a threat to the environments if not handled appropriately (Chatterjee 2008). The major categories of hazardous pollutants present in e-waste belong to; (i) heavy metals, (ii) halogenated molecules, (iii) radioactive compounds and (iv) miscellaneous substances such as plastics, ceramics and resins. In addition, brominated flame retardants, polyaromatic hydrocarbons, polyvinyl chloride, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, polybrominated diphenyl ethers, polybrominated biphenyls and various other organic contaminants are also released from e-waste (Kiddee et al. 2013; Tue et al. 2016). The heavy metal can make up to 60% of total e-waste (Ari 2016), thus making the recycling process more significant. The valuable heavy metals present in e-waste are Au, Pb, Pd, Hg, Ni, Ag, Cd, Cr, Pt, Fe, Zn, Cu, several rare earth metals, alkaline metals and radioactive metals. Therefore, the recycling companies in several African and Asian countries, such as China, Ghana, India, Indonesia, Nigeria, Philippines, Thailand and Vietnam have shown immense interest in recovering valuable metals from e-waste (Awasthi et al. 2016).

## 10.3 Hazardous Impact of E-waste

Majority of e-waste is transported to low- and middle-income countries as there are stringent environmental regulations and standards in high-income countries instead of their on-site treatment (Rwan and Zhu 2016). However, the recycling in many low- and middle-income countries is only dependent on manual labour and public awareness of the about detrimental health, and environmental impact imposed by e-waste is generally non-existent thus these inadequate management strategies further complicate the issue (Pant et al. 2012). Such e-waste management can cause imminent threat to human health and the environment by discharging significant amounts of toxic heavy metals and organic compounds into the surrounding environment (Shen et al. 2009). In e-waste recycling areas, upgrading waste disposal strategies is the most economical way to achieve the solid waste management goals (Pant et al. 2012). Dumping of toxic e-waste into surrounding aquatic bodies and landfills contaminates the groundwater or may enter into the food web and affect human health (Ouabo et al. 2019). Cd is highly toxic heavy metal and mainly targets kidneys and bones and has been shown to impact the neurodevelopment in foetus and young children (Chen et al. 2011). It has also been found to cause non-oxidative stress by interacting with –SH groups of proteins (Patra et al. 2011). Long-term exposure to Pb results in detrimental impact on reproductive, endocrine nervous, excretory and skeletal systems (Sthiannopkao and Wong 2013). Similarly, Hg present in flat panel displays can cause damage to brain and central nervous system (Langford and Ferner 1999). Cr is employed in the manufacture of metal enclosures and is human carcinogen that impacts the neurodevelopment in young children, kidneys, respiratory system and cause metal mediated oxidative stress (Lin et al. 2009; Tsydenova and Bengtsson 2011). Arsenic is employed for the manufacture of LEDs and is reported to affect heart rhythm, respiration and cause oxidative stress, digestive, liver and kidney disorders and increased risk of bladder cancer (Xue 2008). Most heavy metals interfere with reproductive functions by reducing the sperm count, enhancing the amount of testicular germ cells and causing chromosomal abnormalities, cryptorchidism, endometriosis, fertility issues, hypospadias, infertility, miscarriage and genetic instability (Balabanic et al. 2011; Pant et al. 2012). The heavy metals in e-waste affect human health by causing degradation of important bio-molecules inhibiting enzymes and changing the cell-membrane permeability and structure. The free radicals generated from heavy metals result in lipid peroxidation, protein degradation and DNA damage (Ding et al. 2021). Thus, the task of protecting environment has necessitated the development or employed of existent sustainable and economical strategies for extracting these metals from e-waste.

## 10.4 E-waste Management

The recovery of valuable metals from e-waste is of commercial relevance since electronic devices have shorter lifecycles than other types of products (Rienzie et al. 2019). However, only a small number of recycling facilities have been established in developing and underdeveloped countries, where usually the e-waste is transported form developed countries. E-waste management in these countries is generally done by un-skilled labour due to inadequate infrastructure and risky resource recovery techniques (Ikhlayel 2018). The leaching and recovery of precious metals in these unregulated industries has resulted in severe health risks for both humans and the environment due to the use of highly concentrated acids and cyanide (Baniasadi et al. 2019). Thus, there is an urgent need for recycling and/or recovery techniques that are affordable, safe and environmentally benign for processing e-waste. It is necessary to implement a proper recycling system for collecting, segregating, recycling, reusing and recovery of e-waste at the local and provincial levels due to the improper/illegal discharge practises that poses serious environmental and health risks. Informal recyclers utilise physico-chemical techniques to extract the metals and renewable materials from e-waste, however, hazardous materials such as heavy metals, plastics and brominated flame retardants remain untreated. In order to reduce the consequences of pollution and promote the equitable allocation of resources, recycling of e-waste components is therefore viewed as a resource-efficient way to managing e-waste (Needhidasan et al. 2014; Kumar et al. 2017).

Physical, chemical, thermochemical, pyrometallurgical, hydrometallurgical and biometallurgical processes have been employed for recovering metals from e-waste (Dolker and Pant 2019) (Fig. 10.2). The most widely used method for extracting metals from e-waste in the current times is pyrometallurgical extraction and involves mixing of solid e-waste with metal concentrates prior to smelting for metal recovery (Mäkinen et al. 2015). However, this method needs a lot of chemicals and a high temperature, which raises the capital and operating costs. Additionally, this technique produces secondary waste including dust and hazardous gaseous pollutants (dioxins and furans), making this method difficult to control, unsustainable with lower social acceptance (Khaliq et al. 2014).

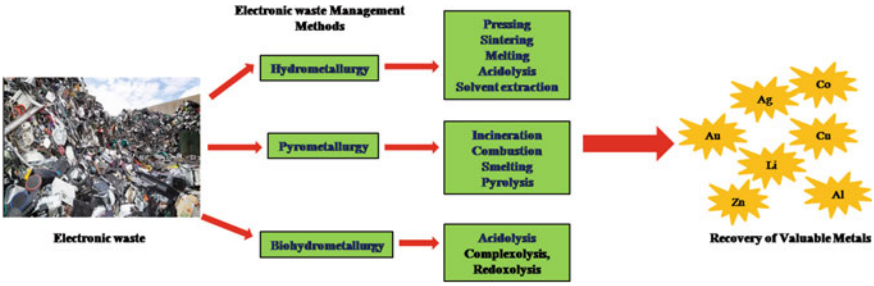



**Fig. 10.2** Electronic waste management methods for recovery of valuable metals

Hydrometallurgy is a metal solubilisation method by applying massive quantities of acids and has been commercially employed for e-waste disposal. Nonetheless, there are a number of drawbacks to this method, including the need for pretreatment, its slowness, the production of enormous amounts of acidic wastewater effluent and its high operational cost (Gorain et al. 2016). Bioleaching is a biological metal recovery process from solid waste and is similar to hydrometallurgy in all aspects except the use of microorganisms for metal extraction. As a bio-hydrometallurgical process, bioleaching is simple, manageable, eco-friendly, highly effective and low operation cost and low energy demanding process. Additionally, this procedure operates at atmospheric pressure and room temperature and does not require professional labour (Natarajan 2018).

## 10.5 Biometallurgy or Biohydrometallurgy

It is a novel, economically viable and cost effective method for recovering valuable metals in an energy-efficient, environmentally beneficial manner. It takes advantage of the bioleaching capability of microbes for converting metals into their extractable, soluble state, which is subsequently recovered from solution (Sun et al. 2016) (Table 10.1). Microorganisms that are primarily capable of mineral leaching in natural habitats have been identified and characterised over the past few decades. The two key steps of biohydrometallurgy are bioleaching and biorecovery. Acidolysis, complexolysis and redoxolysis are the principal methods by which metals can be mobilised by microorganisms from the solid phase to the liquid phase in a process known as bioleaching (Sethurajan et al. 2018). Biosorption or precipitation is employed during bioleaching for bio-recovering of valuable metals from the leachate. During biosorption, living or dead biomass is employed for adsorption of metals on the cell wall as a part of their defence mechanism (Sethurajan et al. 2018), while bioprecipitation involves the interaction between microbial metabolites and metal ions causing the precipitation of the required metal. The potential for selective metal recovery from the poly-metallic leachate is a significant benefit of bioprecipitation (Sethurajan et al. 2018).

## 10.6 Microorganism for Bioleaching

A diverse group of microorganisms are employed for bioleaching; however, sulphur-oxidising acidophiles and iron-oxidising microbes are the most common bioleaching agents. Microorganisms possessing bioleaching capabilities are categorised in to three groups (Abhilash and Pandey 2013).

**Table 10.1** Recent studies on bioleaching of metals from e-waste

| Microorganism | Recovery method | Metal recovery (%) | Operational conditions | References |
|---|---|---|---|---|
| *Pseudomonas fluorescens* | Bioleaching | Au—54 | pH: 9; temp: 30 °C; time: 56 h | Li et al. (2020) |
| *Acidiplasma* sp. | Thiourea bioleaching | Au—98<br>Ag—14 | pH: 1.5; temp: 45 °C; time: 48 h | Rizki et al. (2019) |
| *Acinetobacter* sp. Cr B2 | Bioleaching | Cu—63 | Sequential batch mode; inoculums size: 9% (v/v); frequency: 0.2 $s^{-1}$; amplitude: 6.5 cm; time: 48 h | Jagannath et al. (2017) |
| *Leptospirillum ferriphilum*, *Acidithiobacillus caldus* | Bioleaching | Zn—85.23<br>Cu—76.59<br>Al—70.16 | Temp: 45 °C; pH: 2; 400 rpm; time: 7 days | Xia et al. (2017) |
| *Aspergillus niger* strains MM1 | Bioleaching | Co—82<br>Li—100 | Temp: 30 °C; pH: 3.5; 200 rpm; time: 48 h | Biswal et al. (2018) |
| *Acidithiobacillus thiooxidans* strain 80191 | Bioleaching | Co—22<br>Li—66 | Temp: 30 °C; pH: 4.5; 150 rpm; time: 10 days | Biswal et al. (2018) |
| *Acidithiobacillus ferrooxidans* | Bioleaching | Cu—7387 mg/L (non magnetic fraction)<br>Cu—6606 mg/L (without magnetic separation fraction) | Temp: 30 °C; 185 rpm; time: 48 h | de Andrade et al. (2019) |
| *Aspergillus niger* MXPE6 + *Aspergillus niger* MX7 | Bioleaching | Au—56 | Temp: 28 °C; pH: 4.5; time: 16 h | Argumedo-Delira et al. (2019) |

(continued)

**Table 10.1** (continued)

| Microorganism | Recovery method | Metal recovery (%) | Operational conditions | References |
|---|---|---|---|---|
| *A. niger* MXPE6 | Bioleaching | Ag—54 | Temp: 24 °C; pH: 5; time: 35 days | Díaz-Martínez et al. (2019) |
| *Sphingomonas* sp. MXB8 + *C. orthopsilosis* MXL20 | Bioleaching | Ag—44.2 | Temp: 24 °C; pH: 5; time: 35 days | Díaz-Martínez et al. (2019) |
| *Sphingomonas* sp. MXB8 | Bioleaching | Ag—35.8 | Temp: 24 °C; pH: 5; time: 35 days | Díaz-Martínez et al. (2019) |
| *Acidithiobacillus caldus*, *Leptospirillum ferriphilum*, *Sulfobacillus thermosulfidooxidans*, *Ferroplasma* | Bioleaching | Cu—92<br>Zn—67<br>AL—45 | Batch reactor; time: 10 days | Akbari and Ahmadi (2019) |
| *Acidithiobacillus ferrooxidans* | Bioleaching | Li—100<br>Co—88<br>Mn—20 | Temp: 30 °C; pH: 2; 140 rpm; time: 12 days | Naseri et al. (2019) |
| *A. ferrooxidans*, *A. caldus*, *A. thiooxidans*, *L. ferrooxidans*, *S. thermosulfidooxidans*, *S. metallicus*, *Metallosphaera sedula*, *Acidianus* | Bioleaching | Cu—65–88 | Batch reactor; pH: 1.0–3.5 | Georgiev et al. (2017) |
| *A. caldus*, *S. thermosulfidooxidans* | Bioleaching | Cu—84–90 | Temp: 45 °C; pH: 1; continuous stirred tank reactor | Falagan et al. (2017) |
| *Penicillium simplicissimum* | Bioleaching | Cu—96.94<br>Ni—71.5 | Bubble column reactor | Nili et al. (2022) |
| *Acidithiobacillus thiooxidans* | Thiosulfate bioleaching | Cu—100<br>Au—31<br>Ag—40 | pH: 0.5; time: 48 h | Pourhossein and Mousavi (2022) |

i. Chemolithoautotrophs employ acidolysis and redoxolysis for bioleaching
ii. Organic acid synthesising fungi employ acidolysis and complexolysis for bioleaching
iii. Cyanogenic microbes employ complexolysis for bioleaching.

Chemolithotrophs surviving at low pH levels, typically at pH 2.0 or lower, and generally known as acidophiles and can use inorganic compounds (iron and sulphur) as a source of energy. Generally, the chemolithotrophs employed in bioleaching belong to either reduced sulphur ($S_8$, $S_2O_3^{2-}$, $H_2S$ and polysulphide) oxidizers or ferrous (Fe II) oxidizers. Acidophilic bacteria such as *Leptospirillum*, *Sulfolobus*, *Acidithiobacillus*, *Acidicanus*, *Acidimicrobium* sp., *Ferromicrobium* sp., *Sulfobacillus* sp. and *Acidithiobacillus caldus* either reduce sulphur to $H_2SO_4$ or oxidise $Fe^{2+}$ to $Fe^{3+}$ (Okibe and Johnson 2004). *Leptospirillum*, *Acidimicrobium*, *Sulfolobus*, *Acidithiobacillus*, *Acidicanus*, *A. caldus*, *Ferromicrobium* sp. and *Sulfobacillus* sp. are acidophiles that either oxidise $Fe^{2+}$ to $Fe^{3+}$ and or reduced sulphur to $H_2SO_4$ (Okibe and Johnson 2004). *Acidithiobacillus ferrooxidans* obtains energy for growth by oxidisation of $Fe^{2+}$ to $Fe^{3+}$. *Leptospirillum ferrooxidans* is an acidophile that is not capable of oxidising sulphur to sulphate. Thus, for oxidising $Fe^{2+}$ to $Fe^{3+}$, it is generally co-cultivated with *A. ferrooxidans*. Several *Sulfolobus* sp. such as *S. metallicus*, *S. acidocaldarius*, *S. solfataricus*, *S. brierley*, *S. ambioalous* and *S. thermosulfidooxidans* are capable of oxidising iron and sulphur and thus have been employed in various bioleaching studies (Xia et al. 2010; Lindstrom et al. 1993; Kim et al. 2013; Roshani et al. 2017). During bioleaching, the temperature increases steadily since it is an exothermic process. Majority of microbes are thermophiles and capable of growing at high temperatures, thus bioleaching process can be conducted at higher temperatures, negating the requirement for a heat exchanger (Li et al. 2014; Baniasadi et al. 2019). Organotrophic organisms such as fungi and cyanogenic microorganisms utilise organic carbon as the source of energy. While utilising the organic carbon, fungal strains synthesise organic acids, whereas the cyanogenic microorganisms synthesise HCN. The cyanides are produced by heterotrophs through oxidative decarboxylation of glycine, which can be subsequently employed for extracting valuable metals present in e-waste. In comparison with acidophilic microbes, the heterotrophs are capable of tolerating a wide range of pH and thus can be used to treat slightly alkaline e-wastes (Natarajan and Ting 2015). The most common cyanogens used in bioleaching belong to genus *Pseudomonas* sp., *Chromobacterium* sp., *Bacillus* sp., *Escherichia* sp., *Clitocybe* sp., *Marasmius* sp. and *Polysporus* sp. Extraction of valuable metals such as Ag, Cu, Zn, Au and Pt from their primary ores through *Pseudomonas* sp., *Chromobacterium* sp. and *Gluconobacter* sp. has been reported (Chi et al. 2011; Reed et al. 2016). Various fungi belonging to genus *Aspergillus flavus*, *Aspergillus niger*, *Penicillium chrysogenum* and *Penicillium simplicissimum* are commonly employed for bioleaching studies and employ organic acids such as; gluconic, citric, oxalic acid to extract metals (Wu and Ting 2006; Ilyas et al. 2012, 2013). Metal extraction by fungi is primarily mediated by two mechanisms: acidolysis involving replacement of hydrogen ion with metal ions followed by complexolysis, which involves complex production.

## 10.7 Bioleaching Pathways

Bioleaching employs microbial metabolism for efficient recovery of valuable metals from e-waste. For bioleaching of e-waste, three processes are involved: acidolysis, redoxolysis and complexolysis. The acidolysis is carried out with the help of protons obtained from organic acids (acetic, citric, formic, gluconic, malic, oxalic, pyruvic and succinic) and inorganic acids (sulphuric) produced as by-products of microbial metabolism (Ilyas and Lee 2014). Metal solubilisation via oxidation–reduction is known as redoxolysis. Electron transfer occurring during redoxolysis allows energy transfer required for microbial growth. Acidophiles carry out enzymatic reduction of ferric ions anaerobically and employ hydrogen or sulphur as electron donors during redoxolysis (Hubau et al. 2018). Cyanogenic microbes and several fungi employ complexolysis for metal recovery. In the early stationary phase of growth, microbes synthesise cyanide by decarboxylating glycine on induction of hen genes, which is subsequently detoxified by cyanoalanine synthase to produce cyanoalanine (Lu and Xu 2016). The production of cyanide is affected by variables such as pH, temperature, oxygen and glycine concentration (Isıldar et al. 2019). As described below, there are two basic modes of bioleaching.

### *10.7.1 Direct Bioleaching*

This method requires establishment of contact between microbial and mineral surfaces followed by microbial enzyme-assisted oxidation of metals (Bal et al. 2019; Zhao and Wang 2019). The e-waste is presented at the inoculation stage in this procedure by the addition of organic acids in a single- or two-stage process (Arya and Kumar 2020; Baniasadi et al. 2020). *A. ferrooxidans*, a gram negative acidophile, carries out oxidation of $Fe^{2+}$ to $Fe^{3+}$ and thus acquires vitality for their metabolic capacities (Miao et al. 2020). During the attachment, microbes synthesise exopolysaccharides that fills the space between the microbial outer membrane and the ore. The EPS layer consists of metal–acid complexes where the metal oxidation reaction occurs. The direct leaching mechanism can be depicted by following reaction.

$$MeS_2 + H_2O + 7/2O_2 \xrightarrow{\text{Bacteria}} Me^{2+} + 2SO_4^{2-} + 2H^+$$

In the above reaction, $MeS_2$ depicts an insoluble metal sulphide which is oxidised to $Me^{2+}$, a free metal ion (Chakraborty et al. 2022). Metal sulphides can be oxidised by different types of microbial metabolites. Two methods of oxidation of metal sulphides have been suggested: (i) thiosulphate methods for acid-insoluble metal sulphides; (ii) polysulphide method for acid soluble metal sulphides (Yaashikaa et al. 2022).

### *10.7.2 Indirect Bioleaching*

This is a two-way mechanism, wherein the microbes do not necessarily participate in direct metal mineralisation; however, they produce solid oxidising molecules. Ferric ions and sulphuric acid assist in balancing various metals ion in highly acidic conditions. Iron, sulphur and metal sulphides oxidation plays an important role in maintaining the acidic environment required for metal disintegration (Sajjad et al. 2019). In the indirect oxidation method, microbes such as iron-oxidising microbe produce $Fe^{3+}$. When this $Fe^{3+}$ reacts with the metals, they become soluble in a process as follows (Chakraborty et al. 2022):

$$14Fe^{2+} + 7/2O_2 + 14H^+ \xrightarrow{\text{Bacteria}} 14Fe^{3+} + 7H_2O$$
$$MeS_2 + 8H_2O + 14Fe^{3+} \rightarrow Me^{2+} + 14Fe^{2+} + 2SO_4^{2-} + 16H^+$$

In this process, $Fe^{2+}$ and reduced sulphur species generate in the solution, which can be used as substrates by planktonic cells (Jia et al. 2008; Tao and Dongwei 2014). $Fe^{2+}$ might have arose in the solution owing to $Fe^{3+}$ reduction in conjunction with ore oxidation. Metal ions and sulphur species are generated during the subsequent oxidation reactions. Furthermore, $Fe^{2+}$ and reduced sulphur species may also be generated as a result of the contact process. Planktonic cells oxidise $Fe^{2+}$ and sulphur species in solution to $Fe^{3+}$ and $H_2SO_4$, respectively (Jia et al. 2008; Tao and Dongwei 2014). $Fe^{3+}$ generated from the above oxidation assists in metal solubilisation by oxidising pyrite that cannot be solubilised by $H_2SO_4$ owing to its non-acid soluble nature. However, the direct method is more viable in comparison with this method since acidic conditions enhance the oxidation process and thus the metal extraction (Abilash and Pandey 2013).

## 10.8 Application of Bioleaching in E-waste Management

Numerous studies have investigated the efficacy of bioleaching for recovering valuable metals (Ag, Au, Co) in addition to other base metals (e.g. Cu, Ni, Fe, Zn) from e-waste (Isildar et al. 2016; Son et al. 2020; Brandl et al. 2008; Rienzie et al. 2019). *Pseudomonas*, *Chromobacterium violaceum* and *Chromobacterium* sp. synthesise various microbial by-products such as cyanide that has the ability to dissolve valuable metals from e-waste (Jujun et al. 2014). Hussain et al. (2016) investigated the role of sulphate-reducing microbes for recovering metals from e-waste and metal precipitation resulted due to production of insoluble metal sulphides. The *A. niger* MXPE6 and *Acidithiobacillus thiooxidans* have been found capable of recovering Au, whereas *A. niger* and *Aspergillus nomius* are involved in Cu recovery (Madrigal-Arias et al. 2015). Metal mobilisation was reported to occur by production of either organic or inorganic acid in a two-stage efficient leaching process. Xia et al. (2017) used a stirred tank reactor to perform PCB bioleaching. Initially, PCBs were divided into two fractions consisting of metal rich and metal poor elements by employing a shaking table separator, and subsequent metal extraction was performed on the metal poor fraction using bioleaching. A semi-industrial procedure was suggested on the basis of this method, and simultaneous feasibility analysis was performed to assess the economical nature (Xia et al. 2017). Kim et al. (2016) employed different species of Aspergillus for recovering metals from spent Zn–Mn or Ni–Cd batteries in spent medium consisting organic acids synthesised by the fungi (Kim et al. 2016). *C. violaceum*, a gram negative facultative mesophile, has been found to assist in gold recovery from waste printed circuit boards (Li et al. 2015; Pant and Sharma 2015). *C. violaceum* synthesises cyanide that aids in efficient gold solubilisation in acidic media (Chi et al. 2011). The following chemical reactions summarise the method of gold bioleaching (Liu et al. 2016):

$$4Au + 8CN^- \rightarrow 4Au(CN)_2^- + 4e^-$$
$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
$$4Au + 8CN^- + O_2 + 2H_2O \xrightarrow{\textit{Chromobacterium violaceum}} 4Au(CN)_2^- + 4OH^-$$

Kumar et al. (2018) have employed *Pseudomonas balearica* SAEI strain for recovery of gold and reported a recuperation rate of 68.5%. Some authors have also used *A. niger* for recovery of gold and reported 56% recuperation rate (Argumedo-Delira et al. 2019; Becci et al. 2020). Iron bioleaching by acidophiles such as *A. ferrooxidans* occurs through thiosulphate or polysulphide pathways by oxidation of $Fe^{2+}$ to $Fe^{3+}$ and reduction of sulphur to $S_2O_3{}^2$ (Maluckov 2017; Saavedra et al. 2020). Oxidation of $Fe^{3+}$ to $Fe^{2+}$ occurs due transfer of electron with subsequent reoxidation of $Fe^{2+}$ to $Fe^{3+}$ at the outer membrane (Drits and Manceau 2000; Geerlings et al. 2019). The thiosulphate oxidation method (Masau 1999) is represented in the following generalised equations:

$$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$
$$MeS + 2Fe^{3+} + 1.5O_2 + H_2O \rightarrow Me^{2+} + 2Fe^{2+} + SO_4^{2-} + 2H^-$$

Copper dissolution from e-waste typically occurs in two stages. During the first stage, microbes oxidise the ferrous ion to ferric ions followed the second stage consisting of copper mobilisation from e-waste scrap, activated by ferric ion's reduction to ferrous ions. The continuous cycle of oxidation and reduction of ferric and ferrous ions results in copper bioleaching from e-waste (Wu et al. 2018). The following are the chemical reactions for copper bioleaching:

$$Fe^{2+} + O_2 + 4H^+ \xrightarrow[\substack{\textit{Acidithiobacillus}\\ \textit{thiooxidans}}]{\text{Microbes}} Fe^{3+} + 2H_2O$$
$$2Fe^{3+} + Cu \rightarrow 2Fe^{2+} + Cu^{2+}$$

Priya and Hait (2020) employed *A. ferrooxidans* and *Acidiphilium acidophilum* for valuable metal recovery from waste printed boards. They reported that 96% Cu, 94.5% Zn, 75% Ni and 74.5% Pb were extracted by employing *A. ferrooxidans* and *A. acidophilum* (Priya and Hait 2020).

## 10.9 Hybrid Methods for Metal Recovery

Bioleaching is regarded as an advanced, sustainable and eco-friendly technology used for extraction of both precious and base metals from e-waste and conferring several advantageous such as mild operating temperature, less energy demand, less operational cost and selective bioleaching of valuable metals. However, biohydrometallugy process also faces several limitations such as maintenance of pure culture of microbes, reproducibility in lab and pilot level, requirement of nutrient for microbial growth, toxic impact of metals on microbial metabolism and longer treatment duration in comparison with other techniques (Rene et al. 2021). Therefore, hybrid technique consisting of different physical, chemical and biological methods has also been explored and found to serve as advanced and more effective methods for recovering metals from e-waste (Pant et al. 2012). Priya and Hait (2018) employed an integrated bioleaching and hydrometallurgy and reported that citric acid function as a chelating agent improves the recovery of metals from PCBs. Citric acid enhances the synthesis of EPS by *A. ferrooxidans* and reduce the production of jarosite (Priya and Hait 2018). In a similar study by Dolker and Pant (2019), an integrated chemical-biological process for metal recovery from a lithium-ion battery waste. The authors reported that lithium (25%) separation by bioleaching and cobalt (98%) by adsorption. Additionally, a novel hybrid method of Cu recovery from printed circuit board waste was reported by Sinha et al. (2018). The authors developed a bi-phasic recovery method with initial bioleaching followed by subsequent electrowinning. *Aspergillus oryzae* and Bakers Yeast were used for Cu bioleaching and resulted in > 80% recovery of Cu, which further enhanced on electrowinning to 92.7% (Sinha et al. 2018).

## 10.10 Conclusion and Future Perspectives

The amalgamation of advanced technological equipments in different aspect of our daily life has resulted in extensive enhancement in development of electronic waste. Considering a circular economy and sustainable environment standpoint, the recycling and recovery of metals from e-waste is a significant area in the coming times. However, majority of developed countries lack stringent regulations regarding e-waste management and transport their e-waste to developing and undeveloped nations, where the e-waste is illegally handled by the untrained workers. Thus, there is a immense demand for revisiting the existing rules, regulations, legislations, recycling and recovery infrastructures and creating awareness. In addition, simple, safe, sustainable, cost-efficient and environment-friendly technologies for e-waste management are the need of the hour. Commonly employed methods such as pyrometallurgy and hydrometallurgy have certain limitations, and thus, biohydrometallurgy has been exploited for metal recovery. Hybrid technologies consisting of integrated physical, chemical and biological methods have also been developed. Further research in the area of development and process optimisation hybrid methods, development of sustainable adsorbents for metal recovery, employment of genomic and proteomic tools for development of genetically modified strains for metal recovery can be considered.

## References


Abhilash, Pandey BD (2013) Microbially assisted leaching of uranium—a review. Miner Process Extr Metall Rev 34:81–113. https://doi.org/10.1080/08827508.2011.635731

Akbari S, Ahmadi A (2019) Recovery of copper from a mixture of printed circuit boards (PCBs) and sulphidic tailings using bioleaching and solvent extraction processes. Chem Eng Process Process Intensif 142:107584. https://doi.org/10.1016/j.cep.2019.107584

Argumedo-Delira R, Gómez-Martínez MJ, Soto BJ (2019) Gold Bioleaching from printed circuit boards of mobile phones by *Aspergillus niger* in a culture without agitation and with glucose as a carbon source. Metals 9(5):521. https://doi.org/10.3390/met9050521

Ari V (2016) A review of technology of metal recovery from electronic waste. E-waste in transition—from pollution to resource. IntechOpen Croatia Biot 63:249–257

Arya S, Kumar S (2020) Bioleaching: urban mining option to curb the menace of e-waste challenge. Bioengineered 11(1):640–660. https://doi.org/10.1080/21655979.2020.1775988

Awasthi AK, Zeng X, Li J (2016) Environmental pollution of electronic waste recycling in India: a critical review. Environ Pollut 211:259–270. https://doi.org/10.1016/j.envpol.2015.11.027

Bal B, Ghosh S, Das AP (2019) Microbial recovery and recycling of manganese waste and their future application: a review. Geomicrobiol J 36(1):85–96. https://doi.org/10.1080/01490451.2018.1497731

Balabanic D, Rupnik M, Klemencic AK (2011) Negative impact of endocrine disrupting compounds on human reproductive health. Reproduction Fertility Devel 23(3):403–416. https://doi.org/10.1071/RD09300

Baniasadi M, Vakilchap F, Bahaloo-Horeh N et al (2019) Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J Ind Eng Chem 76:75–90. https://doi.org/10.1016/j.jiec.2019.03.047

Baniasadi M, Graves JE, Ray DA et al (2020) Closed-loop recycling of copper from waste printed circuit boards using bioleaching and electrowinning processes. Waste Biomass Valoriz 1–12. https://doi.org/10.1007/s12649-020-01128-9

Becci A, Karaj D, Merli G et al (2020) Biotechnology for metal recovery from end-of-life printed circuit boards with *Aspergillus niger*. Sustainability 12(16):6482. https://doi.org/10.3390/su12166482

Bhandari G, Bhatt P (2020) Concepts and application of plant–microbe interaction in remediation of heavy metals. In: Sharma A (ed) Microbes and signaling biomolecules against plant stress. Rhizosphere biology. Springer, Singapore. https://doi.org/10.1007/978-981-15-7094-0_4

Biswal BK, Jadhav UU, Madhaiyan M et al (2018) Biological leaching and chemical precipitation methods for recovery of co and li from spent lithium-ion batteries. ACS Sustainable Chem Eng 6(9):12343–12352. https://doi.org/10.1021/acssuschemeng.8b02810

Brandl H, Lehmann S, Faramarzi MA et al (2008) Biomobilization of silver, gold, and platinum from solid waste materials by HCN-forming microorganisms. Hydrometallurgy 94:14–17. https://doi.org/10.1016/j.hydromet.2008.05.016

Chakraborty SC, Zaman MWU, Hoque M et al (2022) Metals extraction processes from electronic waste: constraints and opportunities. Environ Sci Pollut Res Int 29(22):32651–32669. https://doi.org/10.1007/s11356-022-19322-8

Chatterjee P (2008) Health costs of recycling. British Medical J 337:376–377. https://doi.org/10.1136/bmj.a296

Chen A, Dietrich KN, Huo X et al (2011) Developmental neurotoxicants in E-waste: an emerging health concern. Environ Health Perspectives 119(4):431–433. https://doi.org/10.1289/ehp.1002452

Chi T, Lee J, Pandey BD et al (2011) Bioleaching of gold and copper from waste mobile phone PCBs by using a cyanogenic bacterium. Miner Eng 24:1219–1222. https://doi.org/10.1016/j.mineng.2011.05.009

Cole C, Gnanapragasam A, Cooper T et al (2019) Assessing barriers to reuse of electrical and electronic equipment, a UK perspective. Resour Conserv Recycl: X 1:100004. https://doi.org/10.1016/j.rcrx.2019.100004

de Andrade LM, Rosario CGA, de Carvalho MA, et al (2019) Copper recovery from printed circuit boards from smartphones through bioleaching. In: TMS 2019 148th annual meeting & exhibition supplemental proceedings. Springer, pp. 837–84

Díaz-Martínez ME, Argumedo-Delira R, Sanchez-Viveros G et al (2019) Microbial bioleaching of Ag, Au and Cu from printed circuit boards of mobile phones. Curr Microbiol 76(5):536–544. https://doi.org/10.1007/s00284-019-01646-3

Ding R, Cheong YH, Ahamed A et al (2021) Heavy metals detection with paper-based electrochemical sensors. Anal Chem 93(4):1880–1888. https://doi.org/10.1021/acs.analchem.0c04247

Dolker T, Pant D (2019) Chemical-biological hybrid systems for the metal recovery from waste lithium ion battery. J Environ Manage 248:109270. https://doi.org/10.1016/j.jenvman.2019.109270

Drits VA, Manceau A (2000) A model for the mechanism of $Fe^{3+}$ to $Fe^{2+}$ reduction in dioctahedral smectites. Clays Clay Min 48(2):185–195

Falagan C, Grail BM, Johnson DB (2017) New approaches for extracting and recovering metals from mine tailings. Miner Eng 106:71–78. https://doi.org/10.1016/j.mineng.2016.10.008

Garlapati VK (2016) E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew Sustain Energy Rev 54:874–881. https://doi.org/10.1016/j.rser.2015.10.106

Geerlings N, Zetsche EM, Hidalgo-Martinez S et al (2019) Mineral formation induced by cable bacteria performing long-distance electron transport in marine sediments. Biogeosciences 16(3):811–829. https://doi.org/10.5194/bg-16-811-2019

Georgiev P, Spasova I, Groudeva V et al (2017) Bioleaching of valuable components from a pyrometallurgical final slag. In: Solid state phenomena, vol 262. Trans Tech Publications Ltd., pp 696–699. https://doi.org/10.4028/www.scientific.net/SSP.262.696

Gorain BK, Kondos PD, Lakshmanan VI (2016) Innovations in gold and silver processing. In: Innovative process development in metallurgical industry. Springer, Cham, pp 393–428. https://doi.org/10.1007/978-3-319-21599-0_20

Hubau A, Minier M, Chagnes A et al (2018) Continuous production of a biogenic ferric iron lixiviant for the bioleaching of printed circuit boards (PCBs). Hydrometallurgy 180:180–191. https://doi.org/10.1016/j.hydromet.2018.07.001

Hussain A, Hasan A, Javid A et al (2016) Exploited application of sulfate reducing bacteria for concomitant treatment of metallic and non-metallic wastes: a mini review. 3 Biotech 6(2):119. https://doi.org/10.1007/s13205-016-0437-3

Ikhlayel M (2018) An integrated approach to establish e-waste management systems for developing countries. J Clean Prod 170:119–130. https://doi.org/10.1016/j.jclepro.2017.09.137

Ilyas S, Chi R, Lee J (2013) Fungal leaching of metals from mine tailings. Miner Process Extr Metall Rev 34:185–194

Ilyas S, Lee JC (2014) Biometallurgical recovery of metals from waste electrical and electronic equipment: a review. ChemBioEng Rev 1(4):148–169. https://doi.org/10.1002/cben.201400001

Ilyas S, Ruan CHI, Lee JC et al (2012) One step bioleaching of sulphide ore with low concentration of arsenic by *Aspergillus niger* and Taguchi orthogonal array optimization. Chin J Chem Eng 20:923–929. https://doi.org/10.1016/S1004-9541(12)60419-4

Isıldar A, van Hullebuscha ED, Lenz M et al (2019) Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE)—a review. J Hazard Mater 362:467–481. https://doi.org/10.1016/j.jhazmat.2018.08.050

Islam A, Ahmed T, Awual R et al (2020) Advances in sustainable approaches to recover metals from e-waste—a review. J Clean Prod 244:118815. https://doi.org/10.1016/J.JCLEPRO.2019.118815

Ivanu RC (2010) Bioleaching of metals from electronic scrap by pure and mixed culture of *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*. Metal Int 15(4):62–70

Jagannath A, Shetty KV, Saidutta MB (2017) Bioleaching of copper from electronic waste using *Acinetobacter* sp. Cr B2 in a pulsed plate column operated in batch and sequential batch mode. J Environ Chem Eng 5(2):1599–1607. https://doi.org/10.1016/j.jece.2017.02.023

Jia Y, Tan Q, Sun H et al (2008) Sulfide mineral dissolution microbes: community structure and function in industrial bioleaching heaps. Green Energy Environ 4(1):1–92. https://doi.org/10.1016/j.gee.2018.04.001

Jujun R, Jie Z, Jian H et al (2014) A novel designed bioreactor for recovering precious metals from waste printed circuit boards. Sci Rep 5:13481. https://doi.org/10.1038/srep13481

Karimi-Maleh H, Ayati A, Davoodi R et al (2021) Recent advances in using of chitosan-based adsorbents for removal of pharmaceutical contaminants: a review. J Clean Prod 291:125880. https://doi.org/10.1016/j.jclepro.2021.125880

Khaliq A, Rhamdhani MA, Brooks G et al (2014) Metal extraction processes for electronic waste and existing industrial routes: a review and Australian perspective. Resources 3:152–179. https://doi.org/10.3390/resources3010152

Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manag 33:1237–1250

Kim DJ, Srichandan H, Gahan CS et al (2013) Thermophilic bioleaching of spent petroleum refinery catalyst using *Sulfolobus metallicus*. Can Metall Q 51:403–412. https://doi.org/10.1179/1879139512Y.0000000031

Kim MJ, Seo JY, Choi YS et al (2016) Bioleaching of spent Zn–Mn or Ni–Cd batteries by Aspergillus species. Waste Manag 51:168–173. https://doi.org/10.1016/j.wasman.2015.11.001

Kumar A, Holuszko M, Espinosa DCR (2017) E-waste: an overview on generation, collection, legislation and recycling practices. Resour Conserv Recycl 122:32–42. https://doi.org/10.1016/j.resconrec.2017.01.018

Kumar U, Gaikwad V, Sahajwalla V (2018) Transformation of waste toner to iron using E-waste plastics as a carbon resource. J Clean Prod 192:244–251. https://doi.org/10.1016/j.jclepro.2018.05.010

Langford LJ, Ferner RE (1999) Toxicity of mercury. J Hum Hypertens 13:651–656

Li J, Liang C, Ma C (2015) Bioleaching of gold from waste printed circuit boards by *Chromobacterium violaceum*. J Mat Cycles Waste Manag 17(3):529–539. https://doi.org/10.1007/s10163-014-0276-4

Li J, Wen J, Guo Y et al (2020) Bioleaching of gold from waste printed circuit boards by alkali-tolerant *Pseudomonas fluorescens*. Hydrometallurgy 194:105260. https://doi.org/10.1016/j.hydromet.2020.105260

Li S, Zhong H, Hu Y et al (2014) Bioleaching of a low-grade nickel–copper sulfide by mixture of four thermophiles. Biores Technol 153:300–306. https://doi.org/10.1016/j.biortech.2013.12.018

Lin C, Wu M, Yang C et al (2009) Acute severe chromium poisoning after dermal exposure to hexavalent chromium. J Chin Med Assoc 72(4):219–221. https://doi.org/10.1016/S1726-4901(09)70059-0

Lindstrom EB, Wold S, Kettaneh-Word N et al (1993) Optimization of pyrite bioleaching using *Sulfolobus acidocaldarius*. Appl Microbiol Biotechnol 28:702–707. https://doi.org/10.1007/BF00182813

Liu R, Li J, Ge Z (2016) Review on *Chromobacterium violaceum* for gold bioleaching from e-waste. Procedia Environ Sci 31:947–953. https://doi.org/10.1016/j.proenv.2016.02.119

Lu Y, Xu Z (2016) Precious metals recovery from waste printed circuit boards: a review for current status and perspective. Resour Conserv Recycl 113:28–39. https://doi.org/10.1016/j.resconrec.2016.05.007

Madrigal-Arias JE, Argumedo-Delira R, Alarcón A et al (2015) Bioleaching of gold, copper and nickel from waste cellular phone PCBs and computer goldfinger motherboards by two *Aspergillus nigerstrains*. Braz J Microbiol 46(3):707–713. https://doi.org/10.1590/S1517-838246320140256

Mäkinen J, Bachér J, Kaartinen T et al (2015) The effect of flotation and parameters for bioleaching of printed circuit boards. Miner Eng 75:26–31. https://doi.org/10.1016/j.mineng.2015.01.009

Maluckov BS (2017) The catalytic role of *Acidithiobacillus ferrooxidans* for metals extraction from mining-metallurgical resource. Biodivers Int J 1(3):109–119

Masau RJY (1999) The mechanism of thiosulfate oxidation by *Thiobacillus thiooxidans* 8085

Miao B, Shen L, Liu X et al (2020) Bioinformatics and transcriptional study of the Nramp gene in the extreme Acidophile *Acidithiobacillus ferrooxidans* strain DC. Minerals 10(6):544. https://doi.org/10.3390/min10060544

Mishra D, Kim DJ, Ralph DE et al (2008) Bioleaching of metals from spent lithium ion secondary batteries using *Acidithiobacillus ferrooxidans*. Waste Manag 28(2):333–338. https://doi.org/10.1016/j.wasman.2007.01.010

Naseri T, Bahaloo-Horeh N, Mousavi SM (2019) Bacterial leaching as a green approach for typical metals recovery from end-of-life coin cells batteries. J Clean Prod 220:483–492. https://doi.org/10.1016/j.jclepro.2019.02.177

Natarajan G, Ting Y (2015) Gold bio recovery from e-waste: an improved strategy through spent medium leaching with pH modification. Chemosphere 136:232–238. https://doi.org/10.1016/j.chemosphere.2015.05.046

Natarajan KA (2018) Biotechnology of metals: principles, recovery methods and environmental concerns. Susan Dennis, India. Elsevier, pp 1–300. https://doi.org/10.1016/C2015-0-00161-7

Needhidasan S, Samuel M, Chidambaram R (2014) Electronic waste—an emerging threat to the environment of urban India. J Environ Health Sci Eng 12:36. https://doi.org/10.1186/2052-336X-12-36

Nili S, Arshadi M, Yaghmaei S (2022) Fungal bioleaching of e-waste utilizing molasses as the carbon source in a bubble column bioreactor. J Environ Manag 307:114524. https://doi.org/10.1016/j.jenvman.2022.114524

Nnorom IC, Osibanjo O (2008) Electronic waste (e-waste): material flows and management practices in Nigeria. Waste Manag 28:1472–1479. https://doi.org/10.1016/j.wasman.2007.06.012

Okibe N, Johnson DB (2004) Biooxidation of pyrite by defined mixed cultures of moderately thermophilic acidophiles in pH-controlled bioreactors: significance of microbial interactions. Biotechnol Bioeng 87:574–583. https://doi.org/10.1002/bit.20138

Ouabo RE, Ogundiran MB, Sangodoyin AY et al (2019) Ecological risk and human health implications of heavy metals contamination of surface soil in E-waste recycling sites in Douala, Cameroun. J Health Pollut 9(21):190310. https://doi.org/10.5696/2156-9614-9.21.190310

Pant D, Joshi D, Upreti MK et al (2012) Chemical and biological extraction of metals present in E waste: a hybrid technology. Waste Manag 32(5):979–990. https://doi.org/10.1016/j.wasman.2011.12.002

Pant ND, Sharma M (2015) Urinary tract infection caused by *Chromobacterium violaceum*. Int J Gen Med 8:293–295

Patra RC, Rautray AK, Swarup D (2011) Oxidative stress in lead and cadmium toxicity and its amelioration. Res Vet Med Int 9:1–2. https://doi.org/10.4061/2011/457327

Pourhossein F, Mousavi SM (2022) A novel rapid and selective microbially thiosulfate bioleaching of precious metals from discarded telecommunication printed circuited boards (TPCBs). Res Conserv Recycl 187:106599. https://doi.org/10.1016/j.resconrec.2022.106599

Priya A, Hait S (2018) Extraction of metals from high grade waste printed circuit board by conventional and hybrid bioleaching using *Acidithiobacillus ferrooxidans*. Hydrometallurgy 177:132–139. https://doi.org/10.1016/j.hydromet.2018.03.005

Priya A, Hait S (2020) Biometallurgical recovery of metals from waste printed circuit boards using pure and mixed strains of *Acidithiobacillus ferrooxidans* and *Acidiphilium acidophilum*. Process Saf Environ Prot 143:262–272. https://doi.org/10.1016/j.psep.2020.06.042

Qu Y, Wang W, Liu Y et al (2019) Understanding residents' preferences for e-waste collection in China—a case study of waste mobile phones. J Clean Prod 228:52–62. https://doi.org/10.1016/j.jclepro.2019.04.216

Reed DW, Fujita Y, Daubaras DL et al (2016) Bioleaching of rare earth elements from waste phosphors and cracking catalysts. Hydrometallurgy 166:34–40. https://doi.org/10.1016/j.hydromet.2016.08.006

Rene ER, Sethurajan M, Ponnusamy VR et al (2021) Electronic waste generation, recycling and resource recovery: technological perspectives and trends. J Hazard Mater 416:125664. https://doi.org/10.1016/j.jhazmat.2021.125664

Rienzie R, Perera ATD, Adassooriya NM (2019) Biorecovery of precious metal nanoparticles from waste electrical and electronic equipments. In: Electronic waste management and treatment technology. Elsevier, pp 133–152. https://doi.org/10.1016/B978-0-12-816190-6.00006-6

Rizki IN, Tanaka Y, Okibe N (2019) Thiourea bioleaching for gold recycling from e-waste. Waste Manag 84:158–165. https://doi.org/10.1016/j.wasman.2018.11.021

Roshani M, Shojaosadati SA, Safdari SJ et al (2017) Bioleaching of Molybdenum by two thermophilic strains isolated and characterised. Iran J Chem Chem Eng 36:183–194

Saavedra A, Aguirre P, Gentina JC (2020) Biooxidation of iron by *Acidithiobacillus ferrooxidans* in the presence of D-galactose: understanding its influence on the production of EPS and cell tolerance to high concentrations of iron. Front Microbiol 11:759. https://doi.org/10.3389/fmicb.2020.00759

Saini AK, Taneja A (2012) Managing e-waste in India—a review. Int J Appl Eng Res 7:11. ISSN: 0973-4562

Sajjad W, Zheng G, Din G et al (2019) Metals extraction from sulfide ores with microorganisms: the bioleaching technology and recent developments. Trans Indian Inst Met 72(3):559–579. https://doi.org/10.1007/s12666-018-1516-4

Sethurajan M, van Hullebusch ED, Nancharaiah YV (2018) Biotechnology in the management and resource recovery from metal bearing solid wastes: recent advances. J Environ Manag 211:138–153. https://doi.org/10.1016/j.jenvman.2018.01.035

Shen C, Chen Y, Huang S et al (2009) Dioxin-like compounds in agricultural soils near E-waste recycling sites from Taizhou area, China: chemical and bioanalytical characterization. Environ Int 35:50–55. https://doi.org/10.1016/j.envint.2008.07.005

Sinha R, Chauhan G, Singh A et al (2018) A novel eco-friendly hybrid approach for recovery and reuse of copper from electronic waste. J Environ Chem Eng 6:1053–1061. https://doi.org/10.1016/j.jece.2018.01.030

Son J, Hong Y, Han G et al (2020) Gold recovery using porphyrin-based polymer from electronic wastes: gold desorption and adsorbent regeneration. Sci Total Environ 704:135405. https://doi.org/10.1016/j.scitotenv.2019.135405

Sthiannopkao S, Wong MH (2013) Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci Total Environ 463:1147–1153. https://doi.org/10.1016/j.scitotenv.2012.06.088

Sun M, Wang Y, Hong J et al (2016) Life cycle assessment of a bio-hydrometallurgical treatment of spent Zn Mn batteries. J Clean Prod 129:350–358. https://doi.org/10.1016/j.jclepro.2016.04.058

Tao H, Dongwei L (2014) Presentation on mechanisms and applications of chalcopyrite and pyrite bioleaching in biohydrometallurgy—a presentation. Biotechnol Rep 4:107–119. https://doi.org/10.1016/j.btre.2014.09.003

Tsydenova O, Bengtsson M (2011) Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag 31(1):45–58. https://doi.org/10.1016/j.wasman.2010.08.014

Tue NM, Goto A, Takahashi S et al (2016) Release of chlorinated, brominated and mixed halogenated dioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra, Ghana). J Hazard Mater 302:151–157. https://doi.org/10.1016/j.jhazmat.2015.09.062

Wu HY, Ting YP (2006) Metal extraction from municipal solid waste (MSW) incinerator fly ash—chemical leaching and fungal bioleaching. Enzyme Microb Technol 38:839–847. https://doi.org/10.1016/j.enzmictec.2005.08.012

Wu W, Liu X, Zhang X et al (2018) Bioleaching of copper from waste printed circuit boards by bacteria-free cultural supernatant of iron–sulfur-oxidizing bacteria. Biores Bioprocess 5(1):10. https://doi.org/10.1186/s40643-018-0196-6

Xia J, Yang Y, He H et al (2010) Investigation of the sulfur speciation during chalcopyrite leaching by moderate thermophile *Sulfobacillus thermosulfidooxidans*. Int J Miner Process 94:52–57. https://doi.org/10.1016/j.minpro.2009.11.005

Xia MC, Wang YP, Peng TJ et al (2017) Recycling of metals from pretreated waste printed circuit boards effectively in stirred tank reactor by a moderately thermophilic culture. J Biosci Bioeng 123(6):714–721. https://doi.org/10.1016/j.jbiosc.2016.12.017

Xue HJK (2008) Arsenic contents in soil, water, and crops in an E-waste disposal area. J Environ Sci 29(6):1713–1718

Yaashikaa PR, Priyanka B, Senthil Kumar P et al (2022) A review on recent advancements in recovery of valuable and toxic metals from e-waste using bioleaching approach. Chemosphere 287:132230. https://doi.org/10.1016/j.chemosphere.2021.132230

Zhao F, Wang S (2019) Bioleaching of electronic waste using extreme acidophiles. In: Electronic waste management and treatment technology. Elsevier, pp 153–174. https://doi.org/10.1016/B978-0-12-816190-6.00007-8

# Chapter 11
# Microbial Degradation of E-plastics in Diverse Ecosystems

**Ambika, Charul Kainthola, Seema Singh, Manoj Kumar, Amit Pandey, Maneesh S. Bhandari, and Shailesh Pandey**

**Abstract** Plastics are recalcitrant polymers released in the environment through rampant use leading to their accumulation in ecosystem. The increased transportation of these polymers in agricultural soil, sediment and water is causing concerns for environmentalists. The current technological insurgence in electronics combined with growing consumption has bolstered the generation of waste electrical and electronic equipments. Therefore, E-plastic is considered to be one of the fastest-growing waste streams globally. Current chapter synthesizes the understanding of plastics with special focus on E-plastic accumulation in the ecosystem. Bacteria and fungi are reported for their potential to degrade the E-plastic to some extent. Herein, the concerns related to the use of E-plastic and future challenges and opportunities for their eco-friendly degradation are highlighted. Furthermore, potent fungi and bacteria, their growth conditions, type of enzyme produced and the particular plastic polymer degraded are discussed, which would serve as a toolkit for understanding the utilization microbes for E-plastic waste management strategy.

**Keywords** E-plastic · Fungal enzymes · Plastic degradation · Bacteria · E-waste

## 11.1 Introduction

Since the dawn of history, humankind has endeavoured to develop material offering benefits that are not easily found in nature. The development of plastics started with the use of natural materials that had intrinsic plastic properties, such as shellac and chewing gum. The next step in the evolution of plastics involved the chemical modification of natural materials, such as rubber, nitrocellulose, collagen, and galalite. Finally, a wide-range of completely synthetic materials recognized as modern plastics started to develop around 100 years ago (Buragohain et al. 2020). The invention

Ambika · C. Kainthola · S. Singh · M. Kumar · A. Pandey · M. S. Bhandari · S. Pandey (✉)
Forest Research Institute, Dehradun, India
e-mail: pandeysh@icfre.org



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_11

of this marvel material in the late nineteenth century made modern life easier and more sustainable. Plastics are formed by the alignment of monomers together through chemical bonds. Polythene comprises of 64% of total plastic, which is a linear hydrocarbon polymer consisting of long chains of the ethylene monomers (Kale et al. 2015). The plastic materials are being used to a very large extent, and therefore it would be arduous or even impossible to imagine the modern world without plastics. Gradually, plastics take up the space from households electronics to industrial and technological setups. Consequently, global electronic trash has been accumulated due to tremendous advancement of technology and high industrial production. Different plastic resins are now one of the most commonly discarded materials from electronic devices which are contributing to form "E-plastic" waste.

One of the incredible characteristic features of plastics is high resistance to biodegradation which has become central problems to the modern world (Kotova et al. 2021). Accumulation of plastic debris has not only taken up a lot of landfill space but also contributed to the production of secondary pollutants (e.g. dioxins, carbon monoxide, nitrogen oxides and others) that have adversely impacted our environment. For example, asthmatic bronchitis, DNA damage and skin warts are some side effects associated with E-waste. Although mechanical recycling has become the primary recycling method and is applied for reusing thermoplastic wastes, the properties of most recycled materials are significantly compromised after a number of processing cycles, and the resulting commercial values are thus limited (Ru et al. 2020). As an alternative, chemical recycling can recover the monomers and other chemicals from plastic wastes, but its success relies on the affordability of processes and the efficiency of catalysts (Rahimi and García 2017). It has been reported that only 9 and 12% of global plastic wastes are recycled and incinerated, while up to 79% is discarded into landfills or the natural environment, indicating that there is a great need for exploring innovative recycling methods to dispose of plastic wastes (Garcia and Robertson 2017; Geyer et al. 2017). Complex polymeric bonds in plastics help them withstand everyday wear and tear; however, hydrolytic degradation, photo-degradation, thermo-oxidative degradation and biodegradation decay plastic in the environment (Webb et al. 2013; Zeenat et al. 2021).

Natural decaying is mostly caused by microbial degradation (Rutkowska et al. 2002), which involves microbe adhesion and subsequent colonization on surfaces. The microbial extracellular enzymes bind to the plastic substrates and accelerate hydrolytic cleavage. Low molecular weight oligomers, dimers and monomers are released from the polymers before they are mineralized to produce $CO_2$ and $H_2O$. Recent advancements in microbial research reveal that highly compact polymers can be extensively degraded by choosing microorganisms with a wide-range of enzymatic activities. Some strains of *Pseudomonas* sp., *Rhodococcus ruber* and *Bacillus* sp. were also reported as potential plastic degrading bacteria (Mohan et al. 2016). Additionally, some reports state that metabolic routes used by microbes to break down

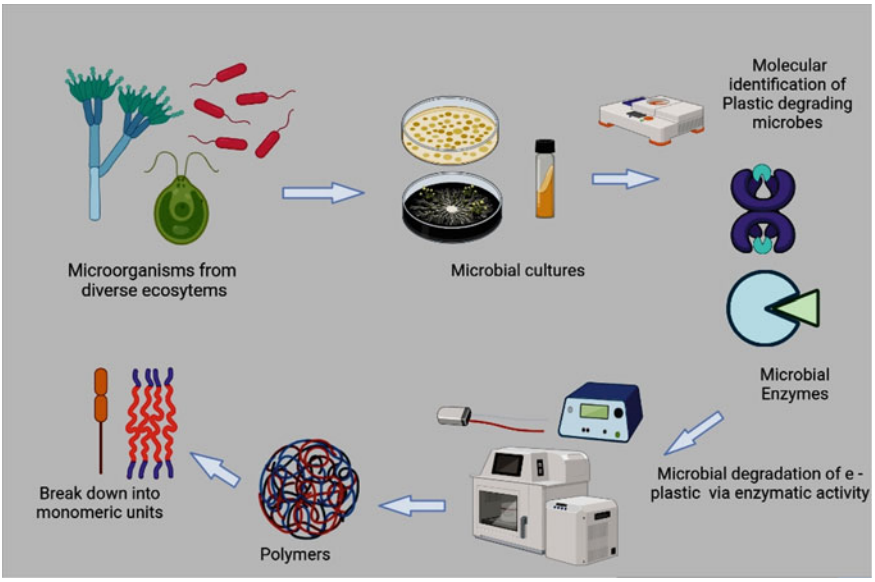



**Fig. 11.1** Role of microbes in degradation process of E-plastic waste

plastic into its component parts and the efforts to use these products as feedstock for the microbial manufacture of high-value compounds (Ru et al. 2020). Although plastic has made its significant inroads in all major and minor spheres of human existence, this chapter is confined to discuss the role of microbes in degradation process of E-plastic waste (Fig. 11.1). Before exploring the different microbial opportunities available for biodegradation of different plastic waste, there is a need to know the nature of plastic polymers and which segment of them have application in electronic device production.

## 11.2 Types of Plastics

The resin identification code (RIC), which has been used by the society of the plastics industry to identify different types of plastics, defines seven different kinds of plastics by resin type, namely (1) Polyethylene Terephthalate (PETE/PET); (2) High-Density Polyethylene (HDPE); (3) Polyvinyl Chloride (PVC); (4) Low-Density Polyethylene (LDPE); (5) Polypropylene (PP); (6) Polystyrene or Styrofoam (PS); and (7) Miscellaneous Plastics. The numbers also represent the general cost-effectiveness of recycling, with 1 being the easiest and 6 and 7 being the toughest (Wilhelm 2008; Hopewell et al. 2009; Smith 2011).

## 11.3 E-plastic (Electronic Plastic Waste): Another Form of E-waste

The term "waste electrical and electronic equipment" (WEEE), also called as "E-waste", refers to the unwanted electronic devices which are discarded for recycling, reuse or refurbishment, for example, computers, VCRs, DVD players, televisions, stereos, copiers, fax machines, etc. (Wright 2020). A wide-range of plastic resins used in consumer electronics includes acrylonitrile butadiene styrene (ABS), expanded polystyrene (EPS), high impact polystyrene (HIPS), polyamide (PA), polycarbonate (PC), polycarbonate-acrylonitrile butadiene styrene (PC-ABS), etc. (Buragohain et al. 2020). Among them, ABS, HIPS and EPS are widely used plastic resin in electronic production process which have been utilized in consumer electronics (Bhaskar et al. 2003). PET, a semicrystalline thermoplastic, is widely used in the manufacture of fibres, electronics, lighting products and other appliances. Polyurethane (PUR) is a polymer connected by carbamate links and is often used in manufacturing electrical compounds and fibres (Gama et al. 2018).

## 11.4 Degradation: A Global Challenge

Plastic garbage production worldwide is rising quickly in tandem with the world's increasing plastic usage. Application of plastic in making of electronic devices and appliances has elevated the accumulation of electronic plastic waste drastically in last few decades. The market for polypropylene and high-impact polystyrene was estimated to be worth \$49.6 billion globally in 2021; by 2031, it is anticipated to have grown to \$81.1 billion, with a CAGR of 5.1%. Plastics Europe's recent statistics show that 348 million tonnes of plastic were produced globally in 2018 (Plastics Europe 2018). China and the European Union use the most plastic globally, with respective shares of 29.4 and 18.5% placing them top and second in the world (China Plastics Industry 2017; Plastics Europe 2018). As a result, plastic waste has turned into an evil representation of our wasteful culture (Ru et al. 2020). By 2050, it is expected that up to 26 billion tonnes of plastic trash would have been created, of which more than half will have been dumped in landfills and eventually enter ecospheres like lakes and oceans, posing a major threat (Jambeck et al. 2015; Lonnstedt and Eklov 2016; Geyer et al. 2017). Among E-plastics, HIPS is a multiphase system with polybutadiene dispersed in a rigid polystyrene (PS) matrix and also has increased fracture resistance, reduced transparency, modulus and tensile strength (Alaee et al. 2003; Sekhar et al. 2016). HIPS commonly contains polybrominated substances, such as decabromodiphenyl ether and antimony trioxide ($Sb_2O_3$), in synergistic flame retardant combinations. The International Agency for Research on Cancer (IARC) found that it is carcinogenic to humans and its exposure results in lung conditions, birth abnormalities and problems with female reproduction. Standard landfills are not an environmentally favourable option, and it is difficult to dispose of waste while adhering to EPA standards (IARC 1989; OEHHA 1997). Additionally, other toxic metals emitted by E-waste, such as lead, mercury, cadmium, hexavalent chromium, barium and beryllium, can damage the central and peripheral nervous system and respiratory system. As a method of melting plastics and removing non-valuable metals, incineration is used most commonly (Lakshmi and Nagan 2010; Mohan et al. 2016). HIPS is commonly used as plastic resin in the production of electronic equipments. Currently, the worldwide production of HIPS is one million tonnes per annum (Sekhar et al. 2016). Only thermal disintegration of HIPS has been documented as a method of degradation so far. Biodegradation using microbial resources has yet been investigated superficially (Mohan et al. 2016). Among various factors, corporate sector and government undertakings require both data security and conventional methods to destroy the E-plastic waste as they contain hazardous chemicals and metals. It can be a quite economically challenging task to recycle E-plastic waste generated from everyday's common electronic devices as quoted by Andrew Rubin, President, FCM Recycling, who financed a hefty amount of money to build an infrastructure in order to recover E-plastics (https://www.paradygm.co/newsandevents/2017/5/10/plastics-recycling-of-e-scrap). Landfilling is a temporary solution for disposal of the material but keeping in mind the environmental safety, a permanent and more naturalistic approach is necessary.

## 11.5 Microbial Degradation

Regarding degradation methods, biodegradation caused by microorganisms (bacteria and fungi) is usually preferred as an eco-friendly and pollution-free mechanism. Microbial biodegradation of plastic occurs in four steps, which include bio-deterioration (modification of polymer properties), bio-fragmentation (polymer carbon chain hydrolysis and fragmentation as well as production of intermediate products of degradation), bio-assimilation (microbial absorption and incorporation of smaller hydrocarbon metabolite molecules) and mineralization (complete plastic degradation into water and carbon dioxide or methane, water and carbon dioxide) (Kotova et al. 2021). Microbes produce extracellular enzymes which degrade complex plastic polymers into their oligomers which are transported into cells and further breakdown by intracellular enzymes for carbon and energy (Ghosh et al. 2019). The enzymes degrading plastics belonging to the class "hydrolases" includes cutinase, esterases, lipases, depolymerase and PETases enzymes, which breakdown the carbon chains of plastic polymer into smaller units. The hydrolase enzyme–polymer interaction involves two stages. These microbial enzymes first adhere to plastic surface by interacting with the hydrophobic groups of the plastic polymers through their hydrophobic cleft followed by action of active site in hydrolytic cleavage of long chains of polymer into short polymer intermediates which are used by the microbes as carbon source (Kaushal et al. 2021). Biodegradation rate depends on a number of factors, including environmental conditions (temperature, pH, moisture, UV radiation, hydrophobicity, extracellular enzymes, nutrients, and biosurfactants) and polymer properties (molecular weight, size and shape, crystallinity, functional groups, cross-linking, blend, copolymer, and additives) (Ahmed et al. 2018). Various techniques given below are commonly used to analyse microbial biodegradation of plastics (Atanasova et al. 2021).

- Macroscopic observation to study mechanical properties.
- Gel permeation chromatography (GPC), X-ray diffraction (XRD), differential thermal analysis and thermogravimetric analysis (DTA and TG), and differential scanning calorimetry (DSC) to study physical properties.
- Electron spectroscopy for chemical analysis (ESCA) and scanning electron microscopy (SEM) to study surface changes.
- Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance and thin-layer chromatography (NMR TLC) and gas chromatography/mass spectrometry (GC–MS) to study chemical properties.
- Matrix-assisted laser desorption/ionization time of flight (MALDI-TOF) to study enzyme products.
- Colony halo and biomass accumulation to study microbial growth on plastic polymers as the sole carbon source.

### *11.5.1 Bacterial Biodegradation of E-plastic Waste*

The presence of bacteria in diverse habitats is due to their high metabolic versatility and adaptability to different abiotic and biotic factors. The capability of bacteria to utilize various types of chemical compounds, including plastic, has attracted researchers to address the problem of E-waste pollution through microbial biodegradation. Different researchers have reported the presence of bacteria in E-waste and their role in biodegradation and recovery of different E-waste components, such as precious metals, rare earth elements, and plastics. Bacterial biodegradation includes bacterial attachment to polymer surfaces (by appendages, biosurfactant and extracellular enzymes), assimilation of smaller units and release of carbon dioxide. Bacterial enzymes play an important role in the depolymerization of plastic polymers. The rate of biodegradation depends on abiotic factors and polymer physical and chemical properties. Since the active sites of enzymes are different for each type of bond, the types of bonds in polymeric chains are likely related to the degradation of petro-plastics. As a result, three categories can be used to categorize the mechanisms of petro-plastic degradation: (i) polymers with carbon backbones; (ii) polymers with ester bond backbones and side chains; and (iii) polymers with hetero/carbamate (urethane) bonds. Polyethylene (PE), polystyrene (PS), polypropylene (PP) and polyvinyl chloride (PVC) are examples of polymers that contain carbon chains. Polyethylene terephthalate (PET) has ester bonds and side chains, while polyurethanes (PUR) contain hetero/carbamate (urethane) bonds (Mohanan et al. 2020). Petro-polymers can be divided into two categories from the perspective of enzymatic degradation: hydrolysable (PET and PUR) and non-hydrolysable (PE, PS, PP and PVC). The lack of hydrolysable group in backbone restricts biodegradation of polymers (Wei and Zimmermann 2017). Such polymers undergo abiotic degradation (photo-oxidative) prior to biodegradation, which makes the polymer vulnerable to microbial enzymes. Several reports accounted for the biodegradation of polymers by bacterial enzymes. For example, hydrolase Tfh isolated from *Thermobifida fusca* depolymerized PET polymer by breaking the esters bonds (Müller et al. 2005). Another example, laccase isolated from bacteria *R. ruber* C208 degraded UV-treated PE polymer (Santo et al. 2013). Some more examples of bacterial hydrolase enzymes reported to degrade plastic polymers (PE, PUR, PET, polycaprolactone (PCL) and nylon) are esterase produced by *Streptomyces* sp., *Bacillus subtilis* and *Alicycliphilus*; lipase by *Alcaligenes faecalis*; 6-aminohexanoate-cyclic-dimer hydrolase, 6-aminohexanoate-dimer hydrolase and endo-type6-aminohexanoate-oligomer hydrolase by *Flavobacterium*; PVA dehydrogenase by *Sphingomonas* sp.; alkane hydroxylase by *Pseudomonas* sp.; and monoxygenases by *Rhodococcus* sp. (Atanasova et al. 2021).

A metagenomic study by Salam and Varma (2019) reported that the most abundant phyla in the soil contaminated with E-waste collected from dumping and recycling sites (National Capital Region, Delhi, India) were Firmicutes and Proteobacteria. E-waste is also the major source of microplastic, a hazardous pollutant. Chai et al. (2020) reported that global E-waste dismantling centre located in Guiyu (China) recorded massive amounts of soil microplastic pollution, with polymers PP, polycarbonate (PC) and acrylonitrile butadiene styrene (ABS) accounting for the majority of E-plastic. The study also explored bacterial communities in three different sites of the dismantling centre and suggested that these microplastic could provide a new ecological niche for microbial communities, and these microplastic-associated bacterial communities can be explored for biodegradation of microplastic. A few workers have reported the biodegradation of E-plastic by bacteria isolated from various environments. For instance, Sekhar et al. (2016) reported in vitro biodegradation of HIPS E-plastic film by four bacteria, viz. *Enterobacter* sp., *Citrobacter sedlakii*, *Alcaligenes* sp. and *Brevundimonas diminuta,* isolated from partially degraded plastic waste samples collected from a local rural market. The biodegraded HIPS film showed structural and morphological changes. Further, the presence of degradation intermediates, adherence of microbial cells on the plastic film and depolymerase enzyme activity of bacterial cultures validated the biodegradation of the HIPS E-plastic film. Another study by Mohan et al. (2016) reported biodegradation of brominated HIPS by *Pseudomonas* and *Bacillus* strains isolated from soil samples collected from a plastic dump yard. A bacterium *Ideonella sakaiensis* isolated from PET contaminated sediment, completely degraded PET after six weeks of incubation (Yoshida et al. 2016). In an in vitro experiment, a marine *Bacillus* species isolated from plastic-polluted coastal water samples degraded PVC, low-density polyethylene (LDPE) and high-density polyethylene (HDPE) films in 90 days (Kumari et al. 2019). There is scarce literature available on biodegradation of E-plastic. Hence, reports available on biodegradation of plastic polymers such as PET, PP, PS and PVC (used in electronic and electrical products) by bacteria and/or their enzymes are given in Table 11.1.

**Table 11.1** Bacteria and/or bacterial enzyme associated with different plastic polymer degradation

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| Soil (Mesocosm study) | *Bacillus subtilis* | Impranil DLN | LB agar plate supplemented with 1% Impranil DLN | 24 h at 30 °C | Polyurethanase-lipase | Clear zone around bacterial colony indicated polyurethane degradation | Rowe and Howard (2002) |
| *Thermobifida fusca* | TfH (hydrolase) | Polyethylene terephthalate (PET) bottle and pellets | Film kept in 5 ml phosphate buffer and 0.5 mg enzyme solution | 21 days at 55 °C | – | Weight loss | Müller et al. (2005) |
| Polyurethane-contaminated water | *B. pumilus* | Impranil DLN (water-dispersible polyurethane-PUR) | Plate assay-Luria–Bertani media supplemented with PUR (0.3% w/v) | 20 h at 37 °C | Lipase and polyurethanase | Clear zone around colony indicated PUR utilization | Nair and Kumar (2007) |
| Decomposed PUR foam (collected from open-air refuse dump Mexico) | *Alicycliphilus* sp. | Polyester PUR foam | Minimal medium (MM) containing bacterial culture supplemented with hydroform and *N*-methylpyrrolidone (NMP) separately | 5 days at 37 °C | Esterase | Utilized (NMP) present in hydrofoam and loss of polymerizing ability of PUR | Oceguera-Cervantes et al. (2007) |
| Polyethylene polluted soil | *Rhodococcus ruber* | Polystyrene (PS) flakes | Synthetic medium containing polystyrene flakes and bacterial inoculum | 56 days | – | Biofilm formation Flakes weight loss | Mor and Sivan (2008) |
| *Pseudomonas mendocina* | PmC (cutinase) | PET film | PET film kept in 3 mL Tris–HCl buffer (pH 8.0) with 10% glycerol and 10 µM cutinase | 96 h at 30–90 °C and pH 6.5–9.5 | – | Weight loss and production of degradation products (terephthalic acid and ethylene glycol) | Ronkvist et al. (2009) |

(continued)

**Table 11.1** (continued)

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| Composted polyester (Apexa) films | *Thermobifida alba* | Apexa films (4026 and 4027) | LB medium containing the particles of Apexa films and bacterial culture | 14 days at 50 °C | Esterase | Reduction in particle size and production of terephthalic acid (PET monomer) | Hu et al. (2010) |
| Plastic dumping site (Chennai, India) | *B. flexus*<br>*B. subtilis* | Unpretreated and pretreated polypropylene (PP) films | Minimal media with polypropylene films and $10^7$ cfu/ml bacterial inoculum | 365 days at 35–37 °C | *B. flexus*—no enzyme production<br>*B. subtilis*—laccase production | Biofilm formation<br>Film weight loss, changes in structural and surface energy<br>Biosurfactant production by *B. subtilis* | Arkatkar et al. (2010) |
| Expanded polystyrene film buried in soil for 8 months | *Paenibacillus urinalis* NA26, *Bacillus* sp. NB6, *Pseudomonas aeruginosa* NB26 | Polystyrene film | Minimal salt media containing pure polystyrene and bacterial inoculum | 56 days at 30 °C | – | Intermediate products detected in extracellular media of bacterial cultures: 1-phenyl 1,2 ethanediol in *P. urinalis*, *Bacillus* sp. and *P. aeruginosa*<br>Phenylethanol in *P. urinalis*, and *P. aeruginosa* | Naima et al. (2010) |
| *Saccharomonospora viridis* | Cut190 (cutinase) | PET films | PET film incubated in reaction mixture including Tris–HCl buffer (pH 8.2), $CaCl_2$ and 1.1 µM Cut190 enzyme | 50–65 °C | – | Weight loss and terephthalic acid production | Kawai et al. (2014) |

(continued)

**Table 11.1** (continued)

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| *Thermobifida fusca* | TfCut1 and TfCut2 variants (hydrolase) | Low crystalline PET films | PET film placed in a 2 mL reaction tube containing 1.5 mL of Tris–HCl buffer (1 M, pH 8.5), 0.4 nmol $cm^2$ enzyme and 10 mM $MgCl_2$ or $CaCl_2$ | 48 h at 55–65 °C | – | Weight loss | Then et al. (2015) |
| Plastic-eating mealworms (larvae of *Tenebrio molitor*) | *Exiguobacterium* sp. | PS film | Liquid carbon-free basal medium (LCFBM) containing PS film and bacterial culture | 60 days | – | Weight loss, decreased molecular weight and degradation product detected | Yang et al. (2015) |
| Plastic waste disposal sites (Thakurdwara, Aligarh, Kashipur and Moradabad city, North India) | *Acanthopleurobacter pedis*, *Bacillus cereus*, *Pseudomonas otitidis* and *Bacillus aerius* | Polyvinyl chloride (PVC) film | PVC film kept below the soil surface in glass beakers inoculated with bacterial culture consortia | 270 days at 28 ± 2 °C | – | Surface degradation, increased surface roughness, decreased molecular weight and structural changes | Anwar et al. (2016) |
| Poly(ethylene terephthalate (PET) contaminated sediment from PET bottle recycling site (Sakai City, Osaka, Japan) | *Ideonella sakaiensis* | PET film | YVS media supplemented with PET film and bacterial inoculum | 42 days at 30 °C | PETase | Completely degraded | Yoshida et al. (2016) |

(continued)

**Table 11.1** (continued)

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| *Thermobifida fusca* | TfCut2 variants (hydrolase) | Low crystalline PET film | PET film was placed in 1.5 mL reaction tube containing 1.5 mL of HEPES buffer (0.5 M, pH 8), 50 µg purified enzyme and with or without $CaCl_2$ (10 mM) | 48 h at 65–70 °C | – | Weight loss | Then et al. (2016) |
| Plastic dumping yard (Thiruvananthapuram, India) | *Pseudomonas* sp. and *Bacillus* sp. | Brominated high-impact polystyrene (HIPS) E-plastic | Mineral medium broth containing 0.5% E-plastic HIPS film and bacterial culture | 14 days at 30ºC | Depolymerase | Weight loss<br>Structural and morphological changes<br>Intermediate products detected | Mohan et al. (2016) |
| Plastic dumping yard | *Enterobacter* sp., *Citrobacter sedlakii*, *Alcaligenes* sp. and *Brevundimonas diminuta* | HIPS E-plastic | Mineral medium broth containing 0.5% E-plastic HIPS film and bacterial culture ($2 \times 10^8$ cfu/mL) | 30 days at 30 °C | Depolymerase | Weight loss<br>Structural and morphological changes<br>Intermediate products detected | Sekhar et al. (2016) |
| Soil | *Bacillus subtilis* and *Pseudomonas aeruginosa* consortia | Polyester PUR pellets | Minimal salt media with PUR film and bacterial consortia | 30 days at 37 °C | Esterase | Changes in surface features, urethane linkage breakdown, $CO_2$ production and presence of degradation products (1,4-butanediol 8 and adipic acid) | Shah et al. (2016) |

(continued)

**Table 11.1** (continued)

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| Mangrove sediments (Peninsular Malaysia) | *Bacillus cereus* and *Sporosarcina globispora* | Polypropylene (PP) granules | Minimal salt media containing polypropylene granules and bacterial culture | 40 days at 33 °C | – | Weight loss | Helen et al. (2017) |
| Sewage and landfills sites (Karnataka, India) | *Aneurinibacillus aneurinilyticus*, *Brevibacillus agri*, *Brevibacillus* sp. and *Brevibacillus brevis* | PP film and pellets | Minimal media broth containing PP film and bacterial inoculum | 140 days at 50 °C | – | Weight reduction, biofilm formation, structural and variation, decrease in carbon content, appearance of methyl and aldehyde moieties and presence of fatty acid end products | Skariyachan et al. (2018) |
| Municipal compost waste (Okhla, New Delhi, India) | *Bacillus* sp. | Polypropylene blended with poly-L-lactide film | Minimal media broth containing polypropylene blended with poly-L-lactide film and bacterial inoculum | 15 days at 37 °C | – | Surface erosion, biofilm formation, decreased thermal stability, increased no. of carbonyl group | Jain et al. (2018) |
| Wetland water samples (U.P., India) | *Exiguobacterium sibiricum* and *E. undae erium* | PS chips | LCFBM containing PS chips and bacterial inoculum ($10^8$ cfu/mL) | 30 days at 30 °C | – | Biofilm formation, weight reduction and structural and morphological changes | Chauhan et al. (2018) |
| Plastic-polluted coastal area (Arambhada, Gujarat, India) | *Bacillus* sp. | Un-plasticized PVC film | Bushnell–Haas minimal medium containing PVC film and 1% marine bacterial culture | 90 days at 30 °C | – | Weight loss, $CO_2$ production, surface deterioration and structural modification | Kumari et al. (2019) |

(continued)

**Table 11.1** (continued)

| Source | Microorganism/enzyme | Type of plastic polymer | Experimental condition | Incubation time | Enzyme produced by microorganism | Results | References |
|---|---|---|---|---|---|---|---|
| *Tribolium castaneum* larvae | *Acinetobacter* sp. | PS powder | Minimal salt medium containing PS powder and bacterial culture | 60 days at 27 °C | – | Biofilm formation, and deduced mass, molecular weight and thermal stability | Wang et al. (2020) |
| Sediments of the Arabian Sea (3538 m depth, India) | *Bacillus paralicheniformis* | PS film | Minimal salt medium containing PS film and bacterial culture | 60 days at 28 °C | – | Biofilm formation, reduction in weight, thermal stability and change in chemical structural | Kumar et al. (2021) |
| Ocean sediment (Huiquan Bay, Qingdao, China) contaminated with plastic debris | Consortia (*Exiguobacterium* sp., *Halomonas* sp. and *Ochrobactrum*) | PET film | Minimal medium containing PET film and bacterial consortia | 28 days | – | Reduced film relative crystallinity degree and molecular weight | Gao and Sun (2021) |

Some studies have pointed to bacterial association with other living organisms, including insects. The role of gut microbes of plastic-eating insects was reported in biodegradation of polystyrene. A few examples of such microbial taxa are *Exiguobacterium* sp. strain YT2 present in the gut of *Tenebrio molitor* larvae (Yang et al. 2015), *Massilia* sp. FS1903 in *Galleria mellonella* (Jiang et al. 2021), *Acinetobacter* sp. in *Tribolium castaneum* larvae (Wang et al. 2020), *Klebsiella, Pseudomonas* and *Stenotrophomonas* present in *Alphitobius diaperinus* (Cucini et al. 2022). There is plenty of literature on the biodegradation of plastic by bacteria in various conditions, but relatively less research has been done especially on E-plastic. To better understand E-plastic degrading microorganisms and their biodegradation routes, it is essential to examine E-plastic dumpsites in various environments for their isolation and further investigation on biodegradation.

### *11.5.2 Fungal Biodegradation of E-plastic Waste*

Fungal biodegradation involves microbes growing on the plastic surface as substrates, releasing enzymes and deriving nutrition from it accompanied by optimum temperature, moisture and pH; water, carbon dioxide and methane being the end products. The environmental factors are highly impactful in the activation and action of fungal enzymes in degradation of polymers. Biodegradation becomes more effective when it is succeeded by photo-degradation and thermo-oxidative degradation for breakdown of polymers from complex to simple molecules. Some surface-active proteins in the form of hydrophobins are also produced by fungi which help them to attach hyphae to hydrophobic substrates.

Fungi work upon plastics by secreting enzymes, viz. cutinase, lipase, protease, esterase, carboxylesterase, and lignocelluloses. Through the oxidation and hydrolysis processes, hydrophilic layer of high-density polymers de-polymerizes into less complex low-density polymers (Srikanth et al. 2022). The activity of enzymes is highly dependent on the polarity and viscosity of the solvent. It increases with the polarity and decreases with the viscosity in the biodegradation of the high-density polymers (Patel et al. 2013). Fungal biodegradation occurs through intra- and extracellular enzymatic activities. Intra-cellular enzymatic system acts as detoxifying mechanism and helps in fungal adaption (Jeon et al. 2016; Shin et al. 2018) while the extracellular enzymatic system produces hydrolases which is responsible in the breakdown of polysaccharides and lignin (Sanchez 2009). *Cephalosporium* sp. and *Mucor* sp. have shown degrading activity against polystyrene analysed by FTIR, SEM and TGA (Chaudhary and Vijayakumar 2019). Changes in texture of the surface and decrease in thermal stability of polystyrene with 95% weight reduction were observed after eight-week incubation. In an another study, white rot fungi (*Pleurotus ostreatus*, *Phanerochaete chrysosporium* and *Trametes versicolor*) and the brown rot fungi (*Gloeophyllum trabeum*) co-incubated with lignin caused de-polymerization of polystyrene (Krueger et al. 2015). *Geomyces* sp. and *Mortierella* sp. have also been recently reported to be causing degradation of polystyrene (Oviedo-Anchundia et al. 2021). *Aspergillus* sp., *Penicillium* sp. and *Fusarium* sp. have been reported to degraded PET and PS foam (Umamaheswari and Murali 2013). Many fungal species, viz. *Gliocladium roseum*, *Aspergillus* sp., *Emericella* sp., *Fusarium* sp., *Plectosphaerella* sp., *Phoma* sp., *Alternaria* sp., *Penicillium* sp., *Trichoderma* sp., *Gliocladium pannorum*, *Nectria gliocladiodes*, *Penicillium ochrochloron*, *Aureobasidium pullulans*, *Rhodotorula aurantiaca* and *Kluyveromyces* sp., have been reported to degrade PUR (Cosgrove et al. 2007; Lagauskas and Peciulytė 2009). In addition, *Cladosporium pseudocladosporioides*, *C. tenuissimum*, *C. asperulatum*, *C. montecillanum*, *Aspergillus fumigatus* and *Penicillium chrysogenum* have also been found to be involved in PUR degradation (Álvarez-Barragan et al. 2016). Polycarbonate (PC), a thermoplastic polymer containing carbonate groups is used in the manufacture of TV and computer screens, CDs and DVDs, etc. In 2010, Artham and Doble reported *P. chrysosporium* NCIM 1170 strain causing degradation of polycarbonates in a slow process. Other fungal species like *Geotrichum*, *Fusarium*, *Ulocladium*, *Chrysosporium* and *Penicillium* have also been found showing biodegrading properties against polycarbonates (Arefian et al. 2013). Some more investigations on E-plastic degradation by fungal interventions are given in Table 11.2.

#### 11.5.2.1 Role of Fungal Enzymes in Degradation

(a) Cutinases: These enzymes belong to esterase family and widely known by their ability to hydrolyze high-density polymers (Chen et al. 2013). They are found in fungi as α or β hydrolases and carboxylic ester hydrolases. Cutinases were found to be produced by *Fusarium solani*, *Penicillium citrinum*, *Aspergillus oryzae* and *Humicola insolens* (Kolattukudy et al. 1981; Alisch-Mark et al. 2006; Liebminger et al. 2007; Munari 2019). A 97% weight loss of low crystalline PET film by *Fusarium solani* pisi cutinase (FsC) and *Humicola insolens* cutinase (HiC) within 96 h had been earlier reported by Ronqvist et al. (2009).
(b) Lipases: Being a member of esterase family, these are responsible for the hydrolysis of lipids. Some well-known fungal species, e.g., *Rhizopus delemar*, *Candida antarctica*, *Candida rugosa* and *Thermomyces lanuginosus*, produce lipases and hence act upon plastic degradation. *C. rugosa* had been found to degrading butylene succinate-cohexamethylene succinate complex polymer (Pereira et al. 2001) while *R. delemar* was involved in the degradation of 53% of polyester type-polyurethanes (ES-PU) film within 24 h (Tokiwa and Calabia 2009). *C. antarctica* produces lipase B which have been to be effective in hydroxylation of PET to thermoplastic polyamide elastomer (TPA) (Carniel et al. 2017).
(c) Esterases: These are hydrolase enzymes which break up esters into alcohols and acids by the addition of water molecules and are involved in the degradation of low molecular weight plastics obtained from renewable resources. Plant pathogenic fungi *Purpureocillium lilacinum* and *Curvularia senegalensis* produce esterases that lead to degradation of butylene succinate-co-adipate complex to simpler polyurethane (Yamamoto-Tamura et al. 2015). Similarly,

**Table 11.2** Fungal and/or fungal enzyme associated with different plastic polymer degradation

| Fungal sp. | Source of isolation | Type of e-plastic | Incubation time (days) | Loss (%) | References |
|---|---|---|---|---|---|
| *Chaetomium globosum* | Soil | Polyether PUR film | 21 | – | Darby and Kaplan (1968) |
| *Aspergillus niger*; *Cladosporium herbarum* | Natural humid conditions | Polyether PUR foam | 70 | – | Filip (1979) |
| Lipase enzyme (*Candida rugosa*) | Sigma (St. Louis, MO) | Butylene succinate-cohexamethylene succinate complex polymer | – | 94 | Pereira et al. (2001) |
| *Alternaria* spp.; *Aspergillus* spp.; *Aureobasidium pullulans*; *Emericella* spp.; *Fusarium* spp.; *Gliocladium pannorum*; *G. roseum*; *Kluyveromyces* sp.; *Nectria gliocladiodes*; *Penicillium ochrochloron*; *Phoma* spp.; *Plectosphaerella* spp.; *Rhodotorula aurantiaca*; *Trichoderma* spp. | Soil | Polyurethane | 150 | 95 | Cosgrove et al. (2007) and Lagauskas and Peciulytė (2009) |
| HiC; PsC enzymes (*Humicola insolens*; *Fusarium solani*) | Novozymes (Bagsvaerd, Denmark), DNA 2.0 (Menlo Park, CA) | Low-crystallinity PET film | 6 | 97 | Ronkvist et al. (2009) |
| *Rhizopus delemar* | Soil | Polyester type-polyurethanes (ES-PU) film | 1 | 53 | Tokiwa and Calabia (2009) |
| *Alternaria* sp. PURDK2 | Environment | Polyether PUR film | 70 | 27.5 | Matsumiya et al. (2010) |
| *Engyodontium album* MTP091; *Penicillium* sp.; *Phanerochaete chrysosporium* NCIM 1170 | Plastic dumpsite | Polycarbonate | 120–360 | 27–40 | Artham and Doble (2010) |
| *Aspergillus flavus* | Soil | Polyester PUR film | 30 | 60.6 | Mathur and Prasad (2012) |

(continued)

**Table 11.2** (continued)

| Fungal sp. | Source of isolation | Type of e-plastic | Incubation time (days) | Loss (%) | References |
|---|---|---|---|---|---|
| *Aspergillus* sp.; *Penicillium* sp.; *Fusarium* sp. | Soil, cow dung and sewage | Polyethylene terephthalate and polystyrene foam | 30 | – | Umamaheswari and Murali (2013) |
| *Chrysosporium* sp.; *Fusarium* sp.; *Geotrichum* sp.; *Penicillium* sp.; *Ulocladium* sp. | Garden soil and garbage leachate | Polycarbonate | 15 | – | Arefian et al. (2013) |
| Esterases enzymes (*Purpureocillium lilacinum*; *Curvularia senegalensis*) | Soil from cultivated fields | Butylene succinate-co-adipate complex | 14 | – | Yamamoto-Tamura et al. (2015) |
| *Gloeophyllum trabeum*; *Pleurotus ostreatus*; *Phanerochaete chrysosporium*; *Trametes versicolor* | German collection of microorganisms and cell cultures (DSMZ, Braunschweig, Germany) | Polystyrene | 20 | 8.3–63.5 | Krueger et al. (2015) |
| Lipase B enzyme (*Candida antarctica*) | Novozymes | Polyethylene terephthalate (PET) | 28 | 0.52 | Carniel et al. (2017) |
| *Alternaria tenuissima* | Infected leaves | Polyether PUR film | 60 | | Oprea et al. (2018) |
| *Penicillium* sp. | PUR wastes | Polyester/polyether PUR film | 60 | 8.9 | Magnin et al. (2019) |
| *Laccase* enzyme (*Bjerkandera adusta* TBB-03) | Ohgap Mountains, North Chungcheong Province, South Korea | HDPE | 90 | – | Bo et al. (2019) |
| *Cephalosporium* sp.; *Mucor* sp. | National Collection of Industrial Microorganism (NCIM), NCL, Pune, India | Polystyrene | 56 | 1.81–2.17 | Chaudhary and Vijayakumar (2019) |
| *Geomyces* sp.; *Mortierella* sp. | Antarctic soils | Polystyrene | 90 | 6.82–8.39 | Oviedo-Anchundia et al. (2021) |

*Aspergillus flavus*, *Aspergillus tubingensis*, *Xepiculopsis graminea* and *Penicillium griseofulvum* are also reported to be responsible for the degradation of different forms of complex polymers into simpler ones (Khan et al. 2017; Brunner et al. 2018).

(d) Proteases: Proteases cleave down long peptide chains to short ones by the process of proteolysis. A number of fungal genera are known to degrade high-density polymers via proteolytic degradation, e.g., *Alternaria*, *Aspergillus*, *Fusarium*, *Humicola*, *Mucor*, *Penicillium*, *Pestalotiopsis*, *Phanerochaete*, *Purpureocillium*, *Rhizopus*, *Thermoascus*, *Thermomyces* and *Trichoderma* (Loredo-Trevino et al. 2011; Souza et al. 2015).

(e) Laccases: These are multi-copper oxidase enzymes involved in the oxidation of phenolic compounds and lignin by utilizing molecular oxygen as co-substrate and producing water as by-product. *Bjerkandera adusta* TBB-03 have been reported for the degradation of HDPE by laccase production (Bo et al. 2019). *Cochliobolus* sp., *Penicillium*-derived laccase, *P. ostreatus*, *T. versicolor* and *Trametes pubescens* had been found to be actively involved in the Polyvinyl chloride degradation (Osma et al. 2010; Sumathi et al. 2016).

(f) Peroxidases: These enzymes are member of oxidoreductase family which catalyzes oxidation–reduction reactions to form oxidized polymerized compounds by the action of free radicals. Often known as catalases, these enzymes are considered to be quite effective in converting lignin. White-rot fungi (*P. chrysosporium* and *T. versicolor*) and other ascomycetous fungi (*Fusarium graminearum*, *A. flavus*, *Aspergillus niger*) are found to be rich in lignin peroxidases (LiP), manganese peroxidases (MnP) and versatile peroxidases (VP) and have shown degradation of high-density polyethylene and lignin at pH 9–11 (Hofrichter and Ullrich 2006; Ganesh et al. 2017).

## 11.6 Conclusion

In the past few years, the production of plastics has increased at a significantly faster rate as compared to other products. There has also been a remarkable increase in their use in electronics owing to the exponentially increasing demand of these goods. Due to the harmful consequences of thermal and chemical degradation, environmentally friendly biodegradation of E-plastics has become critically important. A variety of microbes, predominantly bacteria and fungi collected from the diverse ecosystems, found capable of releasing enzymes which can break down plastics. The macromolecular aggregation structures of plastics, such as the crystalline structures and cross-linking networks, make it difficult to improve the efficiency of enzymatic breakdown. Therefore, it would be more exciting to develop the paths which create microbial cell factories using synthetic biology that could depolymerize them for the production of valuable chemical compounds (Blank et al. 2020). Some reports also highlighted the microbial metabolic pathways for plastic de-polymerization products and efforts now being made to use such products as feedstocks for microbial synthesis of high-value chemicals. An effort to develop technology that emphasizes both the biological upcycling–recycling of plastic wastes and offer its commercially viable solutions is needed.

## References


Ahmed T, Shahid M, Azeem F et al (2018) Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ Sci Pollut Res 25(8):7287–7298

Alaee M, Arias P, Sjodin A, Bergman A (2003) An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environ Int 29(6):683–689

Alisch-Mark M, Herrmann A, Zimmermann W (2006) Increase of the hydrophilicity of polyethylene terephthalate fibers by hydrolases from *Thermomonospora fusca* and *Fusarium solani* f. sp. *pisi*. Biotechnol Lett 28:681–685

Álvarez-Barragan J, Dominguez-Malfavon L, Vargas-Suarez M et al (2016) Biodegradative activities of selected environmental fungi on a polyester polyurethane varnish and polyether polyurethane foams. Appl Environ Microbiol 82:5225–5235

Anwar MS, Kapri A, Chaudhry V et al (2016) Response of indigenously developed bacterial consortia in progressive degradation of polyvinyl chloride. Protoplasma 253(4):1023–1032

Arefian M, Zia M, Tahmourespour A et al (2013) Polycarbonate biodegradation by isolated molds using clear-zone and atomic force microscopic methods. Int J Environ Sci Technol 10:1319–1324

Arkatkar A, Juwarkar AA, Bhaduri S et al (2010) Growth of *Pseudomonas* and *Bacillus* biofilms on pretreated polypropylene surface. Int Biodeterior Biodegrad 64(6):530–536

Artham T, Doble M (2010) Biodegradation of physicochemically treated polycarbonate by fungi. Biomacromol 11(1):20–28

Atanasova N, Stoitsova S, Paunova-Krasteva T et al (2021) Plastic degradation by extremophilic bacteria. Int J Mol Sci 22(11):5610

Bhaskar T, Matsui T, Uddin MA et al (2003) Effect of $Sb_2O_3$ in brominated heating impact polystyrene (HIPS-Br) on thermal degradation and debromination by iron oxide carbon composite catalyst (Fe-C). Appl Catal B 43(3):229–241

Blank LM, Narancic T, Mampel J, Tiso T, O'Connor K (2020) Biotechnological upcycling of plastic waste and other non-conventional feedstocks in a circular economy. Current Opinion in Biotech 62:212–219. https://doi.org/10.1016/j.copbio.2019.11.011

Bo RK, Soo BK, Hyun AS et al (2019) Accelerating the biodegradation of high-density polyethylene (HDPE) using *Bjerkandera adusta* TBB-03 and lignocellulose substrates. Microorganisms 7:304

Brunner I, Fischer M, Ruthi J, Stierli B (2018) Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. PLoS ONE 13(8):1–14

Buragohain P, Nath V, Sharma HK (2020) Microbial degradation of waste: a review. Curr Trends Pharm Res 7

Carniel A, Valoni E, Nicomedes J et al (2017) Lipase from *Candida antarctica* (CALB) and cutinase from *Humicola insolens* act synergistically for PET hydrolysis to terephthalic acid. Process Biochem 59:84–90

Chai B, Li X, Liu H et al (2020) Bacterial communities on soil microplastic at Guiyu, an E-waste dismantling zone of China. Ecotoxicol Environ Saf 195:110521

Chaudhary AK, Vijayakumar RP (2019) Studies on biological degradation of polystyrene by pure fungal cultures. Environ Dev Sustain 22:4495–4508

Chauhan D, Agrawal G, Deshmukh S et al (2018) Biofilm formation by *Exiguobacterium* sp. DR11 and DR14 alter polystyrene surface properties and initiate biodegradation. RSC Adv 8(66):37590–37599

Chen S, Su L, Chen J et al (2013) Cutinase: characteristics, preparation and application. Biotechnol Adv 31:1754–1767

China Plastics Industry (2017) Data from: In 2017, the total output of China's plastic products was 751.155 million tons, an increase of 3.4% year-on-year (EB/OL). Available at: http://www.iplast.cn/shownews.asp?id=6625. Accessed 21 Aug 2022

Cosgrove L, McGeechan PL, Robson GD et al (2007) Fungal communities associated with degradation of polyester polyurethane in soil. Appl Environ Microbiol 73:5817–5824

Cucini C, Funari R, Mercati D et al (2022) Polystyrene shaping effect on the enriched bacterial community from the plastic-eating *Alphitobius diaperinus* (Insecta: Coleoptera). Symbiosis 1–9

Darby RT, Kaplan AM (1968) Fungal susceptibility of polyurethanes. Appl Microbiol 16:900–905

Filip Z (1979) Polyurethane as the sole nutrient source for *Aspergillus niger* and *Cladosporium herbarum.* Appl Microbiol Biotechnol 7:277–280

Gama N, Ferreira A, Barros-Timmons A (2018) Polyurethane foams: past, present, and future. Materials 11(10):1841

Ganesh P, Dineshraj D, Yoganathan K (2017) Production and screening of depolymerising enzymes by potential bacteria and fungi isolated from plastic waste dump yard sites. Int J Appl Res 3(3):693–695

Gao R, Sun C (2021) A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. J Hazard Mater 416:125928

Garcia JM, Robertson ML (2017) The future of plastics recycling. Science 358:870–872

Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3(7):e1700782

Ghosh S, Qureshi A, Purohit HJ (2019) Microbial degradation of plastics: biofilms and degradation pathways. In: Kumar V, Kumar R, Singh J, Kumar P (eds) Contaminants in agriculture and environment: health risks and remediation, vol 1. Agro Environ Media, Publication Cell of AESA, Agriculture and Environmental Science Academy, Haridwar, India, pp 184–199

Helen AS, Uche EC, Hamid FS (2017) Screening for polypropylene degradation potential of bacteria isolated from mangrove ecosystems in Peninsular Malaysia. Int J Biosci Biochem Bioinform 7:245–251

Hofrichter M, Ullrich R (2006) Heme-thiolate haloperoxidases: versatile biocatalysts with biotechnological and environmental significance. Appl Microbiol Biotechnol 71(3):276–288

Hopewell J, Dvorak R, Kosior E (2009) Plastics recycling: challenges and opportunities. Philos Trans Roy Soc B Biol Sci 364(1526):2115–2126

Hu X, Thumarat U, Zhang X et al (2010) Diversity of polyester-degrading bacteria in compost and molecular analysis of a thermoactive esterase from *Thermobifida alba* AHK119. Appl Microbiol Biotechnol 87(2):771–779

IARC (International Agency for Research on Cancer) (1989) Antimony trioxide and antimony trisulfide. Internet address: http://www.inchem.org/documents/iarc/vol47/47-11.html.

Jain K, Bhunia H, Sudhakara Reddy M (2018) Degradation of polypropylene–poly-L-lactide blend by bacteria isolated from compost. Bioremediat J 22(3–4):73–90

Jambeck JR, Geyer R, Wilcox C, Siegler TR et al (2015) Marine pollution. Plastic waste inputs from land into the ocean. Science 347:768–771

Jeon H, Durairaj P, Lee D et al (2016) Improved NADPH regeneration for fungal cytochrome P450 monooxygenase by co-expressing bacterial glucose dehydrogenase in resting-cell biotransformation of recombinant yeast. J Microbiol Biotechnol 26:2076–2086

Jiang, S, Su T, Zhao J et al (2021) Isolation, identification, and characterization of polystyrene-degrading bacteria from the gut of *Galleria mellonella* (Lepidoptera: Pyralidae) larvae. Front Bioeng Biotechnol 746

Kale SK, Deshmukh AG, Dudhare MS, Patil et al (2015) Microbial degradation of plastic: a review. J Biochem Technol 6(2):952–961

Kaushal J, Khatri M, Arya SK (2021) Recent insight into enzymatic degradation of plastics prevalent in the environment: a mini-review. Clean Eng Technol 2:100083

Kawai F, Oda M, Tamashiro T et al (2014) A novel $Ca^{2+}$-activated, thermostabilized polyesterase capable of hydrolyzing polyethylene terephthalate from *Saccharomonospora viridis* AHK190. Appl Microbiol Biotechnol 98(24):10053–10064

Khan S, Nadir S, Shah ZU et al (2017) Biodegradation of polyester polyurethane by *Aspergillus tubingensis*. Environ Pollut 225:469–480

Kolattukudy PE, Purdy RE, Maiti IB (1981) Cutinases from fungi and pollen. In: Lowenstein JM (ed) Methods in enzymology. Academic, New York, p 652

Kotova IB, Taktarova YV, Tsavkelova EA et al (2021) Microbial degradation of plastics and approaches to make it more efficient. Microbiology 90(6):671–701

Krueger MC, Hofmann U, Moeder M et al (2015) Potential of wood rotting fungi to attack polystyrene sulfonate and its depolymerisation by *Gloeophyllum trabeum* via hydroquinone-driven Fenton chemistry. PLoS ONE 10:e0131773

Kumar AG, Hinduja M, Sujitha K et al (2021) Biodegradation of polystyrene by deep-sea *Bacillus paralicheniformis* G1 and genome analysis. Sci Total Environ 774:145002

Kumari A, Chaudhary DR, Jha B (2019) Destabilization of polyethylene and polyvinylchloride structure by marine bacterial strain. Environ Sci Pollut Res 26(2):1507–1516

Lagauskas LL, Peciulytė D (2009) Micromycetes as deterioration agents of polymeric materials. Int Biodeterior Biodegrad 52:233–242

Lakshmi R, Nagan S (2010) Studies on concrete containing E plastic waste. Int J Environ Sci 1(3):270

Liebminger S, Eberl A, Sousa F et al (2007) Hydrolysis of PET and bis-(benzoyloxyethyl) terephthalate with a new polyesterase from *Penicillium citrinum.* Biocatal Biotransform 25:171–177

Lonnstedt OM, Eklov P (2016) Environmentally relevant concentrations of microplastic particles influence larval fish ecology. Science 352(6290):1213–1216

Loredo-Trevino A, Garcia G, Velasco-Tellez A (2011) Polyurethane foam as substrate for fungal strains. Adv Biosci Biotechnol 2(2):52–58

Magnin A, Hoornaert L, Pollet E et al (2019) Isolation and characterization of different promising fungi for biological waste management of polyurethanes. Microb Biotechnol 12:544–555

Mathur G, Prasad R (2012) Degradation of polyurethane by *Aspergillus flavus* (ITCC 6051) isolated from soil. Appl Biochem Biotechnol 167:1595–1602

Matsumiya Y, Murata N, Tanabe E et al (2010) Isolation and characterization of an ether-type polyurethane-degrading microorganism and analysis of degradation mechanism by *Alternaria* sp. J Appl Microbiol 108:1946–1953

Mohan AJ, Sekhar VC, Bhaskar T et al (2016) Microbial assisted High Impact Polystyrene (HIPS) degradation. Biores Technol 213:204–207

Mohanan N, Montazer Z, Sharma PK, Levin DB (2020) Microbial and enzymatic degradation of synthetic plastics. Front Microbiol 11:580709

Mor R, Sivan A (2008) Biofilm formation and partial biodegradation of polystyrene by the actinomycete *Rhodococcus ruber*. Biodegradation 19(6):851–858

Müller RJ, Schrader H, Profe J et al (2005) Enzymatic degradation of poly(ethylene terephthalate): rapid hydrolyse using a hydrolase from *T. fusca.* Macromol Rapid Commun 26(17):1400–1405

Munari (2019) Enzymatic hydrolysis of poly(1,4-butylene 2,5-thiophenedicarboxylate) (PBTF) and poly(1,4-butylene 2,5-furandicarboxylate) (PBF) films: a comparison of mechanisms. Environ Int 130:104852

Naima A, Safia A, Bashir A et al (2010) Isolation and identification of polystyrene biodegrading bacteria from soil. Afr J Microbiol Res 4(14):1537–1541

Nair S, Kumar P (2007) Molecular characterization of a lipase-producing *Bacillus pumilus* strain (NMSN-1d) utilizing colloidal water-dispersible polyurethane. World J Microbiol Biotechnol 23(10):1441–1449

Oceguera-Cervantes A, Carrillo-García A, López N et al (2007) Characterization of the polyurethanolytic activity of two *Alicycliphilus* sp. strains able to degrade polyurethane and N-methylpyrrolidone. Appl Environ Microbiol 73(19):6214–6223

OEHHA (1997) Antimony in drinking water. Office of Environmental Health Hazard Assessment, California Environmental Protection Agency

Oprea S, Potolinca VO, Gradinariu P et al (2018) Biodegradation of pyridine-based polyether polyurethanes by the *Alternaria tenuissima* fungus. J Appl Polym Sci 135:46096

Osma JF, Toca-Herrera JL, Rodriguez-Couto S (2010) Uses of laccases in the food industry. Enzyme Res 2010:918761

Oviedo-Anchundia R, del Castillo DS, Naranjo-Moran J et al (2021) Analysis of the degradation of polyethylene, polystyrene and polyurethane mediated by three filamentous fungi isolated from the Antarctica. Afr J Biotechnol 20(2):66–76

Patel C, Yadav S, Rahi S et al (2013) Studies on biodiversity of fungal endophytes of indigenous monocotaceous and dicotaceous plants and evaluation of their enzymatic potentialities. Int J Sci Res Publ 3:1–5

Pereira EB, De Castro HF, De Moraes FF et al (2001) Kinetic studies of lipase from *Candida rugosa*. Appl Biochem Biotechnol 91:739

Plastics Europe (2018) Data from: Plastics—the facts 2018: an analysis of European plastics production, demand and waste data (EB/OL). Available at: http://www.plasticseurope.org. Accessed 21 Aug 2022

Rahimi A, García JM (2017) Chemical recycling of waste plastics for new materials production. Nat Rev Chem 1(6):1–1

Ronkvist AM, Xie W, Lu W et al (2009) Cutinase-catalyzed hydrolysis of poly(ethylene terephthalate). Macromolecules 42(14):5128–5138

Ronqvist AM, Xie W, Lu W et al (2009) Cutinase-catalyzed hydrolysis of poly (ethyleneterephthalate). Macromolecules 42:5128–5138

Rowe L, Howard GT (2002) Growth of *Bacillus subtilis* on polyurethane and the purification and characterization of a polyurethanase-lipase enzyme. Int Bio Deterior Biodegrad 50(1):33–40

Ru J, Huo Y, Yang Y (2020) Microbial degradation and valorization of plastic wastes. Front Microbiol 11:442

Rutkowska M, Heimowska A, Krasowska K et al (2002) Biodegradability of polyethylene starch blends in sea water. Pol J Environ Stud 11(3):267–272

Salam M, Varma A (2019) Bacterial community structure in soils contaminated with electronic waste pollutants from Delhi NCR, India. Electron J Biotechnol 41:72–80

Sanchez C (2009) Lignocellulosic residues: biodegradation and bioconversion by fungi. Biotechnol Adv 27:85–194

Santo M, Weitsman R, Sivan A (2013) The role of the copper-binding enzyme–laccase in the biodegradation of polyethylene by the actinomycete *Rhodococcus ruber*. Int Biodeterior Biodegrad 208:1–7

Sekhar VC, Nampoothiri KM, Mohan AJ et al (2016) Microbial degradation of high impact polystyrene (HIPS), an e-plastic with decabromodiphenyl oxide and antimony trioxide. J Hazard Mater 318:347–354

Shah Z, Gulzar M, Hasan F et al (2016) Degradation of polyester polyurethane by an indigenously developed consortium of *Pseudomonas* and *Bacillus* species isolated from soil. Polym Degrad Stab 134:349–356

Shin J, Kim JE, Lee YW et al (2018) Fungal cytochrome P450s and the P450 complement (CYPome) of *Fusarium graminearum*. Toxins 10:112

Skariyachan S, Patil AA, Shankar A et al (2018) Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of *Brevibacillus* sps. and *Aneurinibacillus* sp. screened from waste management landfills and sewage treatment plants. Polym Degrad Stab 149:52–68

Smith JG (2011) Organic chemistry, 3rd edn. McGraw-Hill, New York, p 1169

Souza PMD, Bittencourt MLDA, Caprara CC et al (2015) A biotechnology perspective of fungal proteases. Braz J Microbiol 46(2):337–346
Srikanth M, Sandeep TSRS, Sucharitha K et al (2022) Biodegradation of plastic polymers by fungi: a brief review. Biores Bioprocess 9:42
Sumathi T, Viswanath B, Lakshmi AS et al (2016) Production of laccase by *Cochliobolus* sp. isolated from plastic dumped soils and their ability to degrade low molecular weight PVC. Biochem Res Int 8:1–10
Then J, Wei R, Oeser T et al (2015) $Ca^{2+}$ and $Mg^{2+}$ binding site engineering increases the degradation of polyethylene terephthalate films by polyester hydrolases from *Thermobifida fusca*. Biotechnol J 10(4):592–598
Then J, Wei R, Oeser T et al (2016) A disulfide bridge in the calcium binding site of a polyester hydrolase increases its thermal stability and activity against polyethylene terephthalate. FEBS Open Bio 6(5):425–432
Tokiwa Y, Calabia BP (2009) Biodegradability of plastics. Int J Mol Sci 10:3722–3742
Umamaheswari S, Murali M (2013) FTIR spectroscopic study of fungal degradation of poly(ethylene terephthalate) and polystyrene foam. Chem Eng 64:19159–19164
Wang Z, Xin X, Shi X et al (2020) A polystyrene-degrading *Acinetobacter bacterium* isolated from the larvae of *Tribolium castaneum*. Sci Total Environ 726:138564
Wei R, Zimmermann W (2017) Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? Microb Biotechnol 10(6):1308–1322
Wilhelm R (2008) Resin identification codes—new ASTM standard based on society of the plastics industry code will facilitate recycling. Standardization News ASTM International. Archived from the original on 25 Nov 2020. Retrieved 21 Jan 2016
Webb H, Arnott J, Crawford R, Ivanova E (2013) Plastic degradation and its environmental implications with special reference to poly(ethylene terephthalate). Polymers 5:1–18. https://doi.org/10.1016/j.biortech.2016.03.021
Wright SL, Ulke J, Font A, Chan KLA, Kelly FJ (2020) Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environ Int 136:105411. https://doi.org/10.1016/j.envint.2019.105411
Yamamoto-Tamura K, Hiradate S, Watanabe T et al (2015) Contribution of soil esterase to biodegradation of aliphatic polyester agricultural mulch film in cultivated soils. AMB Express 5:10
Yang Y, Yang J, Wu WM et al (2015) Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 2. Role of gut microorganisms. Environ Sci Technol 49(20):12087–12093
Yoshida S, Hiraga K, Takehana T et al (2016) A bacterium that degrades and assimilates poly(ethylene terephthalate). Science 351(6278):1196–1199
Zeenat EA, Bukhari DA, Shamim S et al (2021) Plastics degradation by microbes: a sustainable approach. J King Saud Univ Sci 33(6):1015388

# Chapter 12
# Metal Bioleaching from E-waste Using Fungal Communities

**Varun Dhiman**

**Abstract** This article is intent on the bioleaching of metals from e-waste using fungal communities. These communities are employed to retrieve valuable HMs present in the e-waste. The key components of e-waste cause an enormous level of environmental pollution. The toxic metals impose serious health concerns on the residing flora and fauna of the earth. The conventional bioleaching methods such as chemical bioleaching using solvents and different chemicals result in the generation of secondary waste. However, microbial bioleaching is an alternative to chemical bioleaching. But, the use of bacteria for bioleaching purposes has its limitations too in their reaction cycle and leaching efficiency. The literature on the use of fungal species for e-waste bioleaching purposes is very limited. Therefore, the present article provides an overview of the fungal bioleaching mechanism from e-waste.

**Keywords** Bioleaching · Electronic waste · Environmental pollution · Fungal communities

## 12.1 Introduction

Numerous fungal communities are heterotrophs in nature (Naranjo-Ortiz and Gabaldón 2019). They are highly capable of metal bioleaching using their organic acids. Various metal bioleaching mechanisms involve chelate complexation, redoxolysis, and bioaccumulation processes (Dusengemungu et al. 2021). In the recent past, e-waste (involving electronic and electric equipment) generates an enormous amount, and its management becomes a challenge to the scientific community. New technologies for transmitting information and advanced way of lifestyle add a huge amount of waste to the environment causing a wide range of environmental issues. From the total waste produced, e-waste accounted for 53.6 million tons with a total increase of 21% in gross in the year 2019. Asia tops the e-waste generator with 46.4% followed by the USA (24.4%), Europe (22.4%), Africa (5.4%), and Oceania (1.3%)

V. Dhiman (✉)
Department of Environmental Sciences, Central University of Himachal Pradesh, Dharamshala 176215, India
e-mail: varundhiman79@gmail.com



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_12

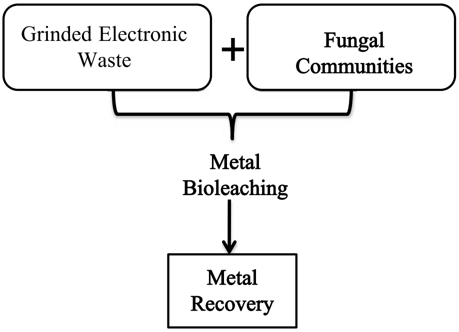



**Fig. 12.1** Fungal bioleaching of grinded electronic waste for metal recovery

(Nithya et al. 2021). The unscientific methods of e-waste recycling such as incineration, metal acid stirring, open burning, and acid baths cause a higher risk of environmental impacts including human health. More efficient, bio-friendly, and economic methods are the need of the hour to deal with this problem. Hence, the scientific community works on and encourages the use of environmentally friendly techniques to deal with the persisting problem of e-waste and its management. Literature review reports the use of different microorganisms for successful e-waste bioleaching. Apart from them, several kinds of research suggested the use of numerous fungal communities for e-waste bioleaching. Filamentous fungi, *Aspergillus*, *Penicillium simplicissimum*, and *Penicillium chrysogenum* are some of the known fungal strains used for metal bioleaching filamentous fungi for e-waste management (Dusengemungu et al. 2021). Their higher tolerance power and adaptability prove advantageous in metal bioleaching (Fig. 12.1). Further, the cell membrane structure of fungi makes them suitable for the metal bioleaching process.

Fungal communities for bioleaching purpose are more economical and environment friendly rather than traditional metal extraction processes. Due to its higher employability in metal bioleaching, it is important to further explore and highlight the concept of fungal bioleaching for metal recovery from e-waste. Therefore, the current chapter provides an important overview of metal bioleaching of e-waste using fungal communities.

## 12.2 E-waste Sources and Composition

There is a huge variety of electronic waste components including thousands of toxic and nontoxic substances. The existing models of electric and electronic equipment are quickly replaced due to the onset of rapid technological advancements. The non-functioning and redundant equipment generate a constant source

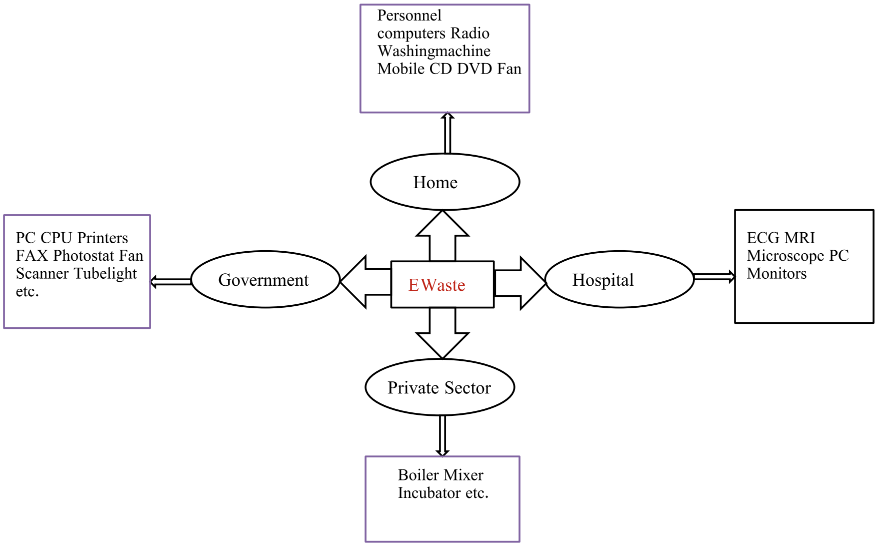



**Fig. 12.2** Composition and major sources of e-waste (Chakraborty et al. 2022)

of electronic waste. Appliances such as refrigerators, washing machines, personnel computers, vacuum cleaners, bulbs, and heaters are one of the main sources of e-waste (Fig. 12.2). Different categories of e-waste have been identified. They are described in Table 12.1.

## 12.3 Influencing Factors for Metal Bioleaching

Industrial-scale electronic waste management systems are often driven by economic feasibility while several factors influence the metal bioleaching (Fig. 12.3) from e-waste (Ji et al. 2022). Some of these are as follows.

### *12.3.1 pH*

Fungal bioleaching is highly influenced by varied pH ranges which ultimately affect the process mechanism (Dusengemungu et al. 2021). Different fungal communities prefer alkaline and acidic pH conditions (Zhang et al. 2016).

**Table 12.1** E-waste sources representing their category and heavy metals content

| Sources | Category | Heavy metals content (%) |
|---|---|---|
| Refrigerators, washing machine, dishwasher | LHA | Al: 1.3–2.0<br>Sn: 1.6–2.0<br>Ag: 0.0042–0.045<br>Pb: 0.021–2.5<br>Cd: 0.036–1.9 |
| Vacuum cleaners, kitchen machines | SHA | Cu: 18.8<br>Pb: 4.79<br>Al: 0.912<br>Cr, Cd, Ni: 0.0051–0.0179 |
| IT and telecommunication | Mobile, telephones, printers, etc. | Cu: 7.0–30<br>Al: 1.41–14.17<br>Pb: 1.20–6.29<br>Sn: 1.0–3.15 |
| Stereo and TV | Consumer equipment | Cu: 10<br>Al: 10<br>Pb: 1.0<br>Ni: 0.3 |
| Toys, video games, sport computers | Leisure and sports equipment | Pb: 31–34<br>Cd: 30–38<br>Hg: 4.0–16<br>Cu: 0.014<br>Sn: 0.0039 |

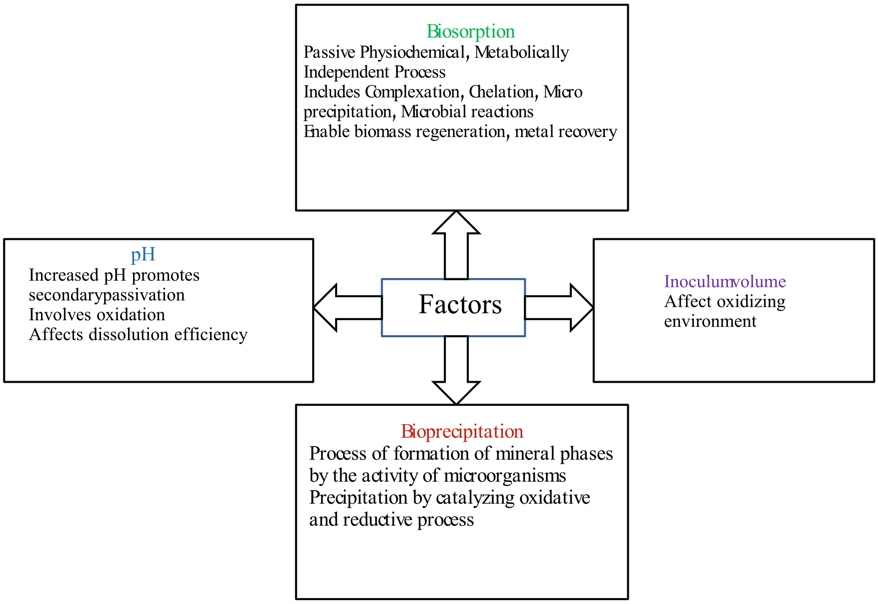



**Fig. 12.3** Influencing factors for metal bioleaching (Ji et al. 2022)

### *12.3.2 Temperature*

Different temperature scales have a different effects on fungal growth and their associated bioleaching mechanism. For example, *Aspergillus flavus* and *Aspergillus niger* prefer 22 ℃ and 37 ℃ for copper (II) and lead (II) bioleaching in a medium, respectively (Dusengemungu et al. 2021). Broad transformation of Mn nodules has been observed using *A. niger* at these temperature scales (Ferrier et al. 2019).

### *12.3.3 Fungal Consortium*

The fungal consortium also affects the bioleaching efficiency. It has been observed that the fungal consortium improves nickel extraction (Talukdar et al. 2020). Further proves beneficial in extracting numerous metals from low-grade e-waste. Research is highly recommended to find out the best mixed fungal cultures for efficient metal recovery (Dusengemungu et al. 2021).

### *12.3.4 Biosorption*

The metal recovery from e-waste is remediated using the biosorption mechanism of fungal communities. Fungus *Aspergillus carbonarius* is one of the suitable bio-adsorbents for noxious metal recovery from e-waste (Lakshmi et al. 2020). It effectively adsorbs hexavalent chromium from the medium. The process of biosorption is highly pH dependent as it directly influences the metal chemistry and surface charge of the adsorbent (Liu et al. 2011).

### *12.3.5 Bioprecipitation*

Phosphatase-mediated metal precipitation seems to be one of the common methods of metal bioleaching (Liang et al. 2016).

## 12.4 Common Metal Solubilization Reaction Mechanisms

There are numerous metal solubilization reaction mechanisms (Table 12.2) which are discussed below.

**Table 12.2** Metal solubilization reaction mechanisms

| Leaching process | Reaction mechanism | References |
|---|---|---|
| Halogen leaching | $2Au + I_3^- + I \rightarrow 2(AuI_2)^-$<br>$2Au + 3I_3^- \rightarrow 2(AuI_4)^- + I^-$<br>$Au + 2Br^- \rightarrow AuBr_2^- + e^-$<br>$Au + 4Br^- \rightarrow AuBr_4^- + 3e^-$ | (Cui and Anderson 2020) |
| Ferric ion + thiourea leaching | $Au + 2SC(NH_2)_2 + Fe^{3+} \rightarrow AuISC(NH_2)_2^+ + Fe^{2+}$<br>$Ag + 3SC(NH_2)_2 + Fe^{3+} \rightarrow Ag(SC(NH_2)_2)_3^+ + Fe^{2+}$ | (Jing-ying et al. 2012) |
| Thiosulfate leaching | $Au + 5S_2O_3^{2-} + Cu(NH_3)_4^{2+} \leftrightarrow Au(S_2O_3)_2^{3-} + Cu(S_2O_3)_3^{5-} + 4NH_3$<br>$Ag + 5S_2O_3^{2-} + Cu(NH_3)_4^{2+} \leftrightarrow Ag(S_2O_3)_2^{3-} + Cu(S_2O_3)_3^{5-}$ | (Oh et al. 2003) |
| Cyanide leaching | $4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4Au(CN)_2^- + 4OH^-$<br>$4Ag + 8CN^- + O_2 + 2H_2O \rightarrow 4Ag(CN)_2^- + 4OH^-$ | (Montero et al. 2012) |
| Ferric leaching | $2Fe^{3+} + M \rightarrow 2Fe^{2+} + M^{2+}$<br>M = metal | (Karwowska et al. 2014) |

### 12.4.1 Halogen Leaching

It involves the use of halogens as lixiviants for the bioleaching of Pt, Au, and Ag. As compared to cyanides, halogens provide environmentally friendly bioleaching mechanisms. They are relatively safe with higher level of chemical stability (Akcil et al. 2015).

### 12.4.2 Thiourea Leaching

Precious metals like Au can be bioleached using microbiologically mediated thiourea leaching process. This mechanism lowers the consumption of reagents. Ferric ion regeneration has been observed during the process that supports gold dissolution (Rizki et al. 2019). Thiourea bioleaching is known for its fast reaction kinetics. However, rapid decomposition of thiourea is considered as a major flaw in case of industrial applications (Ray et al. 2022).

### 12.4.3 Thiosulfate Leaching

This leaching mechanism provides nontoxic alternative for metal bioleaching. Fast leaching reaction kinetics, higher stability, low price, low corrosivity, and less reagent consumption are some of the main advantages of thiosulfate leaching. However, the selective recovery of gold and other precious metals is hindered by other metal complexes formed during thiosulfate leaching (Pourhossein and Mousavi 2022).

### 12.4.4 Cyanide Leaching

This leaching mechanism involves an electrochemical process which involves gold oxidation and oxygen reduction at anodic and cathodic side, respectively. Alkaline cyanide solution dissolves the gold and results in the formation of cyanide complexes. Here, oxygen concentration affects the gold solubility in cyanide solution (Akcil et al. 2015).

### 12.4.5 *Ferric Leaching*

This leaching mechanism involves the use of ferric sulfate solution. The metals like Ni, Ag, and Pb from waste PCBs have been bioleached using ferric leaching (Yazici and Deveci 2014).

## 12.5 Fungal Bioleaching of E-waste

Fungal bioleaching being a highly economical and environment-friendly approach for metal bioleaching. The fungal communities in particular possess the ability to sequester the metals present in electronic waste using their organic acids, amino acids, and numerous secondary metabolites. These acids and secondary metabolites displace metal ions by dissolving metals by formation of soluble metal complexes and chelate formation. A few reports have also been found where mixed culture of fungi has been used to sequester metals from waste PCBs. Table 12.3 shows the different fungal strains used for metal bioleaching process.

## 12.6 Conclusion

Fungal bioleaching is a proven bioleaching technology that needed extensive research as it has numerous challenges with countless opportunities. Fungi can grow at a higher pH thus making it a suitable candidate for metal bioleaching in an alkaline medium. The chelation and complexation mechanisms along with shortened leaching period are some of the advantageous characteristics of fungal bioleaching. The present article shows that fungal bioleaching proves to be a potential process for metal sequestration from electronic waste. The mixed fungal cultures to e-waste further enhance metal solubilization.

**Table 12.3** Fungal strains used for metal bioleaching process showing their maximum leaching efficiency with other important parameters

| Fungal strain | Source material | HM extracted | Max. leaching efficiency (%) | pH | Temperature (°C) | References |
|---|---|---|---|---|---|---|
| *Aspergillus niger* | WEEE | Al, Ni, Sn, Cu, Zn, Pb | 65 | NA | 30 | (Brandl et al. 1999) |
| *Aspergillus tubingensis* | WEEE, discarded PCBs | Ni, Cu, Zn | NA | 4.8–6.0 | NA | (Ghosh et al. 2020) |
| *Penicillium simplicissimum* | Electronic scrap | Al, Sn, Pb, Zn | NA | NA | NA | (Brandl et al. 1999) |
| *Penicillium simplicissimum* | Mobile handset PCBs | Cu | 90 | 7 | 30 | (Arshadi et al. 2019) |
| *Aspergillus niger* | Electronic scrap | Co, Cu | 90–95 | 5.5 | NA | (Borja et al. 2016) |
| *Aspergillus niger* (MXPE 6) | GMFICMS + PCBs | Au | 42 | 5–6 | 25 | (Madrigal-Arias et al. 2015) |
| *Aspergillus niger* MX7 + (MXPE 6) | GMFICMS + PCBs | Au | 87<br>28 | 5–6 | 25 | |
| *Aspergillus niger* (MXPE 6) | GMFICMS + PCBs | Cu | 24 | 5–6 | 25 | |
| *Aspergillus niger* MX7 | GMFICMS + PCBs | Cu | 5 | 5–6 | 25 | |
| *Aspergillus niger* MX7 + (MXPE 6) | GMFICMS + PCBs | Cu | 0.2–29 | 5–6 | 25 | |
| *Aspergillus niger* MX7 + (MXPE 6) (consortium) | Waste cellular phone, computer, motherboard, gold finger | Au<br>Cu and Ni | 87 and 28<br>0.2 and 29 | 4–5 | 28 | |

## References


Akcil A, Erust C, Gahan CS et al (2015) Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants—a review. Waste Manag 45:258–271. https://doi.org/10.1016/j.wasman.2015.01.017

Arshadi M, Nili S, Yaghmaei S (2019) Ni and Cu recovery by bioleaching from the printed circuit boards of mobile phones in non-conventional medium. J Environ Manag 250:109502. https://doi.org/10.1016/j.jenvman.2019.109502

Borja D, Nguyen KA, Silva RA, Park JH, Gupta V, Han Y, Lee Y, Kim H (2016) Experiences and future challenges of bioleaching research in South Korea. Minerals 6:128. https://doi.org/10.3390/min6040128

Brandl H, Bosshard R, Wegmann M (1999) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. In: Amils R, Ballester A (eds) Process metallurgy. Elsevier, pp 569–576

Chakraborty SC, Qamruzzaman M, Zaman MWU et al (2022) Metals in e-waste: occurrence, fate, impacts and remediation technologies. Process Saf Environ Prot 162:230–252. https://doi.org/10.1016/j.psep.2022.04.011

Cui H, Anderson C (2020) Hydrometallurgical treatment of waste printed circuit boards: bromine leaching. Metals 10:462

Dusengemungu L, Kasali G, Gwanama C, Mubemba B (2021) Overview of fungal bioleaching of metals. Environ Adv 5:100083. https://doi.org/10.1016/j.envadv.2021.100083

Ferrier J, Yang Y, Csetenyi L, Gadd GM (2019) Colonization, penetration and transformation of manganese oxide nodules by *Aspergillus niger*. Environ Microbiol 21:1821–1832

Ghosh SK, Sen R, Chanakya H, Pariatamby A (2020) Bioresource utilization and bioprocess. Springer

Ji X, Yang M, Wan A et al (2022) Bioleaching of typical electronic waste—printed circuit boards (WPCBs): a short review. Int J Environ Res Public Health 19:7508. https://doi.org/10.3390/ijerph19127508

Jing-ying L, Xiu-li X, Wen-quan L (2012) Thiourea leaching gold and silver from the printed circuit boards of waste mobile phones. Waste Manag 32:1209–1212. https://doi.org/10.1016/j.wasman.2012.01.026

Karwowska E, Andrzejewska-Morzuch D, Łebkowska M et al (2014) Bioleaching of metals from printed circuit boards supported with surfactant-producing bacteria. J Hazard Mater 264:203–210

Lakshmi S, Suvedha K, Sruthi R et al (2020) Hexavalent chromium sequestration from electronic waste by biomass of *Aspergillus carbonarius*. Bioengineered 11:708–717. https://doi.org/10.1080/21655979.2020.1780828

Liang X, Kierans M, Ceci A et al (2016) Phosphatase-mediated bioprecipitation of lead by soil fungi. Environ Microbiol 18:219–231

Liu W-J, Zeng F-X, Jiang H, Yu H-Q (2011) pH-dependent interactions between lead and *Typha angustifolia* biomass in the biosorption process. Ind Eng Chem Res 50:5920–5926. https://doi.org/10.1021/ie200413e

Madrigal-Arias JE, Argumedo-Delira R, Alarcón A et al (2015) Bioleaching of gold, copper and nickel from waste cellular phone PCBs and computer goldfinger motherboards by two *Aspergillus niger* strains. Braz J Microbiol 46:707–713

Montero R, Guevara A, dela Torre E (2012) Recovery of gold, silver, copper and niobium from printed circuit boards using leaching column technique. J Earth SciEng 2:590

Naranjo-Ortiz MA, Gabaldón T (2019) Fungal evolution: major ecological adaptations and evolutionary transitions. Biol Rev 94:1443–1476. https://doi.org/10.1111/brv.12510

Nithya R, Sivasankari C, Thirunavukkarasu A (2021) Electronic waste generation, regulation and metal recovery: a review. Environ Chem Lett 19:1347–1368. https://doi.org/10.1007/s10311-020-01111-9

Oh CJ, Lee SO, Yang HS et al (2003) Selective leaching of valuable metals from waste printed circuit boards. J Air Waste Manag Assoc 53:897–902. https://doi.org/10.1080/10473289.2003.10466230

Pourhossein F, Mousavi SM (2022) A novel rapid and selective microbially thiosulfate bioleaching of precious metals from discarded telecommunication printed circuited boards (TPCBs). Resour Conserv Recycl 187:106599. https://doi.org/10.1016/j.resconrec.2022.106599

Ray DA, Baniasadi M, Graves JE et al (2022) Thiourea leaching: an update on a sustainable approach for gold recovery from E-waste. J Sustain Metall 8:597–612. https://doi.org/10.1007/s40831-022-00499-8

Rizki IN, Tanaka Y, Okibe N (2019) Thiourea bioleaching for gold recycling from e-waste. Waste Manag 84:158–165. https://doi.org/10.1016/j.wasman.2018.11.021

Talukdar D, Jasrotia T, Sharma R et al (2020) Evaluation of novel indigenous fungal consortium for enhanced bioremediation of heavy metals from contaminated sites. Environ Technol Innov 20:101050

Yazici EY, Deveci H (2014) Ferric sulphate leaching of metals from waste printed circuit boards. Int J Miner Process 133:39–45. https://doi.org/10.1016/j.minpro.2014.09.015

Zhang T, Wang N-F, Liu H-Y et al (2016) Soil pH is a key determinant of soil fungal community composition in the Ny-Ålesund Region, Svalbard (High Arctic). Front Microbiol 7:227

# Chapter 13
# Association of Algae to Water Pollution and Waste Water Treatment

**Rakesh Pant, Amit Gupta, Simran Srivastava, Arsh Singh, and Nirmal Patrick**

**Abstract** Algae are a significant food source for aquatic creatures and play a vital part in the aquatic food chain or food web. Algae differ from other groups of tiny or microscopic microbes in that they have an inner green colour called chlorophyll, which can sometimes be concealed or partly disguised by other pigments and allows them to integrate water and $CO_2$ to form starch or related substances and release $O_2$ into the water in the presence of sunlight. Biotic and abiotic variables have the most influence on algal-based wastewater treatment. The main aim of this paper is to know more about algae, how it affects water pollution, and how it is used in wastewater treatment. Algae are the principal producers in all types of water bodies, and they contribute to water pollution in a variety of ways. Flow management has recently been proposed as a feasible approach for controlling hazardous algal blooms and mitigating their consequences in particular river systems. The structure and richness rates of algal communities are heavily impacted by physicochemical changes in the climate. Wastewater is a plentiful resource that may be used to promote algae growth. Chemical techniques for algal bloom control involve treating bodies of water with specific chemicals that reduce the number of algae.

**Keywords** Algae · Wastewater treatment · Pollution · Algal bloom · Bioindicator

## 13.1 Introduction

The word "algae" is not exactly a taxonomic word, but rather an umbrella term covering a variety of separate phyla that fulfil the general definition mentioned previously. Prokaryotes and eukaryotes are amongst these species. Algae cells can be separate units, with each unicell acting as an autonomous organism. Hundreds of algal

R. Pant · A. Gupta (✉) · S. Srivastava · A. Singh
Department of Microbiology and Biotechnology, Graphic Era (Deemed to be) University, Dehradun, Uttarakhand 248001, India
e-mail: dr.amitgupta.bt@geu.ac.in

R. Pant · N. Patrick
Department of Quality, Eureka Forbes Ltd, Lal Tappar, Dehradun, Uttarakhand 248140, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_13

genera are single-celled organisms. The cell colony might be defined and distinct, as in Volvox, or it can be vague and asymmetrical, as in Anacystis. Some freshwater algae contain cells that form thick, huge edges, with the edges being made up of far too many cells and having core and marginal (peripheral) cells that vary from one another (Palmer et al. 1977). They have a very basic body termed a thallus that lacks circulatory tissues and cannot be divided into genuine roots, stems, and leaves. They vary greatly in size, form, structure, colour, behaviour, and environment. Because of their wide biological range, algae may be found in a wide range of ecosystems; they may be found from the bottom of the sea to the highest summit on the planet. Algae are a significant food source for aquatic creatures and play a vital part in the aquatic food chain (Khalil et al. 2021). Many big groups of algae are distinguished by their generic names, such as diatoms, desmids, armoured flagellates, euglenoids, green, blue-green, yellow-green, brown, golden-brown, and red. Various distinctive types are present in these categories, which likely number in the thousands. Pigmentation, food stores, and exterior covering are all important metabolic characteristics of freshwater algae (Plohn et al. 2021).

Algae are frequent and natural residents of surface waterways and may be found in any water source that receives sunlight. While some algae are found on the ground and on external surfaces, the vast most of them are actually water and thrive in loch, reservoirs, ocean, and rivers. Furthermore, algae are regarded as significant in the water system in a variety of ways, including their ability to affect pH, alkalinity, colour, turbidity, and radioactivity of water. Some are nuisance microbes are undeniably the most annoying, while others can really help to improve water system. One of the major factors for algae's relevance is their capacity to produce vast amounts of organic materials in water. Disintegrated and floating materials are present in all water bodies (Plohn et al. 2021; Bagayas 2020). Several of them act as nutrients, promoting the growth of not just algae but also many other types of sea species, the numbers of which are heavily influenced by the quantity and type of nutrient supply. Algae are distinguished from other kinds of tiny or microscopical creatures by the presence of an inner green pigment known as chlorophyll, which is occasionally buried or partly disguised by other colours. It enables them to combine $H_2O$ and $CO_2$ to create starch or similar compounds and discharge $O_2$ into the water when exposed to light. Photosynthesis is missing in all common microbes, actinomycetes, fungi, yeasts, protozoa, and crustacea. In the water, algae produce significant chemical changes through the release of $O_2$ during the daytime. Another key chemical consequence of algae is the constant elimination of $CO_2$ from the water as a result of photosynthesis during the day. The overall hardness of the water changes as a result of all of this. Algae growths have been shown to lessen water hardness by up to one-third. The pH of water is also affected by changes in $CO_2$ and hardness. Water's corrosive activity is frequently enhanced as a result of algae development (Sen et al. 2013). The intensity of light, sunlight duration, and temperature is essential ecological characteristics that influence the performance and cost-effectiveness of algae treatment methods. Seasonal variations in day length and light intensities vary by region and have a vital impact on algae populations and their macromolecular framework. Biotic and abiotic variables have the most influence on algal-based wastewater treatment (Khalil et al. 2021; Plohn et al. 2021).

## 13.2 Microalgae

Microalgae are a broad and varied species of photosynthetic microbes in freshwater and marine habitats that can reside as solitary cells, chains, or groups. Microalgae such as *Cyanophyceae*, *Chlorophyceae*, *Bacillariophyceae*, and *Charophyceae* are the most highly referenced big groups of microalgae that have received a lot of attention in recent times for biofuel production, $CO_2$ fixation, and wastewater treatment because they suddenly convert $CO_2$ and auxiliary nutrients into biofuels in the sunlight through photosynthesis, at much greater rates than traditional oil-producing plants. Microalgae biofuel generation may be made more efficient by integrating microalgal biomass production with current electricity production and wastewater treatment facilities. A lot of scientists have looked into the integration of algal $CO_2$ fixation, wastewater treatment, and biofuel manufacturing. Heavy metals and organic waste have also been removed using microalgae. Approximately, 40,000 genera of algae and cyanobacteria have been discovered so far (Sen et al. 2013; Mohsenpour et al. 2021).

Microalgae might use the copious daylight that lands on wastewater surface to meet their power needs for development while also removing toxins. Microalgae may also thrive in dry conditions and in very salty water. Recent research has reported the use of microalgae to eliminate medicinal chemicals and insecticides from industrial and agrarian wastewaters, in addition to removing nutrients from wastewater produced by WWTPs. As a result of their capacity to proliferate, absorb, and withstand hazardous conditions in wastewater, microalgae are flexible organisms for cleaning many forms of water contaminants produced by diverse industrial and agricultural processes. A suspended growing system, either open or closed, is the most prevalent technique of microalgae culture in wastewater. The development of microalgae in the PBR might prevent or minimize undesired pollution, vaporization water loss, and $CO_2$ loss. Despite various limitations, the open growing of microalgae in wastewater might be highly promising. The essential stages of microalgal bioremediation of wastewater are the elimination of microalgal biomass from treated wastewater. As a result, if the treated wastewater is to be used for other reasons, efficient preparatory collection of microalgae will be critical. In comparison to the feed normally created by terrestrial plants, microalgal biofuel has the capability to be a sustainable different feed. Water and nutrient supply are two aspects that affect the prices and power of microalgal biomass generation; in this context, growing microalgae in wastewater might give further advantages, but this would restrict the use of generated algae biomass (Al Momani et al. 2019).

Clime variation, caused by manmade GHGs emissions, has been identified as one of humankind's most serious challenges. Increased temperature of the wastewater promotes microalgae development until the optimal temperature is attained, but the subsequent temperature rises significantly reduce microalgae growth and performance (Al Momani and Ormeci 2020). The use of algal-based wastewater improvement in hot regions has its own set of obstacles. Temperatures above the appropriate growing conditions significantly reduced growth and production (Plohn et al. 2021). Contamination concentrations in wastewater can be high, posing a risk to wildlife, people, as well as the ecosystem. As industrial operations develop to meet the requirements of our rising population, an increasing amount of wastewater is created as a "by-product." Methods for properly treating the vast amounts of generated wastewater must be devised quickly (Khalil et al. 2021; Plohn et al. 2021). In warmer climates, the temp in shallow wastewater ponds can exceed 32–35 °C. Changes in wastewater temperatures can have an impact on biochemical processes and, as a result, the biochemical composition of algae. Multiple types of research have revealed that the majority of microalgae types thrive in temperatures ranging from 5 to 30 °C, with optimal growth occurring between 20 and 30 °C (Yuan et al. 2012).

## 13.3 Algal Blooms

Harmful algal blooms can have severe ecological and health consequences because they create phycotoxins that gather in suspension-feeders like bivalve shellfish and can lead to injury to breathing procedures, as well as feed intake responses via toxin transfer, resulting in the death of fish and other aquatic animals. High biomass blooms create annoyance and deplete oxygen levels. Blooms can disturb ecosystems and have various cascading consequences on species relationships. Those that emit aerosolized poisons have an impact on human lung health. The habitant, causes, and magnitude of detrimental effects of localized blooms of hazardous benthic or epiphytic microalgae differ from those of planktonic HABs (Jabri et al. 2021). HABs pose a serious risk to human well-being, food safety, coastal economy, and marine environments. Biotoxins generated by harmful algae can be bioaccumulated effectively by filter-feeders like bivalves and tiny zooplankton, move up the food web, and can eventually trigger catastrophic death incidents in aquatic species (Rioux et al. 2022). Example of Song River sites in Dehradun (Fig. 13.1).

**Fig. 13.1** Algal bloom in different sites of Song River Dehradun

## 13.4 Categories of Algae

### *13.4.1 Blue-Green Algae*

They are common in freshwater habitats, with sizes varying from single-celled forms like Synechococcus to massive colonies of algae like Microcystis and Anabaena. The ratio of chlorophyll activity in blue-green algae changes with light spectrum and power, giving in a spectrum of hues ranging from brown to blue-green. Blue-green algae like Gram −ve microbes have an extra outer cell membrane. Outside the cell wall, specific genera have a mucilage layer that can be thick or watery, organized or unorganized (Al-Jabri et al. 2021).

Blue-green algae are notable inside the prokaryote kingdom for exhibiting the previously mentioned spectrum in size and morphology, with some species forming rather massive, intricate, and three-dimensional colonies. They are considered to have evolved around 3.5 billion years ago and have been the dominating form of life for around 1.5 billion years. Blue-green algae's potential to govern freshwater habitats is especially crucial in still waters where blooms can occur owing to eutrophication.

#### 13.4.1.1 Algal Blooms

Eutrophic temperate loch typically generates huge colonies of colonial blue-green algae in the middle to late summer. Blue-green algae's capacity to beat other freshwater algae has been determined by a variety of features, such as proper development at extreme temps, resilience to low light, resilience of low N/P ratios, buoyancy depth regulation, opposition to zooplankton grazing, the resilience of high pH/low $CO_2$ concentrations, and harmonious relationship with aerobic microorganisms (Mahapatra et al. 2013; Jabri et al. 2021).

#### 13.4.1.2 Blue-Green Algae as Bioindicators

The existence or absenteeism of precise species might be a sign of environmental quality. The predominance of colony blue-green algae in loch phytoplankton is a helpful signal of excessive nutrient level; also, these algae are an essential element of several ecological indicators. Variations in the number of colonial blue-greens in loch and rivers can potentially serve as a climate change indication (Sen et al. 2013; Mohsenpour et al. 2021).

### *13.4.2 Green Algae*

Green algae in freshwater vary in size from tiny single cells to huge circular colonies and broad filamentous development. They have a bright green hue because of the existence of chlorophyll a and -b, which are not masked by pigment molecules like -carotene and other carotenoids. Green algae also exhibit a variety of specific cytological characteristics, such as the presence of flagella in pairs. Chloroplasts differ in form, size, and quantity. The photosynthetic store is produced and stored within the plastid, with granules usually concentrated near the pyrenoid. Green algae's cell wall is comprised of cellulose. They are the utmost varied category of algae, with over 17,000 types recognized. The variance in shape reflects this variability, with microorganisms classified as single-celled, colonies, or filamentous development types. Green algae are significant environmentally because they are substantial providers of biofuels in freshwater environments, also as planktonic or attached microbes, where they may create thick blooms and periphyton progresses (Sen et al. 2013; Mohsenpour et al. 2021).

#### 13.4.2.1 Algal Blooms

They don't generally create the thick blooms observed with diatoms and blue-green algae in mesotrophic and eutrophic loch, but they do become leading/co-leading in early summer, amid the clear-water phase and the mid-summer mixed algal bloom.

When nutrient levels are extremely high, a shift from colonies of blue-green algae to green algae as main bloom formers may occur. It is evident in certainly accomplished hatchery, where organic and inorganic fertilizers are used to boost fish production by improving carbon flow throughout the food web.

#### 13.4.2.2 Green Algae as Bioindicators

Present-day green algae ecological requirements are usually valuable in giving data on the physicochemical features of the water habitats. They don't often develop robust walls that remain in watery remains, making them far less helpful as bioindicators in the fossil record than diatoms and chrysophytes.

### *13.4.3 Euglenoids*

Euglenoid algae are virtually completely single-celled microbes with 40 species in the world, the majority of which are found in freshwater. Cells are often motile, either by flagella or through the body's capacity to alter form. One-third of the euglenoids are photosynthetic and classified as algae. The coloration of photosynthetic microbes is quite similar to that of green algae; however, because of the varying existence of carotenoid pigments, these microorganisms can frequently shift in colour from fresh green to yellow–brown. Euglenoids are often elongated, spindly creatures with multiple chloroplasts per cell that range in form from discoid to star, plate, or ribbon shaped.

The existence of an anterior flask-shaped depression or reservoirs into which the flagella are placed distinguishes euglenoids. The manufacturing of paramylon as a backup storage material of euglenoids. The existence of a top layer or pellicle causes the cell to seem striated. This is found immediately under the plasmalemma and is made up of interlocked protein stripes that loop helically around the cell. Euglenoids are typically found in areas with a high concentration of decomposing organic material. Not very deep lakes, agricultural ponds, marshes, brackish sand, and mudflats are common ecosystems (Rioux et al. 2022; Karlson et al. 2021).

#### 13.4.3.1 Euglenoids as Bioindicators

In terms of both present numbers and fossil data, euglenoid algae are not especially effective as ecological biomonitors.

### *13.4.4 Yellow-Green Algae*

Non-motile, single-celled colonies of algae with a unique colouring that gives the cells a yellow or fresh green look are known as yellow-green algae. When examined fresh, they are most likely to be mistaken for green algae; however, they vary in a number of crucial characteristics. Carbohydrate storage as oil droplets or chryso-laminarin granules provides distinct colouring. The walls are mostly made of pectin or pectic acid: Fine shape of chloroplasts, there might be an eyespot. They have a variety of morphologies, ranging single-celled to colonies to filaments. In the mature condition, single-celled forms are non-flagellate, with motility limited to biflagellate zoospores or motile gametes during reproduction phases. These algae are somewhat restricted in their use of watery settings, preferring wet mud and soil but not appearing widely in lentic or lotic habitats. Planktonic types are typically found in drains or tiny lakes.

#### 13.4.4.1 Bioindicators of Yellow-Green Algae

These algae have not been frequently exploited as biomonitor species, owing in part to their lack of prominence in the water habitats. Various species do have various ecological requirements, which might be utilized to offer data on ecological circumstances.

### *13.4.5 Diatoms*

Diatoms are a separate type of algae distinguished by their yellow–brown colouring and the existence of a generally dense silica cell wall under a light microscope, and this looks extremely refractive, providing the cell a well-defined form.

There are several distinguishing cytological characteristics of plastids, including the presence of the periplasmic endoplasmic reticulum and girdle lamellae. Outside plastid, chrysolaminarin and lipid food stores exist. The frustule is a unique cell wall made of opaline silicon dioxide and organic layers. Silica in diatom cell walls can be detected in cold digestion with an oxidizing acid to eliminate organic materials. Diatoms have an extremely thick cell wall. A sufficient quantity of soluble silica in the surrounding water is required for the development of the diatom cell wall. Unlike other cell wall substances, silica is stiff and cannot spread. The morphological variety of diatoms may be categorized into two categories: centric/pennate diatoms and the spectrum of single-celled to colonies forms. Diatoms are found in both stagnant and flowing freshwaters and can be found as planktonic, benthic, epiphytic, and epizoic species.

#### 13.4.5.1 Algal Blooms

Diatoms like *Asterionella* and *Tabellaria* rule the phytoplankton population in several temperate lakes throughout the spring and early summer, when inorganic nutrients (N, P, Si) are abundant, light, and temperature points are increasing, and loch turbulence is preserved by mild wind activity. Diatoms are capable to outpace other microalgae at this stage in the seasonal cycle because of their endurance to low temperature and low sunlight circumstances, as well as their capacity to develop in unstable water.

#### 13.4.5.2 Diatoms as Bioindicators

Diatoms in loch sediments have proven particularly helpful as bioindicators of previous lake acidification, eutrophication point sources, and overall phosphorus content. The European Diatom Database Initiative supports the broad use of ponds sediment diatoms for reconstructing previous water quality. This is an Internet information service meant to improve the use of diatom analysis to surface water acidification, eutrophication, and clime alteration concerns. Diatoms in sediments are chemically cleansed to expose frustule morphology, and varieties of numbers are given as a proportion of the total.

### *13.4.6 Red Algae*

They are mostly oceanic in distribution, with only three per cent of the approximately 5000 genera found in genuine freshwater settings. While freshwater red algae are mostly located in rivers, Rhodophyta may also be found in lakes and brackish habitats as ocean invaders.

## 13.5 Algae and Water Pollution

Groundwater contamination has become one of the most serious environmental issues. On a worldwide scale, two forms of major and long-term pollution problems may be identified: organic pollution, which leads to elevated organic content in aquatic ecosystems, and, in the long run, eutrophication. Contaminated water can impair the quality of the water, limiting the usage of water bodies for a variety of functions (Wanga et al. 2015). Organic pollution in waterways causes eutrophication, which speeds up the growth of a specific variety of algae genera in the water body. Numerous investigations by many authors have demonstrated a substantial link between algal species and contaminated and uncontaminated water. They are affected by elements such as water mass mixing, light, temperature, salinity, and nutrients. Contaminant impacts in aquatic habitats can be identified using bioindicator species

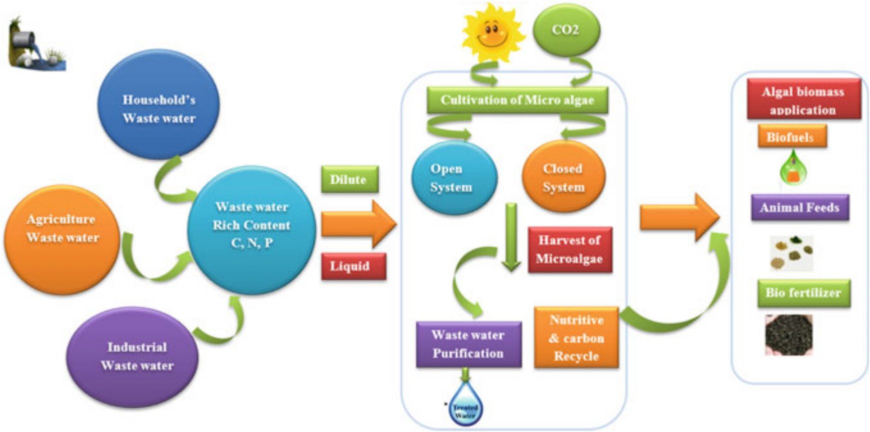



**Fig. 13.2** Types of wastewaters, cultivation of microalgae and their bioproduct process

(Hsu et al. 2013). Water contamination has become a growing worry for the public and social authorities ever since industrialization. The demand for fresh water is increasing dramatically as the industrial world develops and the population grows. By 2050, worldwide water requirement for agriculture, industrial, and municipalities is predicted to climb by 20–30%. A consequence of this rise is the production of vast quantities and types of wastewaters polluted by extensive range of chemicals and concentrations (Fig. 13.2). Furthermore, the agricultural industry uses a large quantity of pesticides and produces a great deal of organic waste, which contributes a great deal to water pollution (Hsu et al. 2013; Glibert 2020).

Algae are the principal generators in all types of water bodies, and they contribute to aqua contamination in a variety of ways. For starters, organic effluent supplementation of algal nutrients in water may preferentially boost the development of algal species, resulting in large surface growths or "blooms" that impair the quality of the water and influence its usage. Some contamination algae, on the other hand, thrived in organic waste-polluted water and play a vital role in the "self-purification of water bodies." Various contaminant algae are commonly dangerous to fish, as well as humans and animals who consume contaminated water. In reality, algae can play a main part in the food web of water life; thus, any changes in the amount and types of algae have a substantial impact on other animals in the chain, even fish (Hsu et al. 2013). Understanding the endurance of algae in the presence of flow, as well as the geographical variation of algal quantity and toxins during bloom and flow episodes, is critical. Flow management has recently been proposed as a feasible approach for controlling hazardous algal blooms and mitigating their consequences in particular river systems. Another truth is that riverside reservoir coves may signify ecosystems where the dynamics of hazardous algae vary from the main reservoir (Wanga et al. 2015).

*Prymnesium parvum* (golden algae) is accountable for hazardous algal blooms that have killed thousands of fish and cost the economy millions of dollars. The perseverance of toxic algae is a conundrum. High flow, on the surface, wipes off scattered algae, and continuous strong flow can overwhelm the reproductive potential of planktonic algae (Wanga et al. 2015; Al-Jabri et al. 2021). The quantity and impact of nutrient pollution from land and air on HAB expansion are determined not only by how much is exported but also by how much is reserve within the receiving waters. The fact that nutrient loads have increased in general is inadequate to promote HABs. A shift in nutrient loads results in the provision of the necessary nutrients at the right time, which helps to produce circumstances favourable to certain HABs. Hydrographically, retentive zones are critical for HABs, particularly those that develop cysts since cysts collect and can lead to blooms anytime favourable conditions exist (Hsu et al. 2013; Karlson et al. 2021). Surface water HABs caused by cyanobacterial blooms appear to be the prime examples of temperature rise upsurge, with a few case reports from nearly every mainland implying that the optimal rate of development for several cyanobacterial HABs is globally greater than those of non-detrimental eukaryotic algae. HABs moving to new environments, on the other hand, may pose a serious risk to the freshwater environments and the people who reside nearby. Temperature is predicted to surpass thresholds that pose considerable physical stress to sea creatures in certain environments. Meanwhile, dissolved oxygen levels in the sea have been falling ever since half-decade, and this pattern is predicted to continue throughout the twenty-first century as higher seas retain reduced dissolved oxygen (Yuan and Ergas 2010). Algal biofuel generation incorporated into the WWTP anaerobic digestion framework has the future to raise biofuel yield, decrement of excessive and unexpected internal nitrogen loads, and repair mud digestibility and dewaterability (Ouhsassia et al. 2018). Wastewater discharge is rising because of increased industrial, agricultural, and urban activities. The flow of nutrients into the atmosphere caused by wastewater causes eutrophication in aquatic bodies. Furthermore, numerous governmental organizations have recently embraced the circular economy idea in order to decrease and control wastewater contamination (Jabri et al. 2021).

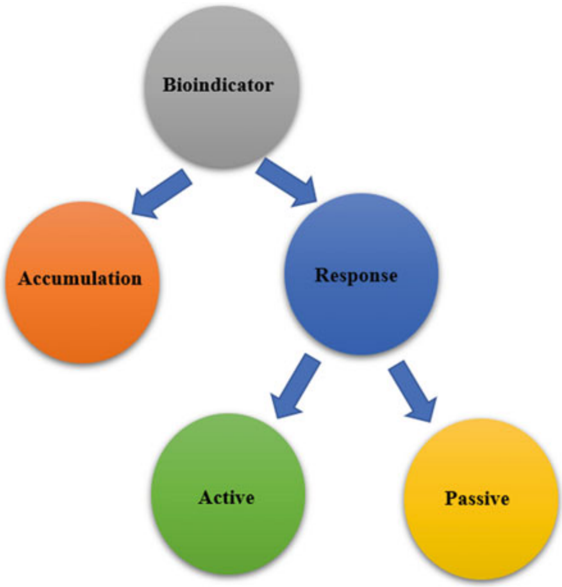
Different kinds of wastewater with high ammonia concentrations, like livestock contaminants and anaerobic sludge digestion products, have been proposed for algal cultures. Toxins found in these pollutants, on the other hand, can inhibit the growth of microalgae. With these toxins, free ammonia is a serious issue (Ouhsassia et al. 2018). Numerous water reservoirs in Morocco are undergoing water quality degradation owing to numerous pollution sources, including over-enrichment with nutrients like phosphorus and nitrogen, indicating an advanced degree of eutrophication. This phenomenon disrupts the equilibrium of a water environment by causing undesirable algal growth and excessive oxygen demand at the reservoir's bottom level (Zurano et al. 2021). Since untreated wastewater release contaminated water bodies and causes water-related illnesses, the huge amount of wastewater created should be cleansed before being released into natural watercourses or recycled (Zurano et al. 2021).

## 13.6 Algae as Bioindicators

An atmospheric stress factor, the input of inorganic nutrients into a previously low-nutrient system, causes changes in the ecosystem. Bioindicator species can be used to recognize and classify the environmental impacts of contaminants (Fig. 13.3). Bioindicators may tell us about the cumulative impacts of various contaminants in the environment, as well as how long a problem may last (Plohn et al. 2021; Bagayas 2020). Because of their fast reactivity to pollution, algae are regarded as an excellent bioindicator of water quality. Algae soak organic and inorganic contaminants, heavy metals, and radiogenic chemicals; they are vital biological organisms for water treatment (Khalil et al. 2021). Microalgae are bioindicators of eutrophication and may be used to monitor water quality. The impacts of various contaminants on aquatic environments are indicated by bioindicator organisms (Zurano et al. 2021).

Even if index organisms can be any biological kind that specifies an environmental quality or traits, algae are recognized to be useful markers of many forms of pollution because algae are found all across the world, both in time and space. A wide variety of algae species are accessible all year. They respond rapidly to pollution-related charges in the environment. Algae are a varied collection of creatures that are abundant, and it is simpler to detect and sample. The existence of certain algae is strongly linked to a specific type of pollution, notably organic contamination (Al-Jabri et al. 2021; Yuan et al. 2012). Phytoplankton are reliable indicators of wetland water quality. The major algae groupings in freshwater bodies and lakes are used to classify them (Yuan et al. 2012). The environmental method of assessing water quality involves diatom species and associations that are utilized as markers of organic contamination. Algae are also

**Fig. 13.3** Types of bioindicators



useful markers of freshwater since several genera are found almost exclusively in the potable water region of river. To identify the safe water zone, it is preferable to stress the existence or absence of numerous kinds of clean water algae rather than any one species. Much research by numerous authors highlights the connections between algae and clean water. The segment of the stream that has returned to normal after being contaminated and purified is said to have a community of the diatom Cocconeis and the blue-green algae Chamaesiphon. The lack of blue-green algae is frequently seen as a sign of safe water.

### *13.6.1 Characteristics of Bioindicators*

Kolenati and Cohn discovered the ability of the aquatic microbes to reflect changes in ecosystem circumstances when they discovered that biota in contaminated waterways differed from those in non-polluted settings. In monitoring water quality, specific indicator genera/mixtures of genera have been discovered which are fastest and most reliable to respond to ecosystem changes. The necessary characteristics of an indicator species include a small atmospheric scope, a rapid response to ecosystem changes, a precise taxonomy, accurate recognition with standard laboratory equipment, and a wide geographic distribution. In all environmental conditions, water quality is determined by a mixture of several indicator species or groups. The benefits of biological monitoring over distinct physicochemical measures for assessing quality of water are as follows:

- Reflects total quality of water by including impacts of various stressors throughout time.
- Physicochemical assessments offer data for a single moment in time.
- The ecological influence of environmental elements on aquatic creatures is measured directly.
- Provides a quick, dependable, and reasonably priced method of recording environmental data across several sites.

Environmental monitoring of aquatic systems, especially water quality monitoring, offers data on:

*Ecological consequences*: Variations in phytoplankton populations can be utilized to detect significant changes in reservoir hydrology.
*Seasonal fluctuations*: include hydrological measures, temperature, and chemical stratification, and variations in nutrient supply at the lake surface in temperate lakes.
*Ecological categorization*: is founded on water quality, output, and component microorganisms. The most common categorization is established on inorganic nutrient contents, with systems classified as oligotrophic, mesotrophic, or eutrophic.

Nutrients and contaminant entry patterns into aquatic systems through point or diffuse loading. Pollutant entry, whether localized or diffuse, may be explored using benthic algae populations.

*Human consequences*: Long-term observation of anthropogenic effects on the environment, such as eutrophication, a rise in organic contaminants, acidification, and heavy metal pollution.

*Water's suitability for human consumption*: This involves meeting water quality standards for human consumption and leisure. It is possible for lakes used for drinking water supply and leisure purposes to shut down due to the growth of colonial blue-green algae and higher concentrations of algal toxins.

*Conservation evaluation*: Freshwater algal research has become an essential aspect of the survey and data gathering programme used to assess the nature conservation value of lakes (Yuan and Ergas 2010; Glibert 2020).

### *13.6.2 Saprobic System*

The saprobic system is used to assess the extent of such water contamination by taxonomic and quantitative examination of all biocoenosis components ranging from prokaryotes, lower algae, and protozoans to higher plants and animals. But, the saprobic system primarily interacts with zoo- and phyto-benthos, or animals dwelling on the water habitat's bottom. Even though the saprobic system may be used to analyse effluents, it is most commonly employed to examine surface waters, which fall under the purview of the Limnos probity group (Table 13.1).

Saprobity is divided into four categories: catharobity, limnosaprobity, eusaprobity, and transsaprobity. Limnosaprobity is classified into five groups based on the level or degree of pollution, ranging from unpolluted waters of the highest quality to extremely contaminated waters, as follows: xenosaprobity (x), oligosaprobity (o), β-mesosaprobity (β), α-mesosaprobity (α), and polysaprobity (p) (Yuan and Ergas 2010).

**Table 13.1** Saprobic index classes for water quality

| Saprobic index | Class | Condition |
|---|---|---|
| 1–1.5 | I | Very slightly contamination |
| 1.5–2.5 | II | Moderate contamination |
| 2.5–3.5 | III | High contamination |
| 3.5–4 | IV | Very high contamination |

## 13.7 Use of Algae in Wastewater Treatment

Overall municipal wastewater output rises directly proportionate to the increasing population. The water utilized in houses accounts for the majority of municipal wastewaters. As a result, the majority of their pollution is attributable to cheaply biodegradable organic waste. But, numerous POPs are found in trace amounts. Chemicals in these concentration levels are sometimes known as micropollutants. Medicines, hormones, detergents, plasticizers, flame retardants, and insecticides are the most common micropollutants. The globe's population expansion necessitates not just increased municipal wastewater output but also increased food production. Not only is farming the greatest user of potable water, but it is also the largest generator of wastewater. Poultry generates "runoff" water, which is high in phosphate and nitrogen. Industrial effluents occur in a number of forms. The pulp, cotton, and plywood sectors have very significant water use and pollution. This industry's effluent has a significant percentage of particles, organic material, and nitrogen, but also hazardous compounds like phenol and heavy metals like copper, cadmium, or lead. The colour of effluent is essential in wastewater treatment because it influences microalgal development and nutrient removal. Dark brownish-greyish and opaque effluent absorbs a lot of light, reducing microalgae photosynthetic light intake and hence their development and nutrition intake. While numerous microalgal variants have the ability to eliminate contaminants from wastewater, some appear to be utilized much often than others, most probably because of their quick development rate, low manufacturing price, and great resistance to harsh, possibly stressful climate factors (Yuan et al. 2011). Several developed and developing nations are working on enhancing the ecological quality of water sources, particularly by lowering $N_2$ and P in wastewater discharge. In latest years, there has been considerable interest in using mixotrophic microalgae in wastewater treatment.

The primary goal of treating wastewater is to remarkably reduce the number of carbonaceous materials and, in the case of sensitive waters, N and P compounds before they are drained into receiving systems. This is due to the fact that the existence of these materials in high quantities can have a negative impact on dissolved oxygen ($O_2$) concentration range, the trophic state, and eventually, the well-being of the aquatic plant and animal life (Yuan et al. 2012). World socioeconomic and cultural growth has raised water consumption while also creating a scarcity of water. According to studies, with present water use methods, the world might face a 40% water shortfall by 2030 (Ota et al. 2015). New wastewater treatment methods have been created with the objectives of improving efficiency, lowering expanses, and lowering the carbon footprint of massive treatment facilities as our awareness of the issues and requirement for treatment of wastewaters from all sources improves (Fig. 13.4). Several techniques, like ozonation, adsorption, or membrane bioreactors, are commonly used, such as coagulation, precipitation, filtering, oxidation, ion exchange, but also solvent extraction, or electrochemical treatment (Barnharst et al. 2018).


**Fig. 13.4** Process of wastewater treatment

The primary purpose of obtaining filtered wastewater in the wastewater treatment system is to eliminate biochemical oxygen demand (BOD), suspended particles, nutrients, coliform bacteria, and toxicity. The preliminary sewage treatment process eliminates big solid debris transported by sewers that might clog the plant's flow or harm pieces of equipment. These are floating things such as rags, wood, faeces, and coarser grit particles. After the rough materials are removed, the sewage is routed to sedimentation tanks, which use gravity to remove the settleable solids. A well-built sedimentation tank may remove 40% of the BOD as settleable solids. Pathogen clearance rates during first therapy vary greatly, with variable extraction efficiency reported for different pathogens. By removing organic materials, the secondary treatment step seeks to lower the BOD exerted. This is principally mediated by a heterotrophic bacterial population that uses the organic ingredient for energy and growth. The tertiary treatment method tries to eliminate all organic ions. It can be done both biologically and chemically. When compared to chemical methods, which are generally too expensive to execute in most regions and may result in secondary contamination, the biological tertiary treatment technique looks to function well. Furthermore, each extra treatment stage in a wastewater system significantly raises the overall cost. Because primary, secondary, and even tertiary treatment cannot eliminate 100% of the entering garbage load, several microorganisms linger in the waste stream. Regulatory authorities may compel the elimination of harmful organisms in wastewater to avoid the spread of waterborne illnesses and to reduce public health concerns.

## 13.8 Conclusion

The structure and richness rates of algal communities are heavily impacted by physicochemical changes in the climate. Because of their sensitivity to environmental change, algae are strong indicators of water quality and an essential component of many sampling programmes. Organic and inorganic pollutants that are discharged into the ecosystem as a result of residential, farming, and industrial water activities cause contamination. Wastewater is a plentiful resource that may be used to promote algae growth. Abiotic conditions have a considerable impact on algal bloom development, and the related algae genera can be thought of as potential producers of physiologically active compounds. Chemical techniques for algal bloom control involve treating bodies of water with specific chemicals that reduce the number of algae. Algae are vital in water supplies. They are a great bio-monitoring indicator for detecting water quality and marine populations that can give suitable remedies to environmental challenges. It can help in the development of systems for managing and enhancing drinking water quality.

## References


Al Momani F, Judd S, Bhosale RR, Shurair M, Aljaml K, Khraisheh M (2019) Intergraded wastewater treatment and carbon bio-fixation from flue gases using Spirulina platensis and mixed algal culture. Process Saf Environ Prot 124:240–250

Al Momani F, Ormeci B (2020) Assessment of algae-based wastewater treatment in hot climate region: treatment performance and kinetics. Process Saf Environ Prot 141:140–149

Al-Jabri H, Das P, Khan S, Mahmoud Thaher M, Quadir MA (2021) Treatment of wastewaters by microalgae and the potential applications of the produced biomass—a review. Water 13(27):1–26

Bagayas M (2020) The close relationship between algae and water quality. Kraken Sense Ltd., pp 1–19

Barnharst T, Rajendran A, Hu B (2018) Bioremediation of synthetic intensive aquaculture wastewater by a novel feed-grade composite biofilm. Int Biodeterior Biodegrad 126:131–142

Glibert PM (2020) Harmful algae at the complex nexus of eutrophication and climate change. Harmful Algae 91(101583):1–15

Hsu SB, Wang FB, Zhao XQ (2013) Global dynamics of zooplankton and harmful algae in flowing habitats. J Differ Equ 255:265–297

Jabri HA, Das P, Khan S, Thaher M, Quadir MA (2021) Treatment of wastewaters by microalgae and the potential applications of the produced biomass—a review. Water 13(27):1–26

Karlson B, Andersen P, Arneborg L, Cembella A, Eikrem W, John U, West JJ, Klemm K, Kobos J, Lehtinen S, Lundholm N, Marzec HM, Naustvoll L, Poelman M, Provoost P, Rijcke MD, Suikkanen S (2021) Harmful algal blooms and their effects in coastal seas of Northern Europe. Harmful Algae 102(101989):1–22

Khalil S, Mahnashi MH, Hussain M, Zafar N, Nisa WU, Khan FS, Afzal U, Shah GM, Niazi UM, Awais M, Irfan M (2021) Exploration and determination of algal role as Bioindicator to evaluate water quality—probing fresh water algae. Saudi J Biol Sci 28(10):5728–5737

Mahapatra DM, Chanakya HN, Ramachandra TV (2013) Treatment efficacy of algae-based sewage treatment plants. Environ Monit Assess 185:7145–7164

Mohsenpour SF, Hennige S, Willoughby N, Adeloye A, Gutierrez T (2021) Integrating micro-algae into wastewater treatment: a review. Sci Total Environ 752(142168):1–23

Ota M, Takenaka M, Sato Y, Smith RL, Inomata JH (2015) Effects of light intensity and temperature on photoautotrophic growth of a green microalga, *Chlorococcum littoral*. Biotechnol Rep 7:24–29

Ouhsassia M, Khaya ELO, Bouyahyaa A, Abrinia J (2018) Isolation and characterization of cyanobacteria strains based on the compositional approach of fatty acids: case of drinking water reservoirs in the region of Tetouan (Northern Morocco). J Algal Biomass Util 9(1):57–67

Palmer CM, Walter HJ, Adams S, Lewis RL (1977) Algae and water pollution. An illustrated manual on the identification, significance, and control of algae in water supplies and in polluted water, pp 1–133

Plohn M, Spain O, Sirin S, Silva M, Oñate CE, Climent LF, Allahverdiyeva Y, Funk C (2021) Wastewater treatment by microalgae. Physiol Plant 173:568–578

Rioux AB, Starr M, Chass J, Scarratt M, Perrie W, Long Z, Lavoie D (2022) Harmful algae and climate change on the Canadian East Coast: exploring occurrence predictions of *Dinophysis acuminata*, *D. norvegica*, and *Pseudo-nitzschia seriata*. Harmful Algae 112(102183):1–17

Sen B, Alp MT, Sonmez F, Ali M, Kocer T, Canpolat O (2013) Relationship of algae to water pollution and waste water treatment. INTECH, pp 335–354

Wanga FB, Hsu SB, Zhaoc XQ (2015) A reaction–diffusion–advection model of harmful algae growth with toxin degradation. J Differ Equ 259:3178–3201

Yuan X, Ergas SJ (2010) High-strength wastewater treatment by microalgae. Environ Water Resour Eng 9:1–92

Yuan X, Kumar A, Sahu AK, Sarina J, Ergas SJ (2011) Impact of ammonia concentration on *Spirulina platensis* growth in an airlift photobioreactor. Biores Technol 102(3):3234–3239

Yuan X, Wang M, Park C, Sahu AK, Ergas SJ (2012) Microalgae growth using high strength wastewater followed by anaerobic codigestion. Water Environ Res 84(9):396–404

Zurano SA, Guzmán JL, Acién FG, Sevilla JMS (2021) An interactive tool for simulation of biological models into the wastewater treatment with microalgae. Front Environ Sci 9(721324):1–17

# Chapter 14
# E-waste and Its Management by Using Algae

**J. P. Shabaaz Begum, Leirika Ngangom, Divya Venugopal, Balwant Rawat, and Janhvi Mishra Rawat**

**Abstract** The presence of numerous potentially dangerous product components that can pollute the environmental surroundings and endanger the health of individuals unless destruction processes are not rigorously handled, electronic waste (also known as "e-waste") is a major environmental risk with the speediest global trend. E-waste is classified as a toxic chemical, when it is not adequately disposed of and processed; it may result in detrimental effects on the environment. Recycling elements such as gold, silver, copper, lead, zinc, and mercury from e-waste have gained significant attention. The movement, distribution, and transit of toxic metals at the sediment–water interface all depend heavily on microbial activity, and this has an impact on how the metals are distributed throughout the food chain. This review explores how heavy metal speciation and transformation in sediments are impacted by microbial algae activities. Additionally, it highlights recent developments in the recovery of metals in sediments by algae as well as future possible applications and drawbacks, and it emphasises the significance of contemporary modern biotechnology and strategies in enhancing microbial activities' ability to alter heavy metals more effectively and quickly. Bioprocessing of waste products for recovery of metals is a promising and new technology with minimal negative effects on the environment and great cost-effectiveness.

**Keywords** Electronic waste · Heavy metals · Toxicity · Algae · Microbial treatment · Recycling metal waste

J. P. Shabaaz Begum · L. Ngangom · D. Venugopal
Department of Life Sciences, Graphic Era (Deemed to be University), Dehradun, Uttarakhand 248002, India

B. Rawat
School of Agriculture, Graphic Era Hill University, Dehradun, Uttarakhand 248002, India

J. M. Rawat (✉)
Department of Biotechnology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand 248002, India
e-mail: janhvi.mishra03@gmail.com; janhvimishra.ls@geu.ac.in

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_14

## 14.1 Introduction

In the sphere of ecological sustainability, waste management is a persistent problem, and the microbial treatment method has surely drawn interest due to its ecologically beneficial and economically practical properties. Smartphones, laptops, camcorders, televisions, espresso machines, microwaves, and medical instruments that provide convenience, leisure, and grandeur to contemporary life have evolved into an irreplaceable part of contemporary society. But, despite the short lifespans, restricted repair choices, and rapidly evolving technology, a large number of digital devices are discarded as they reach the decline stage due to deterioration, non-operational hazards, or the introduction of advanced substitutes (Montalvo et al. 2016). Across most nations, e-waste created at the home level is treated in three different ways, i.e. by putting it into trashcans, public pickup by the official authorised entities, and collected from the outside systematic procedure by disposal collectors and firms (Chi et al. 2014). E-waste disposed of in dumps or given to purveyors frequently contaminates the environment via seeping into groundwater and soil as well as dispersion into the ambient air, soils, and groundwater (Cesaro et al. 2019). A significant quantity of useful materials is also eliminated during recycling or waste disposal under poor conditions. Therefore, formalised e-waste management is the most secure method of managing e-waste. It is commonly established that contaminants made by humans can harm the environment and public health, compromising both social and economic viability (Landrigan et al. 2018). In every scenario, it is assumed that their entry into the environment by dumping and transportation with water, air, and soils will result in contamination including both groundwater and surface water systems along with marine wetlands (Li and Achal 2020; Freitas et al. 2020).

Monitoring electrical litter (or e-waste) is currently one of the world's most widening pollution issues. Technological advances are fast replacing millions of conventional devices, resulting in their destruction in designated dumps associated with excessive negative environmental effects. Due to the reduced volume and prolonged half-life of electrical items in certain developing nations due to budget limitations, both on a local area as well as a national scale, the development of e-waste in those nations is not as concerning at this moment. The main source of e-waste amongst developing nations is the importing of electronic waste and electrical items from developed nations since earlier, lesser environmentally sustainable technology gets dumped from such Western nations. Technology advancement has accelerated over the past 20 years, turning outdated and later part digital devices into e-waste (electronic waste) (Kiddee et al. 2013). Eighty per cent of all the e-waste in developed nations is transported (Hickset al. 2005). Caution is raised about both the quantity of electronic waste transported to developing nations and the wide spectrum of hazardous substances linked to it. Several studies have proven that polyhalogenated compounds (PHCs) and hazardous metals, such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), could be discharged from e-waste, creating severe hazards of exposure to individuals and also the ecosystem (Williams

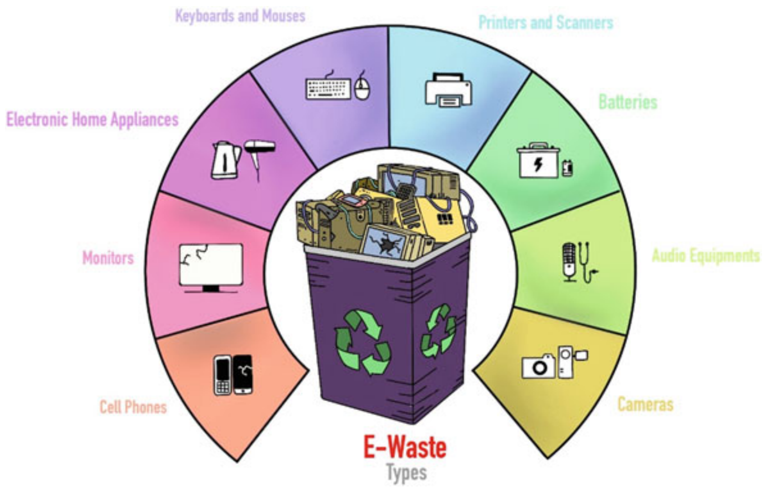



**Fig. 14.1** Types of electronic waste

et al. 2008; Robinson 2009). According to a review of previously published findings on e-waste issues in developing and transitional countries, advanced countries export their e-wastes to China, Cambodia, India, Indonesia, Pakistan, and Thailand as well as African nations like Nigeria. However, the specific e-waste issues in each of these countries vary significantly. For example, Asian nations frequently destroy discarded electrical items while African nations mostly reuse them (Wong et al. 2007; Stephenson 2009). Especially in Asian and African parts, the labour pool is in charge of disposing of the majority of the e-waste. The availability of various useful metals, including iron, aluminium, cobalt, germanium, bismuth, and antimony, as well as important and valuable metals like gold, platinum, silver, palladium, rhodium, and copper, makes e-waste an alluring revenue source for regional trash vendors, junkyards, and recycling plants (Fig. 14.1) (Deubzer et al. 2019).

## 14.2 Toxic Elements in E-waste Are Potentially Hazardous to Humans

Some researchers provided toxicity findings and emphasised the potential adverse health consequences of e-waste contact (Law et al. 2008; Tsydenova and Bengtsson 2011). Despite the fact that exposure routes depend on the toxins and the amount of reuse of materials, humans are exposed is often likely to occur via inhaling, ingesting, and skin contact (Grant et al. 2013). Furthermore, humans will be susceptible to e-waste-based contaminants (e.g. polychlorinated biphenyls and PBDEs, lead, and cadmium) by indirect channels, such as direct exposure to contaminated soils, dirt, atmosphere, groundwater, and food products (Zou et al. 2007; Wu et al.

2008). Some very hazardous persistent organic pollutants (POPs) have been detected in the blood, scalp, faeces, and foetuses of individuals who are employed in traditional e-waste recycling plants (Bi et al. 2007; Chan et al. 2007). Investigations on wider population susceptibility have also shown that young kids (under 6 years) have elevated plasma lead and cadmium concentrations and that these amounts are associated with their families' participation in rudimentary e-waste resource recovery (Huo et al. 2007; Zheng et al. 2008). Additionally, minors often labour as "rag pickers" were the most negatively impacted by either legal or unofficial e-waste disposal (Shamim et al. 2015). Different researchers have noted abnormally elevated levels of lead and chromium in blood, persistent toxic substances (PTSs), lung problems, leukaemia infections, a greater prevalence of skin irritation, headaches, dizziness, nausea, chronic gastroenteritis, and stomach and duodenal lesions (Lundgren 2012). Researchers made a comparison between the afflicted kids and a healthy control that didn't recycle. Although the negative consequences of ingesting certain poisonous substances through different routes of exposure are known, the impacts brought on by mixes of such substances are still not precisely known (Shamim et al. 2015).

## 14.3 Toxic Chemicals in E-waste and Their Pollutants

E-waste destruction affects the human body in two main ways: (i) through food chain problems, where harmful chemicals from waste or primary recycling methods cause residues to access the food chain and subsequently be transmitted to humans; and (ii) directly through the employees who work in primary recycling sectors, where they are exposed to harmful chemicals on the work. Various studies have also shown that waste recycling has an immediate effect on workers. A consequential issue is the risk that e-waste toxic effects may negatively affect human health over the long run and also in the short term (Zhao et al. 2008; Xing et al. 2009; Eguchi et al. 2012).

The elements and proportions in e-waste are mostly determined by the supplier, device type, design, technology, and duration of the equipment (Stenvall et al. 2013). Seventy per cent of the total toxic chemicals in heavy metal ions are found in e-waste. These harmful chemicals account for only around 2.7% of the overall, yet they cause a wide range of health problems owing to contamination of the environment. Metals are introduced to the biological process via soil, water, and air. Table 14.1 shows the health implications of toxic metals as well as other substances derived from e-waste.

## 14.4 Recent Worldwide E-waste Output Statistics

In the past few years, there has been a noticeable upsurge of 3–4% percentage of e-waste disposal (Balde et al. 2015, 2017). Globally, the disposal of e-waste has grown at a pace of about 6% around the year 2019 (Forti et al. 2020). According to estimates, 17.4 Mt of technological inputs, 13.1 Mt of heavy machinery, 10.8

**Table 14.1** Negative health hazards of various toxic chemicals encountered in e-waste (Kiddee et al. 2013, 2020)

| S. No. | Element | Electronic component | Impact on health |
|---|---|---|---|
| 1 | Aluminium | Microprocessors, hard drives, central processing unit (CPUs), cell phones | Neurotoxic, embryotoxicity |
| 2 | Arsenic | Cell phones | Ageing skin, higher diabetes, and cancer risk |
| 3 | Antimony | Cathode-ray-tubes (CRTs), cell phones | Pulmonary diseases |
| 4 | Barium | Fluorescent tubes, CRTs, cell phones | Irregular heartbeat, respiratory disorder, excessively high blood pressure, loss of muscle function |
| 5 | Beryllium | X-ray devices, laptops | Affects the nervous system and organs such as kidneys and liver |
| 6 | Cadmium | Pinter ink, printer toner, CRTs, pyroelectric detectors, cell phones | Kidney infection, fertility problems, pulmonary emphysema, osteoporosis |
| 7 | Chromium | Cell phones, floppy diskettes, tape drives | Stimulates DNA damage, lung carcinoma, carcinogen to living beings |
| 8 | Cobalt | CRTs, cell phones, hard disk drives | Increases osteoblast number |
| 9 | Copper | Microprocessors, CPUs, cell phones, CRTs | Liver disease |
| 10 | Iron | CRTs, cell phones, printed circuit broads (PCBs) | Liver disease |
| 11 | Lead | CRTs, cell phones, led bulbs | Renal disease, damaged central nervous system (CNS), cardiovascular disease |
| 12 | Lithium | Dry-cell, electric batteries | Causes nauseousness, lethargy, amyotonia |
| 13 | Manganese | Cell phones, CRTs | Pulmonary problems |
| 14 | Mercury | PCB, electric batteries | Effects on the brain, liver, and infant neurobehavioral development |
| 15 | Nickel | CRTs, PCB, cell phones | Causes lung carcinoma, heart disease, developmental disorders in infants, hypertension |
| 16 | Palladium | Hard disk drives, cell phones, PCB | Skin inflammation, sore eyes |
| 17 | Selenium | Cell phones, PCB | Loss of hair, brittle nails |
| 18 | Silver | Cell phones, PCB, condensers (capacitors), microchips | Damages nucleic acids |
| 19 | Tantalum | Power supply unit (PSU), PCB | Ocular pruritus, pulmonary problems |
| 20 | Vanadium | Cell phones, CRTs | The damaged central nervous system, cardiovascular disease |

(continued)

**Table 14.1** (continued)

| S. No. | Element | Electronic component | Impact on health |
|---|---|---|---|
| 21 | Zinc | Cell phones, CRTs, PCB | Hypocupraemia, neurological disorders |

Mt of thermal exchanger hardware, 6.7 Mt of computers and displays, 4.7 Mt of tiny IT and telephone devices, and 0.9 Mt of bulbs made up the world's e-waste during 2019 (Forti et al. 2020). It is important to note that across all countries, the amount of e-waste generated overall per individual has risen yearly. The majority of e-waste in the year 2019 came from Asia, which includes 17 nations. A majority of Asian nations' e-waste was produced in China, India, Japan, and Indonesia. The laws governing e-waste in many Asian countries forbid the transfer of e-waste across international borders and require the authorised collection of created e-waste for disposal at facilities equipped with the necessary technologies (Pathak and Srivastava 2017; Amemiya 2018; Wang et al. 2020). Due to different e-waste policy initiatives across many Asian countries, official e-waste recycling has only slightly increased and has neither managed to keep up also with an unparalleled increase in global e-waste accumulation. Ineffective regional and worldwide e-waste laws and agreements restricted EEE treatment under e-waste operational guidelines, and inadequate e-waste landfilling, gathering, and reusing norms are thought to be variables that contribute to the continued use of construction wastes in Asian countries under adverse circumstances (Wei and Liu 2012; Balde et al. 2017; Wang et al. 2017).

## 14.5 Advantages and Drawbacks Involved in Managing E-waste

E-waste contains rich secondary resources such as metals, polymers, glasses, and rare earth metals. According to statistics, an average cathode-ray tube television contains about 450 g of copper, 227 g of aluminium, and 5.6 g of gold, making e-waste a rich source of precious metals (Zeng et al. 2018). Meanwhile, collecting essential and conveniently economically recoverable components, including elements that are available in relatively large quantities and recoverable states, has traditionally been the primary focus of conventional e-waste reduction and reuse (Baccini and Brunner 2012).

E-waste management is primarily challenging because of its immense complexity and sheer volume. Hazardous compounds are also released during the treatment and regeneration of e-waste; thus, it is not just a source of important commodities. For example, the environmental and health impacts are greatly concerned by toxic compounds found in e-waste such as primary pollutants like lead, mercury, arsenic, cadmium, and polychlorinated biphenyls, and secondary pollutants like dioxins and furans are formed as residues through treatment and regeneration (Orlins and Guan 2016). Regarding effective e-waste control, a comprehensive strategy that includes collecting all types of e-waste at the end of their useful lifespan and recycling them completely to ensure that no components are discarded is needed (Song et al. 2015). In nations like China and India, which seem to be major producers of e-waste and suppliers of e-waste around the globe, the volume of e-waste is expanding, causing a major challenge (Wang et al. 2016). When combined with the challenging task of extracting e-waste elements (some of which are hopped, while others are bolted, or connected around each other), the domestic custom of disposing of all types of e-waste at once makes it even more challenging to separate e-waste elements into different groups like metallic materials, plastic containers for their efficient device reprocessing. Because of inadequate initiatives made by regional government agencies to commercialise e-waste recycling regulations and collection approaches after the execution of pertinent regulations, residents are forced to advertise their electronic waste to peddlers or dispose of it as waste material as a result of environmental information and awareness about the alternatives for e-waste landfilling and collection (Wang et al. 2017).

Considering various obstacles, reprocessing e-waste presents a wide range of possibilities due to the enormous wealth of materials it contains and its function in slowing the rate at which e-waste is produced. The far more striking advantage of a structured recycling programme for electronic trash is the fact that it offers a controllable processing mechanism for the junk that would normally be disposed of in landfills or incinerators, causing environmental damage (Song et al. 2015). Additionally, a significant major advantage of reusing e-waste is the decrease in the amount of mining equipment to obtain the metals. Conserving resources lowers waste disposal and encourages the consumption of additional raw materials in processing (Cossu et al. 2012). The demand for new mines for such economically recoverable metals also decreases as a result of e-waste processing, making it one of its biggest advantages. Additionally, due to the growing global growth and diminishing metals grades, it is necessary to extract finer-grained and much more complex metals and minerals. This can be offset, at the very least by reprocessing e-waste because the content and average of metallic materials in e-waste are generally greater than those of metals that is retrieved from mining area (Zeng et al. 2018).

## 14.6 Metal Recovery Through Microbial-Mediated Techniques

Metals are mobilised by microbes through a process known as bioleaching, which involves changing the solid form of the metal into one that is soluble in water. Biohydrometallurgy depends on this process. In the presence of micro-organisms that are indigenous to these mining settings, metals are extracted from ore deposits

(Brierley and Brierley 2013). Procedures combining environmental microbiology, biotechnology, hydrometallurgy, environmental engineering, mineralogy, and mining engineering are referred to as bioleaching and biorecovery techniques in biohydrometallurgy. The chemistry and morphological characteristics of natural minerals are changed by a variety of biological mechanisms, such as bioleaching (the microbially catalysed leaching of metals), bio-oxidation (the microbial oxidation of minerals), bio-weathering (the long-term organic transition of rocks and minerals), and bioreduction (the microbially induced reductive precipitation of metals) (Işıldar et al. 2017). The ability of a microbial community to constrain and concentrate metals from the aqueous phase is known as biosorption. On a cell level, biosorption occurs at the cell wall or by a variety of metabolites, such as extracellular polysaccharides (EPS), metal-binding peptides, and polymeric materials (Gadd 2010). In the process of biosorption, the chemical functional groups of the cell wall are crucial (Ilyas and Lee 2014). Process variables including the metal content in the leachate liquor and the technology's metal-selective behaviour influence the choice of a suitable approach for metal recovery. Many recovery technologies used at the industrial scale combine the aforementioned standard methods (Fig. 14.2).

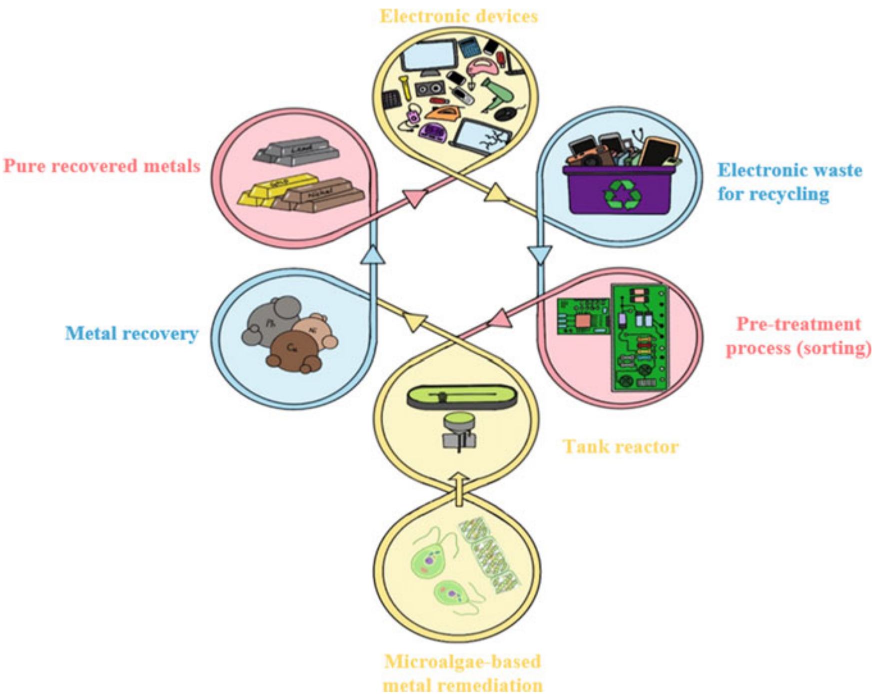



**Fig. 14.2** Graphical representation of microalgae-based metal recovery

## 14.7 Significance of Microbial Algae in the Remediation of E-waste

Microalgae have shown their viability for wastewater clean-up because of their low cost, simple operation, and profitability potential (Rittmann 2008). The synthesis of algal biomass provides an opportunity to reuse waste materials to develop new energy sources and materials (Wollmann et al. 2019). The green alga *Chlorella vulgaris* has active cells that are highly efficient at extracting gold from solutions (Ting and Mittal 2002). *Sargassum natans*, a brown alga, has a strong preference for Au (Das 2010; Table 14.2).

## 14.8 Conclusion and Future Prospect

E-waste is a significant issue on a regional and international scale. E-waste issues first surfaced in affluent nations but have recently expanded rapidly towards other nations. Due to the rapid change in consumer electronics as well as the quick deterioration that arises from technological progress, there is an immense amount of e-waste that is being produced. But, unless end-of-life maintenance is not carefully handled, e-waste can comprise a range of harmful compounds that can cause environmental harm and affect human wellness. E-waste is made up of various sorts of materials. It is anticipated that biotechnological metal recovery approaches would play a crucial role in sustainable development by enabling more cost- and environmentally friendly operations. Because bio-leachate solutions made from waste materials have a very complicated composition, new methods for recovering metals are needed. Although technological advances in precious metal bio-mining are simply the beginning of a new age of biomineral research, the long-term fall in ore grades makes the microbe-mediated biological concentration of metal seem to be the only viable refuge for the clean recovery of precious metals.

Commercial implementation of e-waste bioremediation and resource recovery remains a highly sought goal in a worldwide push towards a zero-waste circular economy, although being hampered by obstacles that are not insignificant. Gaps or deficiencies in our existing understanding or methodologies must be discovered and addressed by focusing intensive research efforts to go beyond technical barriers to enhance the biological approach to managing e-waste. The realisation that relying on a single biological workhorse, even one that has been carefully designed, to remediate complicated e-waste is a huge task comes along with expanding research findings. Thus, research directions have been redesigned to better handle the material heterogeneities of e-waste, whether they be metals or plastics, by utilising microbial communities. Mixed cultures are, in reality, challenging to implement because they present difficult challenges for maintaining favourable growth conditions for various

**Table 14.2** Recovery of electronic waste by different types of algae

| S. No. | Algae | Techniques | Elements | References |
|---|---|---|---|---|
| 1 | *Chlorella pyrenoidosa* | Biosorption | Copper | Moreira et al. (2019) |
| 2 | *Scenedesmus* sp. | Biosorption | Chromium (VI) | Pradhan et al. (2019) |
| 3 | *Botryococcus* sp. | Biosorption | Chromium (VI) | Shen et al. (2019) |
| 4 | *Sargassum filipendula* | Biosorption | Copper (II)<br>Silver (I) | do Nascimento Júnior et al. (2019) |
| 5 | *Sargassum glaucescens* | Biosorption | Arsenic (III)<br>Arsenic (V) | Tabaraki and Heidarizadi (2018) |
| 6 | *Chlorococcum* sp.<br>*Scenedesmus rubescens*<br>*Dunaliella tertiolecta*<br>*Tisochrysis lutea* | Bioleaching | Aluminium<br>Phosphorus<br>Chromium<br>Nickel<br>Copper<br>Zinc | Kalamaras et al. (2021) |
| 7 | *Galdieria phlegrea* | Bioaccumulation | Europium<br>Yttrium<br>Gadolinium<br>Lanthanum<br>Terbium<br>Cerium | Čížková et al. (2021) |
| 8 | *Gracilaria* | Biosorption | Nickel (II) | El-Naggar and Rabei (2020) |
| 9 | *Chlorella vulgaris* | Biosorption | Silver<br>Neodymium | Tunali and Yenigun (2021) |
| 10 | | Biosorption | Neodymium | Kucuker et al. (2017) |
| 11 | *Cladophora fracta* | Bioaccumulation | Copper<br>Zinc<br>Cadmium<br>Mercury | Ji et al. (2012) |
| 12 | *Ulva lactuca* | Biosorption | Copper<br>Zinc<br>Cadmium<br>Lead | Areco et al. (2012) |
| 13 | *Turbinaria conoides* | Biosorption | Gold | Vijayaraghavan et al. (2011) |
| 14 | *Chlorella* sp. | Bioaccumulation | Copper<br>Zinc | Maznah et al. (2012) |

microbes and ensuring the cellular environment is ideal for various enzymes, despite having great potential for handling the complex compositions of e-waste. The need to scale up the process from laboratory to pilot and field operations is equally crucial.

## References


Amemiya T (2018) Current state and trend of waste and recycling in Japan. Int J Earth Environ Sci 3(2):1–11

Areco MM, Hanela S, Duran J, dos Santos Afonso M (2012) Biosorption of Cu(II), Zn(II), Cd(II) and Pb(II) by dead biomasses of green alga *Ulva lactuca* and the development of a sustainable matrix for adsorption implementation. J Hazard Mater 213:123–132

Baccini P, Brunner PH (2012) Metabolism of the anthroposphere: analysis, evaluation, design. MIT Press

Balde CP, Forti V, Gray V, Kuehr R, Stegmann P (2017) The global E-waste monitor 2017: quantities, flows, and resources. United Nations University, International Telecommunication Union, and International Solid Waste Association, Bonn, Geneva, and Vienna, p 116

Balde CP, Wang F, Kuehr R, Huisman J (2015) The global E-waste monitor (2014): quantities, flows and resources. United Nations University, Tokyo & Bonn, p 79

Bi X, Thomas GO, Jones KC, Qu W, Sheng G, Martin FL, Fu J (2007) Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China. Environ Sci Technol 41(16):5647–5653

Brierley CL, Brierley JA (2013) Progress in bioleaching: part B: applications of microbial processes by the minerals industries. Appl Microbiol Biotechnol 97(17):7543–7552

Cesaro A, Belgiorno V, Gorrasi G, Viscusi G, Vaccari M, Vinti G, Salhofer S (2019) A relative risk assessment of the open burning of WEEE. Environ Sci Pollut Res 26(11):11042–11052

Chan JK, Xing GH, Xu Y, Liang Y, Chen LX, Wu SC, Wong MH (2007) Body loadings and health risk assessment of polychlorinated dibenzo-p-dioxins and dibenzofurans at an intensive electronic waste recycling site in China. Environ Sci Technol 41(22):7668–7674

Chi X, Wang MYL, Reuter MA (2014) E-waste collection channels and household recycling behaviors in Taizhou of China. J Clean Prod 80:87–95

Čížková M, Mezricky P, Mezricky D, Rucki M, Zachleder V, Vítová M (2021) Bioaccumulation of rare earth elements from waste luminophores in the red algae, *Galdieria Phlegrea*. Waste Biomass Valoriz 12(6):3137–3146

Cossu R, Salieri V, Bisinella V (eds) (2012) Urban mining: a global cycle approach to resource recovery from solid waste. CISA Publ.

Das N (2010) Recovery of precious metals through biosorption—a review. Hydrometallurgy 103(1–4):180–189

Deubzer O, Herreras L, Hajosi E, Hilbert I, Buchert M, Wuisan L, Zonneveld N (2019) Baseline and gap/obstacle analysis of standards and regulations. CEWASTE Voluntary Certification Scheme for Waste Treatment

do Nascimento Júnior WJ, da Silva MGC, Vieira MGA (2019) Competitive biosorption of $Cu^{2+}$ and $Ag^{+}$ ions on brown macro-algae waste: kinetic and ion-exchange studies. Environ Sci Pollut Res 26(23):23416–23428

Eguchi A, Nomiyama K, Devanathan G, Subramanian A, Bulbule KA, Parthasarathy P, Tanabe S (2012) Different profiles of anthropogenic and naturally produced organohalogen compounds in serum from residents living near a coastal area and e-waste recycling workers in India. Environ Int 47:8–16

El-Naggar, N. E. A., & Rabei, N. H. (2020). Bioprocessing optimization for efficient simultaneous removal of methylene blue and nickel by Gracilaria seaweed biomass. Sci Rep 10(1):1–21

Forti V, Balde CP, Kuehr R, Bel G (2020) The global e-waste monitor 2020: quantities, flows and the circular economy potential

Freitas R, Cardoso CE, Costa S, Morais T, Moleiro P, Lima AF, Pereira E (2020) New insights on the impacts of e-waste towards marine bivalves: the case of the rare earth element Dysprosium. Environ Pollut 260:113859

Gadd GM (2010) Metals, minerals and microbes: geomicrobiology and bioremediation. Microbiology 156(3):609–643

Grant K, Goldizen FC, Sly PD, Brune MN, Neira M, Van den Berg M, Norman RE (2013) Health consequences of exposure to e-waste: a systematic review. Lancet Global Health 1:350–361
Hicks C, Dietmar R, Eugster M (2005) The recycling and disposal of electrical and electronic waste in China—legislative and market responses. Environ Impact Assess Rev 25(5):459–471
Huo X, Peng L, Xu X, Zheng L, Qiu B, Qi Z, Piao Z (2007) Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ Health Perspect 115(7):1113–1117
Ilyas S, Lee J (2014) Biometallurgical recovery of metals from waste electrical and electronic equipment: a review. ChemBioEng Rev 1:148–169
Işıldar A, Vossenberg JVD, Rene ER, Hullebusch EDV, Lens PN (2017) Biorecovery of metals from electronic waste. In: Sustainable heavy metal remediation. Springer, Cham, pp 241–278
Ji L, Xie S, Feng J, Li Y, Chen L (2012) Heavy metal uptake capacities by the common freshwater green alga *Cladophora fracta*. J Appl Phycol 24(4):979–983
Kalamaras G, Kloukinioti M, Antonopoulou M, Ntaikou I, Vlastos D, Eleftherianos A, Dailianis S (2021) The potential risk of electronic waste disposal into aquatic media: the case of personal computer motherboards. Toxics 9(7):166
Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manag 33(5):1237–1250
Kiddee P, Pradhan JK, Mandal S, Biswas JK, Sarkar B (2020) An overview of treatment technologies of e-waste. Handbook of electronic waste management, pp 1–18
Kucuker MA, Wieczorek N, Kuchta K, Copty NK (2017) Biosorption of neodymium on *Chlorella vulgaris* in aqueous solution obtained from hard disk drive magnets. PLoS ONE 12(4):e0175255
Landrigan PJ, Fuller R, Acosta NJ, Adeyi O, Arnold R, Baldé AB, Bertollini R, Bose-O'Reilly S, Boufford JI, Breysse PN, Chiles T (2018) The Lancet Commission on pollution and health. The Lancet 391(10119):462–512
Law RJ, Herzke D, Harrad S, Morris S, Bersuder P, Allchin CR (2008) Levels and trends of HBCD and BDEs in the European and Asian environments, with some information for other BFRs. Chemosphere 73(2):223–241
Li W, Achal V (2020) Environmental and health impacts due to e-waste disposal in China—a review. Sci Total Environ 737:139745
Lundgren K (2012) The global impact of e-waste: addressing the challenge. International Labour Organization
Maznah WW, Al-Fawwaz AT, Surif M (2012) Biosorption of copper and zinc by immobilised and free algal biomass, and the effects of metal biosorption on the growth and cellular structure of *Chlorella* sp. and *Chlamydomonas* sp. isolated from rivers in Penang, Malaysia. J Environ Sci 24(8):1386–1393
Montalvo C, Peck D, Rietveld E (2016) A longer lifetime for products: benefits for consumers and companies
Moreira VR, Lebron YAR, Freire SJ, Santos LVS, Palladino F, Jacob RS (2019) Biosorption of copper ions from aqueous solution using *Chlorella pyrenoidosa*: optimization, equilibrium and kinetics studies. Microchem J 145:119–129
Orlins S, Guan D (2016) China's toxic informal e-waste recycling: local approaches to a global environmental problem. J Clean Prod 114:71–80
Pathak P, Srivastava RR (2017) Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. Renew Sustain Energy Rev 78:220–232
Pradhan D, Sukla LB, Mishra BB, Devi N (2019) Biosorption for removal of hexavalent chromium using microalgae *Scenedesmus* sp. J Clean Prod 209:617–629
Rittmann BE (2008) Opportunities for renewable bioenergy using microorganisms. Biotechnol Bioeng 100(2):203–212
Robinson BH (2009) E-waste: an assessment of global production and environmental impacts. Sci Total Environ 408(2):183–191
Shamim A, Mursheda AK, Rafiq I (2015) E-waste trading impact on public health and ecosystem services in developing countries. J Waste Resour 5(4):1–18

Shen L, Saky SA, Yang Z, Ho SH, Chen C, Qin L, Lu Y (2019) The critical utilization of active heterotrophic microalgae for bioremoval of Cr (VI) in organics co-contaminated wastewater. Chemosphere 228:536–544

Song Q, Li J, Zeng X (2015) Minimizing the increasing solid waste through zero waste strategy. J Clean Prod 104:199–210

Stenvall E, Tostar S, Boldizar A, Foreman MRS, Möller K (2013) An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manag 33(4):915–922

Stephenson JB (2009) Electronic waste: EPA needs to better control harmful US exports through stronger enforcement and more comprehensive regulation. DIANE Publishing

Tabaraki R, Heidarizadi E (2018) Simultaneous biosorption of Arsenic (III) and Arsenic (V): application of multiple response optimizations. Ecotoxicol Environ Saf 166:35–41

Ting YP, Mittal AK (2002) Effect of pH on the biosorption of gold by a fungal biosorbent. Resour Environ Biotechnol 3(4):229–239

Tsydenova O, Bengtsson M (2011) Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag 31(1):45–58

Tunali M, Yenigun O (2021) Biosorption of $Ag^+$ and $Nd^{3+}$ from single-and multi-metal solutions ($Ag^+$, $Nd^{3+}$, and $Au^{3+}$) by using living and dried microalgae. J Mater Cycl Waste Manag 23(2):764–777

Vijayaraghavan K, Mahadevan A, Sathishkumar M, Pavagadhi S, Balasubramanian R (2011) Biosynthesis of Au (0) from Au (III) via biosorption and bioreduction using brown marine alga *Turbinaria conoides*. Chem Eng J 167(1):223–227

Wang K, Qian J, Liu L (2020) Understanding environmental pollutions of informal e-waste clustering in global south via multi-scalar regulatory frameworks: a case study of Guiyu Town, China. Int J Environ Res Public Health 17(8):2802

Wang W, Tian Y, Zhu Q, Zhong Y (2017) Barriers for household e-waste collection in China: perspectives from formal collecting enterprises in Liaoning Province. J Clean Prod 153:299–308

Wang Z, Zhang B, Guan D (2016) Take responsibility for electronic-waste disposal. Nature 536:23–25

Wei L, Liu Y (2012) Present status of e-waste disposal and recycling in China. Procedia Environ Sci 16:506–514

Williams E, Kahhat R, Allenby B, Kavazanjian E, Kim J, Xu M (2008) Environmental, social, and economic implications of global reuse and recycling of personal computers. Environ Sci Technol 42(17):6446–6454

Wollmann F, Dietze S, Ackermann JU, Bley T, Walther T, Steingroewer J, Krujatz F (2019) Microalgae wastewater treatment: biological and technological approaches. Eng Life Sci 19(12):860–871

Wong CS, Duzgoren-Aydin NS, Aydin A, Wong MH (2007) Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environ Pollut 148(1):62–72

Wu JP, Luo XJ, Zhang Y, Luo Y, Chen SJ, Mai BX, Yang ZY (2008) Bioaccumulation of polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) in wild aquatic species from an electronic waste (e-waste) recycling site in South China. Environ Int 34(8):1109–1113

Xing GH, Chan JKY, Leung AOW, Wu SC, Wong MH (2009) Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ Int 35(1):76–82

Zeng X, Mathews JA, Li J (2018) Urban mining of e-waste is becoming more cost-effective than virgin mining. Environ Sci Technol 52:4835–4841

Zhao G, Wang Z, Dong MH, Rao K, Luo J, Wang D, Ma M (2008) PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Sci Total Environ 397(1–3):46–57

Zheng L, Wu K, Li Y, Qi Z, Han D, Zhang B, Huo X (2008) Blood lead and cadmium levels and relevant factors among children from an e-waste recycling town in China. Environ Res 108(1):15–20

Zou MY, Ran Y, Gong J, Mai BX, Zeng EY (2007) Polybrominated diphenyl ethers in watershed soils of the Pearl River Delta, China: occurrence, inventory, and fate. Environ Sci Technol 41(24):8262–8267

# Chapter 15
# Bioremediation of E-waste Through Microbial Exopolysaccharides: A Perspective

**Prasenjit Debbarma, Deep Chandra Suyal, Saurabh Kumar, Divya Joshi, Manali Singh, Jyoti Rajwar, Balwant Rawat, Hemant Dasila, Damini Maithani, and Ravindra Soni**

**Abstract** The industrial revolution followed by technological development successively paved the way to a new era in human civilization. In no case, this revolution will decline, thus, making anthropogenic environmental pollution a major global issue. In the present scenario, e-waste accumulation and management is seriously a daunting task that needs to be tackled efficiently. Traditional methods because of their disadvantages have fuelled the use of biological tools to recover the precious metals present in e-waste and to promote the studies of bioleaching and biodegradation processes. In this context, recently, microbial exopolysaccharides (EPSs) become the emerging

P. Debbarma · B. Rawat
Department of Botany, Iswar Chandra Vidyasagar College, Belonia, Tripura, India

D. C. Suyal (✉) · H. Dasila
Department of Microbiology, Akal College of Basic Sciences, Eternal University, Sirmaur, Himachal Pradesh, India
e-mail: deep.suyal@gmail.com

S. Kumar
Division of Crop Research, ICAR-Research Complex for Eastern Region, Patna, Bihar, India

D. Joshi
Patanjali Herbal Research Division, Patanjali Research Foundation Trust, Haridwar, Uttarakhand, India

M. Singh
Department of Biotechnology, Invertis Institute of Engineering and Technology (IIET), Invertis University, Bareilly, Uttar Pradesh, India

J. Rajwar
Department of Microbiology, Skyline University Nigeria, Kano, Nigeria

D. Maithani
School of Biotechnology, IFTM University, Moradabad, India

R. Soni
Department of Agricultural Microbiology, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

B. Rawat
School of Agriculture, Graphic Era Hill University, Dehradun, Uttarakhand, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_15

topic among environmentalists and biotechnologists due to its eco-friendly nature and diverse applications. Besides its tremendous uses in pharmaceutical industries, the food sector, pesticides, plastics, and many more, it also has to offer its potential use in e-waste bioremediation. The bioactive microbial EPS is a high molecular weight biopolymer having both homo- and hetero-polysaccharides. The biosorption mechanism which is important in the sequestration of heavy metal ions from the environment by this biopolymer is due to the net negative charge associated with this compound. Besides addressing e-waste pollution, this review critically analyzes the role of EPS in the sustainable and economic management of this burning issue. Moreover, it documents and compares the latest research, innovations, and advancements in the field of EPS-mediated e-waste bioremediation.

**Keywords** E-waste · Bioremediation · Exopolysaccharides · Biosorption · Environment

## 15.1 Introduction

During the eighteenth century, the industrial revolution was up swinging as the area of science and technology flourishes which led to a whole new world. With the dawn of the twentieth century, another significant revolution in the field of information and communication has tremendously flipped our way of living, industries, economies, institutions, and agriculture, respectively. Concurrently, these magnificent advancements also inevitably led to numerous troubles including the immense problem of huge quantity of electronic obsoletes or electronic waste (e-waste). E-waste contains both hazardous and non-hazardous wastes. However, all these wastes have a serious concern for environmental health and human society. Therefore, the challenge involves inappropriate management of e-waste is very crucial to sustain our ecosystem, livelihood, and environment. The sustainable approach comprises a majestic task to the digital societies which would further necessitate organized efforts to deal with e-waste (Debbarma et al. 2018).

The constant demand for new generation electronics set this technological advance a new height in the past few decades. With this continuing trend of technological development, e-waste is expanding exponentially worldwide. Recently, estimated data show that in 2019, the worldwide generation of e-waste was approximately 53.6 Mt, of which only about 17.4% of e-waste was collected and recycled, and the other 82.6% was not even documented (Forti et al. 2020). Since e-waste contains heterogeneous waste complex, viz., metals (60%), blends of many polymers (30%) and halogenated compounds, radioactive elements, and other pollutants (10%), respectively (Gaidajis et al. 2010; Tsydenova and Bengtsson 2011; Kumar et al. 2017). The sustainable, efficient, and economic management of e-waste is thus, a challenging task today and in the coming decades. Conventional techniques and its associated improper management of e-waste triggers serious health risks and contamination to the human population and environment, respectively, due to the liberation of toxic and hazardous substances from the waste (Robinson 2009; Kiddee et al. 2013; Debbarma et al. 2018).

In this context, bio-candidates especially microorganisms could be sharp-edged biological recycling tools to manage e-waste sustainably. As microbes are omnipresence and diverse in their physiology and functional aspects, they offer a wide range of bioremediation strategies (Debbarma et al. 2018; Pant et al. 2018). Microbe-based exopolysaccharides (EPSs) have known to have great applications in pharmacy, food industry, agriculture, oil recovery, wastewater treatment, bioremediation, textile industry, etc. (Ates 2015). Microbial EPS is high molecular weight bioactive polymer mainly composed of carbohydrates, pyruvic acid, uronic acid, succinic acid, acetic acid, and phosphate, produced extra-cellularly by diverse microbial communities (bacteria, fungi, algae, cyanobacteria, and archaea) having several ionic groups, viz., –COOH, –OH, –NH, $–PO_3$, and $–SO_4$ (Kranthi Raj et al. 2018). Both toxic and precious metals or metalloids from e-waste (Cd, Pd, Cr, Hg, Zn, Cu, Ni, Se, Au, Ag, Pt, Li, Pd, etc.) which are used in electronic parts including printed circuit boards, cathode ray tubes, liquid–crystal-display, batteries, e-plastics, etc., can be remediated through the ionic and electrostatic interactions between EPS and metals. Generally, this metal sequestration can be accomplished by several processes including biosorption and EPS-metal ion interaction (Pant et al. 2018). Indeed, EPS can't remove the wastes alone, but it can be included in the environmental remediation squad in association with the existing hydro- and/or bio-hydrometallurgical processes. In this perspective, the present mini-review discusses the role of microbial EPS, associated strategies, and hybrid technologies as an auxiliary technique for e-waste remediation and sustainability.

## 15.2 E-waste and Associated Hazardous Substances

E-waste is a multifaceted waste stream as it includes all discarded items of electrical and electronic equipment (EEE) and collectively referred to as waste electrical and electronic equipment (WEEE). Therefore, WEEE is a broad range of electronic gadgets and devices varying from household appliances to personal devices such as refrigerators, televisions, air conditioners, fluorescent lights, calculators, cell phones, and computers (Forti et al. 2020). Total material composition found in e-waste is extremely distinct which varies with items from different WEEE categories. More than 1000 various substances can be found in the entire e-waste composition which becomes hazardous after disposal to the environment. The chemical composition of e-waste indicates that materials such as metals (heavy, base, and precious metals), metalloids, e-plastic polymers, halogenated compounds, radioactive elements, etc., are very harmful (Tsydenova and Bengtsson 2011). The potential hazardous substances and compounds include Al, Ar, Sb, Cd, Pd, Hg, Li, Ba, Be, Cr, Cu, Ni, Se, Pt, Zn, Si, Sn, Ag, Au, Am, chlorofluorocarbon (CFC), tetrabromobisphenol A (TBBA), polychlorinated biphenyls (PCB), polybrominated diphenyl ethers (PBDE), polybrominated biphenyls (PBB), polyvinylchloride (PVC), acrylonitrile–butadiene–styrene (ABS), high-impact polystyrene (HIPS), etc. (Gaidajis et al. 2010; Sekhar et al. 2016).

## 15.3 Conventional Treatment Techniques for E-waste Management and Its Impact on Human and Environmental Health

Improper management of e-waste threatens our ecosystem. Old methods to tackle e-waste, viz., landfilling and incineration pose severe contamination to the environment. Though our landfill is already filled with other solid wastes, e-waste leachates which carry many toxic elements and compounds can move toward groundwater and contaminate it. Burning or incineration of e-waste releases carcinogenic gases that contain free radicals, viz., furans, dioxides, fluorocarbons, etc., into the atmosphere (Robinson 2009; Debbarma et al. 2018). On the other hand, the traditional recycling technique which majorly contributes to e-waste management also has many setbacks and shows partial potentiality to some extent. The informal recycling hub in third world countries produces more contamination than the rest of the world (Balasubramanian and Karthikeyan 2017). It involves manual dismantling and segregation of various parts of the waste followed by inadequate chipping, melting, and metal extraction through hydrometallurgical methods (Chen et al. 2015). In this process of recycling, heavy metals and persistent organic pollutants (POPs) are being exposed to the workers, localities, children, women, and aged people that in later stage gives rise to the acute health condition, sometimes to chronic issues (Kiddee et al., 2013). There is also a report which suggests the biomagnification of harmful heavy metals through soil–plant-human accumulation (Li et al. 2011).

In recent years, bio-hydrometallurgical methods such as bioleaching have emerged as an eco-friendly tool for e-waste management (Habibi et al. 2020; Tipre et al. 2021; Erust et al. 2021). Several autotrophic and chemotrophic microbial genera are employed for this purposes, viz., *Acidithiobacillus*, *Leptospirillum Aspergillus*, *Chromobacterium*, *Metallosphaera*, etc. However, despite of several advantages, these methods face some basic challenges especially related to microbial toxicity, formation of non-desired products and pH imbalance due to the productions of acids and/or other metabolites (Habibi et al. 2020). In this perspective, microbial EPS can be explored to enhance the efficiency of these processes.

## 15.4 An Array of Dynamic Sources of Microbial EPS

Microorganisms are the most abundant source of natural EPS. It is produced by different microbial communities from both eukaryotes and prokaryotes, namely bacteria, fungi, yeasts, microalgae, cyanobacteria, diatoms, and archaea (Payandi-Rolland et al. 2019). Biosynthesis and production of microbial EPS are one of the survival strategies which exhibit important biological functions such as cell aggregation and biofilm formation, cell adherence to the solid surface, cell to cell interaction, tolerance to heavy metal stress, and other environmental stress. Among all microbial sources, bacteria are the predominant producer of EPS, viz., *Bacillus*, *Aeromonas*, *Pseudomonas*, *Methylobacterium*, *Herminiimonas*, *Enterobacter*, *Shewanella*, *Rhizobium*, *Azotobacter*, *Paenibacillus*, *Lactobacillus*, *Ochrobactrum*, *Pantoea*, *Chryseomonas*, *Acetobacter*, *Agrobacterium*, *Thiomonas*, *Marinobacter*, *Sphingomonas*, *Pasteurella*, *Xanthomonas*, *Exiguobacterium*, etc. (Gupta and Diwan 2017; Saba et al. 2019). EPS-producing filamentous fungi and yeasts include *Aureobasidium pullulans*, *Aspergillus terreus* strain AML02, *Beauveria bassiana* strain 4580, *Schizophyllum commune*, *Rhodotorula* sp., *Sclerotium* sp., *Sporobolomyces* sp., etc., respectively (Kranthi Raj et al. 2018). Many algae and cyanobacteria such as *Porphyridium*, *Chlorella*, *Tetraselmis*, *Aphanothece*, *Arthrospira*, *Anabaena*, etc., and archaebacteria or extremophiles, namely *Alteromonas*, *Thermococcus*, *Geobacillus*, *Bacillus thermoantarcticus*, *Methanococcus*, *Thermotoga*, etc., are also a great source of EPS (Cruz et al. 2020).

## 15.5 The Potential Role of EPS in Microbial Remediation of E-waste

Microbes and their EPS have a significant potential role to deliver in sequestering and removing hazardous substances mainly metals or metalloids from e-waste. The acidic nature of EPS pertaining to non-carbohydrate composition in its structure gives the resistance against heavy metal stress in the environment (Fig. 15.1). Further, EPS possesses several functional groups, viz., amine, amide, carbonyl, carboxyl, hydroxyl, imidazole, imine, phosphodiester, phosphonate, sulfhydryl, sulfonate, and thioether that have innate affinities toward metal ions (Gupta and Diwan 2017). Moreover, the higher uronic acid content in EPS strengthens the anionicity which plays an essential role in interacting and binding cationic metals like $Cd^{2+}$, $Pd^{2+}$, $Hg^{2+}$, $Ni^{2+}$, $Cr^{2+}$, $Zn^{2+}$, etc. This characteristic of microbial EPS makes them suitable biological tools to remove metals through biosorption (Bhunia et al., 2018). Interaction between EPS and metal ion depends on various factors such as types of functional ionic groups present on the surface of EPS, the bioavailability of metal ions, pH in the ecosystem, and the EPS-producing microbial consortia. Therefore, the metal-binding properties and mechanism involved is very important to reduce the risks of mobility and bioavailability of hazardous metals via metabolic or non-metabolic accumulation or

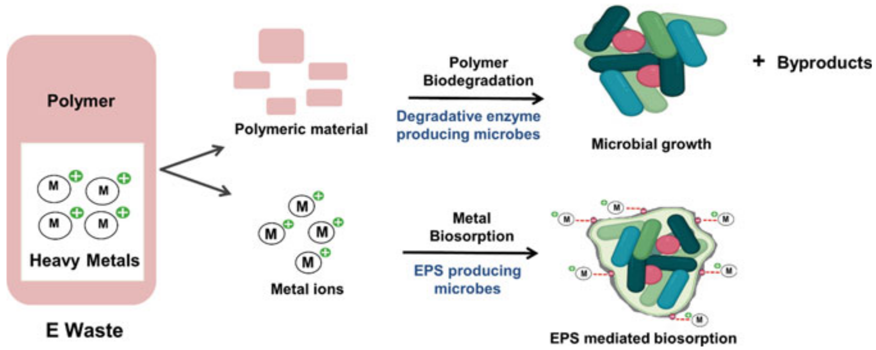



**Fig. 15.1** Role of microorganisms in e-waste bioremediation

immobilization. EPS-mediated bioremediation thus offers not only removal but also recovery of precious metals from e-waste as potential biosorbent (Gupta and Diwan 2017; Saba et al. 2019).

## 15.6 Mechanism of EPS-Mediated Biosorption of Heavy Metals

There are several mechanisms involved for biosorption that primarily make use of EPS to sequestration of metals. Among these, complexation and ion exchange are the methods that involve polysaccharide for the biosorption. Complexation is the removal of metal ion from an aqueous solution by the formation of a complex on the surface of the cell as an interaction between metal ions and carboxyl groups (–COOH) that are generally found in microbial polysaccharides (Muthu et al. 2017). Ion exchange involves polysaccharides on the cell walls of microorganisms. These possess $K^+$, $Na^+$, $Ca^{2+}$, and $Mg^{2+}$ ions resulting in metal ion uptake from the surrounding based on their affinities and interactions (Cui et al. 2020).

The water-soluble glycopolymers impart unique physiochemical and rheological properties to EPS and make them suitable for metal biosorption. Contrary to homo-polysaccharides, hetero-polysaccharides are more efficient in it due to the presence of different functional groups. They confer polyanionic nature to the EPS that helps in sequestering the positively charged metal ions from the waste materials (Gupta and Diwan 2017). It can be via homogeneous consortial EPS or pure cultures, heterogeneous consortial EPS or mixed cultures, dead biomass/cells or immobilized EPS/cells (1).

## 15.7 Sustainable Bioremediation Strategies for E-waste Through EPS-Metal Ion Interaction

Major EPS-mediated strategies for metal ion bioremediation are based on homogeneous consortial EPS, heterogeneous consortial EPS, dead cells EPS, immobilized EPS, and chemically modified EPS (Table 15.1).

### *15.7.1 Homogenous Consortial EPS*

Activated sludge has been exploited for heavy metals bioremediation due to the presence of rich metal ion-resistant bacterial species. *Agrobacterium* spp., *Rhizobium tropici*, and *Shewanella oneidensis* were found effective for cadmium ion adsorption (Muthu et al. 2017). *Marinobacter* has been reported to adsorb more copper ions than lead ions under neutral pH (Bhaskar and Bhosle 2006). Further, *Enterobacter cloacae* EPS was able to reduce the heavy metals by 65 and 20% (Gupta and Diwan 2017). Enhanced chromium ion uptake and tolerance in this bacterium is reported due to EPS synthesis. In addition to this, purified EPS from *Arthrobacter* ps-5 also showed biosorption of $Cu^{2+}$, $Pb^{2+}$, and $Cr^{2+}$.

### *15.7.2 Heterogeneous Consortial EPS (HCE)*

HCE is an attractive strategy for heavy metals bioremediation. Mixed culture EPS from activated sludge has been reported to reduce 85–95% of 10–100 ppm initial zinc, copper, chromium, and cadmium (Liu et al. 2001). Gawali Ashruta et al. (2014) have reported a 75–85% reduction in heavy metal content through Gram-negative bacterial consortia within 2 h of their mutual contact. In another study, a consortium from hydrocarbon-contaminated water reduces 87.12% of $Cd^{2+}$, 19.82% of $Zn^{2+}$, and 37.64% of $Cu^{2+}$ load (Martins et al. 2008).

### *15.7.3 Immobilized EPS*

Microorganisms attached to the solid surface had been reported to produce more polysaccharides without significantly changing the specific growth rate. Therefore, the immobilization of microbial cells with their EPS could facilitate higher biosorption. Immobilization of *Chryseomonas luteola* in alginate beads and *Paenibacillus polymyxa* in agar beads has shown the enhanced heavy metals sequestration from aqueous solution (Gupta and Diwan 2017).

**Table 15.1** Microbial EPS-mediated biosorption

| Microorganisms/sources | Target metals | References |
|---|---|---|
| *Homogenous consortial EPS* | | |
| *Thiomonas* sp. CB2 | As | (Marchal et al. 2011) |
| *Rhizobium radiobacter* | Pb, Zn | (Wang et al. 2013) |
| *Sinorhizobium meliloti* | As, Hg | (Nocelli et al. 2016) |
| *Klebsiella* sp. J1 | Cu | (Yang et al. 2015) |
| *Arthrobacter* ps-5 | Cu, Pb, Cr | (Shuhong et al. 2014) |
| *Nostoc*, *Cyanospira* | Cu | (De Philippis et al. 2007) |
| *Gloeocapsa gelatinosa* | Pb | (Raungsomboon et al. 2006) |
| *Bacillus firmus* | Cu, Pb, Zn | (Salehizadeh and Shojaosadati 2003) |
| *Serratia* sp. | Cd | (Valdman et al. 2005) |
| *Lysinibacillus* sp. HG17 | Hg | (Francois et al. 2012) |
| *Heterogenous consortial EPS* | | |
| EPS from activated sludge treating municipal wastewater | Zn, Cu, Cr | (Liu et al. 2001) |
| Gram-negative bacteria consortium | Zn, Pb, Cr, Cu, Cd | (Gawali Ashruta et al. 2014) |
| Microbial consortium in a hydrocarbon co-contaminated aqueous system | Cd, Zn, Cu | (Martins et al. 2008) |
| Activated sludges domestic wastewater treatment plants | Pb, Cu, Cd, Ni | (Fernando et al. 2020) |
| Activated sludge | Cd, Cu | (Comte et al. 2006) |
| Waste activated sludge | Hg | (Zhang et al. 2020) |
| *Dead biomass/cells* | | |
| Dead biomass of *Ochrobactrum anthropi* | Cd | (Rani et al. 2010) |
| *Bacillus cereus*, *Bacillus pumilus* and *Pantoea agglomerans* | Cr | (Sultan et al. 2012) |
| *Lysinibacillus* sp. HG17 and *Bacillus* sp. CM111 | Hg | (Francois et al. 2012) |
| *Immobilized cells/EPS* | | |
| *Chryseomonas luteola* immobilized in alginate bead with its EPS | Cd, Co, Ni, Cu | (Kemp and Linhardt 2010) |
| *Paenibacillus polymyxa* EPS immobilized in agar beads | Pb | (Kemp and Linhardt 2010) |
| *Modified EPS* | | |
| Phosphorylated bacterial cellulose prepared from *Acetobacter* | Lanthanide ions, transition metal ions | (Oshima et al. 2008) |

### 15.7.4 Dead Biomass EPS (DBE)

DBE of *Ochrobactrum anthropic* is reported to remove cadmium and other heavy metals ions with tolerance up to 30 mg/L of cadmium ion concentration (Rani et al. 2010). Similarly, *Bacillus cereus*, *Bacillus pumilus*, and *Pantoea agglomerans* DBE were also found effective for chromium ion biosorption (Gupta and Diwan 2017). However, dead biomass was found to be less efficient than immobilized EPS, for copper, cadmium, and lead ion biosorption (Gupta and Diwan 2017).

### 15.7.5 Chemically Modified EPS

The presence of ionizable functional groups in microbial EPS makes them suitable to sequester heavy metals. Chemical modifications (acetylation, methylation, and phosphorylation) of functional groups present in EPS modify the interaction of EPS with metal ions thus influencing the biosorption efficiency of EPS. Phosphorylation in bacterial cellulose from *Acetobacter* had more efficient biosorption potential for heavy metals than unmodified bacterial culture (Oshima et al. 2008). However, very few modifications had studied in the past, and the majority of them remain to be studied in detail.

## 15.8 Future of EPS in Hybrid Techniques for Metal Extraction

Chemical and biological metal extraction techniques have not proven efficient when employed alone. The main concern with chemical leaching is ecotoxicity whereas biological leaching is time-consuming and lesser efficient. Therefore, various hybrid approaches are being developed nowadays that comprises both chemo- and bioleaching methods. Different combinations of chemical ligands and microorganisms have been proposed for metal extraction, viz., EDTA and *Acidithiobacillus ferrooxidans* for Zn and Pb (Cheikh et al. 2010); citrate and *Penicillium bilaiae* for Cd (Arwidsson et al. 2010); tartrate and *Aspergillus niger* for Cd, Pb, and Zn (Arwidsson et al. 2010); nitrilotriacetic acid and *Acidithiobacillus caldus* for Cd and Zn (Aston et al. 2010); citrate and *Aspergillus niger* for Cd (Mulligan and Kamali 2003); DTPA and *Candida albicans* for Cr, Pb, Cu, Zn (Sohnle et al. 2001). Mostly, live organisms are employed along with physicochemical extraction methods (Sinha et al. 2018; Priya and Hait 2019). This practice may reduce the efficiency of the processes because extracted metal could be detrimental to the microorganisms. In that scenario, making use of microbial EPS could be beneficial for accelerating metal extraction process. The major advantages of using EPS are—high sensitivity which allows metal extraction even under low concentration environments and the ability to reuse multiple times. However, large-scale applications of EPS-mediated hybrid technologies will require optimization of associated biochemical parameters. Moreover, the extraction of a targeted metal ion would be a challenging task due to the non-specificity of EPS functional groups. Genetic engineering and mutagenesis technique may prove useful to remove these hurdles.

## 15.9 Concluding Remarks

Sustainable and eco-friendly management to tackle the huge burden of e-waste is the need of the hour to digital societies. Microbe-based EPS could be one great aspect to that in the field of bioremediation. This technique employed electrostatic interactions owing to the availability of charged metallic ions which could be enhanced after genetic tailoring to boost more EPS production in microbial consortia or monoculture. Like hybrid technology, both biodegrading microbes for e-plastics where many metals are used as fillers/plasticizers/pigments and EPS-producing microbes for biosorption of those metals should be identified and encourage in the future for best bioremediation.

## References

Arwidsson Z, Johansson E, von Kronhelm T, Allard B, van Hees P (2010) Remediation of metal contaminated soil by organic metabolites from fungi I-production of organic acids. Water Air Soil Pollut 205(1–4):215. https://doi.org/10.1007/s11270-009-0067-z

Aston JE, Apel WA, Lee BD, Peyton BM (2010) Effects of cell condition, pH, and temperature on lead, zinc, and copper sorption to Acidithiobacillus caldus strain BC13. J Hazard Mater 184(1–3):34–41. https://doi.org/10.1016/j.jhazmat.2010.07.110

Ates O (2015) Systems biology of microbial exopolysaccharides production. Front Bioeng Biotechnol 3:200. https://doi.org/10.3389/fbioe.2015.00200

Balasubramanian R, Karthikeyan OP (2017) E-waste recycling environmental and health impacts. In: Chen JP, Wang LK, Wang MS, Hung YT, Shammas NK (eds) Handbook of advanced industrial and hazardous wastes management. CRC Press, Abingdon, pp 339–364

Bhaskar PV, Bhosle NB (2006) Bacterial extracellular polymeric substance (EPS): a carrier of heavy metals in the marine food-chain. Environ Internat 32(2):191–198. https://doi.org/10.1016/j.envint.2005.08.010

Bhunia B, Uday USP, Oinam G, Mondal A, Bandyopadhyay TK, Tiwari ON (2018) Characterization, genetic regulation and production of cyanobacterial exopolysaccharides and its applicability for heavy metal removal. Carbohydr Polym 179:228–243. https://doi.org/10.1016/j.carbpol.2017.09.091

Cheikh M, Magnin JP, Gondrexon N, Willison J, Hassen A (2010) Zinc and lead leaching from contaminated industrial waste sludges using coupled processes. Environ Technol 31(14):1577–1585. https://doi.org/10.1080/09593331003801548

Chen M, Huang J, Ogunseitan OA, Zhu N, Wang Y-M (2015) Comparative study on copper leaching from waste printed circuit boards by typical ionic liquid acids. Waste Manage 41:142–147. https://doi.org/10.1016/j.wasman.2015.03.037

Comte S, Guibaud G, Baudu M (2006) Biosorption properties of extracellular polymeric substances (EPS) resulting from activated sludge according to their type: soluble or bound. Process Biochem 41(4):815–823. https://doi.org/10.1016/j.procbio.2005.10.014

Cruz D, Vasconcelos V, Pierre G, Michaud P, Delattre C (2020) Exopolysaccharides from cyanobacteria: strategies for bioprocess development. Appl Sci 10(11):3763. https://doi.org/10.3390/app10113763

Cui D, Tan C, Deng H, Gu X, Pi S, Chen T et al (2020) Biosorption mechanism of aqueous $Pb^{2+}$, $Cd^{2+}$, and $Ni^{2+}$ ions on extracellular polymeric substances (EPS). Archaea. https://doi.org/10.1155/2020/8891543

De Philippis R, Paperi R, Sili C (2007) Heavy metal sorption by released polysaccharides and whole cultures of two exopolysaccharide-producing cyanobacteria. Biodegradation 18(2):181–187. https://doi.org/10.1007/s10532-006-9053-y

Debbarma P, Zaidi MGH, Kumar S, Raghuwanshi S, Yadav A, Shouche Y et al (2018) Selection of potential bacterial strains to develop bacterial consortia for the remediation of e-waste and its in situ implications. Waste Manage 79:526–536. https://doi.org/10.1016/j.wasman.2018.08.026

Erust C, Akcil A, Tuncuk A, Deveci H, Yazici EY, Pansa S (2021) A novel approach based on solvent displacement crystallisation for iron removal and copper recovery from solutions of semi-pilot scale bioleaching of WPCBs. J Clean Prod 294:126346. https://doi.org/10.1016/j.jclepro.2021.126346

Fernando I, Lu D, Zhou Y (2020) Interactive influence of extracellular polymeric substances (EPS) and electrolytes on the colloidal stability of silver nanoparticles. Environ Sci Nano 7(1):186–197. https://doi.org/10.1039/C9EN00861F

Forti V, Balde CP, Kuehr R, Bel G (2020) The global E-waste monitor 2020: quantities, flows and the circular economy potential. United Nations University, Bonn

Francois F, Lombard C, Guigner J-M, Soreau P, Brian-Jaisson F, Martino G et al (2012) Isolation and characterization of environmental bacteria capable of extracellular biosorption of mercury. Appl Environ Microbiol 78(4):1097–1106. https://doi.org/10.1128/AEM.06522-11

Gaidajis G, Angelakoglou K, Aktsoglou D (2010) E-waste: environmental problems and current management. J Eng Sci Technol Rev 3(1):193–199

Gawali Ashruta A, Nanoty V, Bhalekar U (2014) Biosorption of heavy metals from aqueous solution using bacterial EPS. Int J Life Sci 2:373–377

Gupta P, Diwan B (2017) Bacterial exopolysaccharide mediated heavy metal removal: a review on biosynthesis, mechanism and remediation strategies. Biotechnol Rep 13:58–71. https://doi.org/10.1016/j.btre.2016.12.006

Habibi A, Kourdestani SS, Habibi M (2020) Biohydrometallurgy as an environmentally friendly approach in metals recovery from electrical waste: a review. Waste Manag Res 38(3):1–13. https://doi.org/10.1177/0734242X19895321

Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manage 33(5):1237–1250. https://doi.org/10.1016/j.wasman.2013.01.006

Kranthi Raj K, Sardar UR, Bhargavi E, Devi I, Bhunia B, Tiwari ON (2018) Advances in exopolysaccharides based bioremediation of heavy metals in soil and water: a critical review. Carbohydr Polym 199:353–364. https://doi.org/10.1016/j.carbpol.2018.07.037

Kumar A, Holuszko M, Espinosa DCR (2017) E-waste: an overview on generation, collection, legislation and recycling practices. Resour Conserv Recycl 122:32–42. https://doi.org/10.1016/j.resconrec.2017.01.018

Li J, Duan H, Shi P (2011) Heavy metal contamination of surface soil in electronic waste dismantling area: site investigation and source-apportionment analysis. Waste Manag Res 29(7):727–738. https://doi.org/10.1177/0734242X10397580

Liu Y, Lam MC, Fang HH (2001) Adsorption of heavy metals by EPS of activated sludge. Water Sci Technol 43(6):59–66. https://doi.org/10.2166/wst.2001.0340

Marchal M, Briandet R, Halter D, Koechler S, DuBow MS, Lett M-C et al (2011) Subinhibitory arsenite concentrations lead to population dispersal in *Thiomonas* sp. PLoS ONE 6(8):e23181. https://doi.org/10.1371/journal.pone.0023181

Martins PSDO, Almeida NFD, Leite SGF (2008) Application of a bacterial extracellular polymeric substance in heavy metal adsorption in a co-contaminated aqueous system. Braz J Microbiol 39(4):780–786. https://doi.org/10.1590/S1517-83822008000400034

Mulligan CN, Kamali M (2003) Bioleaching of copper and other metals from low-grade oxidized mining ores by *Aspergillus niger*. J Chem Technol Biotechnol Int Res Process Environ Clean Technol 78(5):497–503. https://doi.org/10.1002/jctb.830

Muthu M, Wu H-F, Gopal J, Sivanesan I, Chun S (2017) Exploiting microbial polysaccharides for biosorption of trace elements in aqueous environments scope for expansion via nanomaterial intervention. Polymers 9(12):721. https://doi.org/10.3390/polym9120721

Nocelli N, Bogino PC, Banchio E, Giordano W (2016) Roles of extracellular polysaccharides and biofilm formation in heavy metal resistance of rhizobia. Materials 9(6):418. https://doi.org/10.3390/ma9060418

Oshima T, Kondo K, Ohto K, Inoue K, Baba Y (2008) Preparation of phosphorylated bacterial cellulose as an adsorbent for metal ions. React Funct Polym 68(1):376–383. https://doi.org/10.1016/j.reactfunctpolym.2007.07.046

Pant D, Giri A, Dhiman V (2018) Bioremediation techniques for E-waste management. In: Varjani S, Gnansounou E, Gurunathan B, Pant D, Zakaria Z (eds) Waste bioremediation. Springer, Singapore, pp 105–125

Payandi-Rolland DD, Roche A, Vennin E, Visscher PT, Amiotte-Suchet P, Thomas C et al (2019) Carbonate precipitation in mixed cyanobacterial biofilms forming freshwater microbial tufa. Minerals 9(7):409. https://doi.org/10.3390/min9070409

Priya A, Hait S (2019) Extraction of Cu and Zn from high-grade printed circuit board scraps by conventional and hybrid bioleaching. In: Kalamdhad A, Singh J, Dhamodharan K (eds) Advances in waste management. Springer, Singapore, pp 511–523

Rani MJ, Hemambika B, Hemapriya J, Kannan VR (2010) Comparative assessment of heavy metal removal by immobilized and dead bacterial cells: a biosorption approach. Afr J Environ Sci Technol 4(2)

Raungsomboon S, Chidthaisong A, Bunnag B, Inthorn D, Harvey NW (2006) Production, composition and $Pb^{2+}$ adsorption characteristics of capsular polysaccharides extracted from a cyanobacterium *Gloeocapsa gelatinosa*. Water Res 40(20):3759–3766. https://doi.org/10.1016/j.watres.2006.08.013

Robinson BH (2009) E-waste: an assessment of global production and environmental impacts. Sci Total Environ 408(2):183–191. https://doi.org/10.1016/j.scitotenv.2009.09.044

Saba, Rehman Y, Ahmed M, Sabri AN (2019) Potential role of bacterial extracellular polymeric substances as biosorbent material for arsenic bioremediation. Bioremed J 23(2):72–81. https://doi.org/10.1080/10889868.2019.1602107

Salehizadeh H, Shojaosadati SA (2003) Removal of metal ions from aqueous solution by polysaccharide produced from *Bacillus firmus*. Water Res 37(17):4231–4235. https://doi.org/10.1016/S0043-1354(03)00418-4

Sekhar VC, Nampoothiri KM, Mohan AJ, Nair NR, Bhaskar T, Pandey A (2016) Microbial degradation of high impact polystyrene (HIPS), an e-plastic with decabromodiphenyl oxide and antimony trioxide. J Hazard Mater 318:347–354. https://doi.org/10.1016/j.jhazmat.2016.07.008

Shuhong Y, Meiping Z, Hong Y, Han W, Shan X, Yan L et al (2014) Biosorption of $Cu^{2+}$, $Pb^{2+}$ and $Cr^{6+}$ by a novel exopolysaccharide from *Arthrobacter* ps-5. Carbohydr Polym 101:50–56. https://doi.org/10.1016/j.carbpol.2013.09.021

Sinha R, Chauhan G, Singh A, Kumar A, Acharya S (2018) A novel eco-friendly hybrid approach for recovery and reuse of copper from electronic waste. J Environ Chem Eng 6(1):1053–1061. https://doi.org/10.1016/j.jece.2018.01.030

Sohnle PG, Hahn BL, Karmarkar R (2001) Effect of metals on Candida albicans growth in the presence of chemical chelators and human abscess fluid. J Lab Clin Med 137(4):284–289. https://doi.org/10.1067/mlc.2001.113577

Sultan S, Mubashar K, Faisal M (2012) Uptake of toxic Cr (VI) by biomass of exo-polysaccharides producing bacterial strains. Afr J Microbiol Res 6(13):3329–3336. https://doi.org/10.5897/AJMR12.226

Tipre DR, Khatri BR, Thacker SC et al (2021) The brighter side of e-waste—a rich secondary source of metal. Environ Sci Pollut Res 28:10503–10518. https://doi.org/10.1007/s11356-020-12022-1

Tsydenova O, Bengtsson M (2011) Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manage 31(1):45–58. https://doi.org/10.1016/j.wasman.2010.08.014

Valdman E, Leite SG, Caldas SM (2005) Effect of biosurfactant concentration on cadmium biosorption by *Serratia* sp. isolated from tropical soil. In: Proceedings of XIII international conference on heavy metals in the environment. Rio de Janeiro, Brazil

Wang L, Yang J, Chen Z, Liu X, Ma F (2013) Biosorption of Pb (II) and Zn (II) by extracellular polymeric substance (EPS) of *Rhizobium radiobacter*: equilibrium, kinetics and reuse studies. Arch Environ Prot 39(2):129–140

Yang J, Wei W, Pi S, Ma F, Li A, Wu D et al (2015) Competitive adsorption of heavy metals by extracellular polymeric substances extracted from *Klebsiella* sp. J1. Biores Technol 196:533–539. https://doi.org/10.1016/j.biortech.2015.08.011

Zhang J, Wang P, Zhang Z, Xiang P, Xia S (2020) Biosorption characteristics of Hg (II) from aqueous solution by the biopolymer from waste activated sludge. Int J Environ Res Pub Health 17(5):1488. https://doi.org/10.3390/ijerph17051488

# Chapter 16
# Genetically Modified Microbes in E-waste Management: A Perspective

**Preeti, Akshita Raj, Namini Joshi, Janhvi Mishra Rawat, Satya Tapas, Bhabjit Pattnaik, and Balwant Rawat**

**Abstract** Global electronic waste is burgeoning day by day and emerging as a dreadful challenge. At the same time, availability of different recycling methods for e-waste is limited and each associated with pros and cons. The technologies used for recycling e-waste mainly involve mechanical and chemical methods. However, scientists and environmentalists are endorsing the biological method over conventional recycling approaches. In the biological recycling, microbes play essential role and use of genetic engineering has now raised the interest in generating microbes with multiple features/traits with improved efficiency. This chapter sheds light on the prospects of using genetically engineered microbes and provides comprehensive information about microbial e-waste management process.

**Keywords** Genetic engineering · Electronic waste · Recycling · Bioremediation

Preeti (✉) · A. Raj · N. Joshi
Department of Life Sciences, Graphic Era Deemed to be University, Bell Road, Clement Town, Dehradun, Uttarakhand, India
e-mail: preeti.ls@geu.ac.in

J. M. Rawat
Department of Biotechnology, Graphic Era Deemed to be University, Bell Road, Clement Town, Dehradun, Uttarakhand, India

S. Tapas
Scidogma Research Pvt Ltd., Mathura Manor, Tata Nagar, Bengaluru 560092, India

B. Pattnaik
Department of Botany, Christ College, Cuttack, Odisha 753008, India

B. Rawat
School of Agriculture, Graphic Era Hill University, Bell Road, Clement Town, Dehradun, Uttarakhand, India

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_16

## 16.1 Introduction

With the advancements in the field of science and technology, an enormous amount of new and smart electronic devices have been generated. These gadgets have revolutionized our world and brought a higher standard of living. Although these brilliant machines brought substantial conveniences to our lifestyle, at the same time caused zillions of environmental stresses including pollution of mother nature and severe health risks (Han et al. 2022).

Global electronic waste (e-waste) generated across the globe so far has been estimated to be ~ 420 million metric tons out of which only 17% have been recycled, the remaining being dumped and piled up in landfills. Moreover, improperly disposed e-waste also releases toxins and hazardous byproducts, heavy metals including Pb, Hg, Cu, and xenobiotics, posing detrimental effect on environment and public health. Furthermore, e-waste is a secondary source for precious metals like gold, silver, palladium, platinum, and ruthenium, compared to traditional virgin mining (Cucchiella et al. 2015). The proportion and quality of precious metal ions obtained from e-waste are greater than those extracted from ores (Zeng et al. 2018; Forti et al. 2020).

The e-waste management is a dreadful challenge using traditional methods either mechanically or chemically. Recycling at large/industrial scale involves pyrometallurgical processes that particularly require thermal treatment, solid–liquid–gas reactions, smelting in furnaces or alkali treatment, whereas the hydrometallurgical processes utilize differential methods such as adsorption, ion exchange, solvent extraction, and leaching processes in turn releasing toxic chemicals that are detrimental to ecological and human health. However, to minimize the emission of pollutants during the recycling, advanced technologies such as ultrasound and vacuum metallurgical technology are being employed along with the conventional methods (Fig. 16.1) (Rawat et al. 2020; Sahajwalla and Gaikwad 2018; Ahirwar and Tripathi 2021).

Our scientific communities throughout the globe are now adapting and recommending green/ biological solution to combat the e-waste. Hence, researchers are getting fascinated by microbial world (Jujun et al. 2014; Kaksonen et al. 2018). Microorganisms are being used extensively to provide a vast range of services (Table 16.1). They are particularly useful because they are easy to cultivate in large numbers, take less time as they have a short life cycle and can survive in harsh conditions using cheap substrates such as waste materials. Their genetic content can be manipulated to produce a desirable trait which can perform desired function in efficient manner. Use of microbial technology, where microbes help in the leaching of metal from e-waste is indeed advantageous with economic and environmental perspective (Fig. 16.1) (Arshadi and Mousavi 2015; Arshadi et al. 2016).

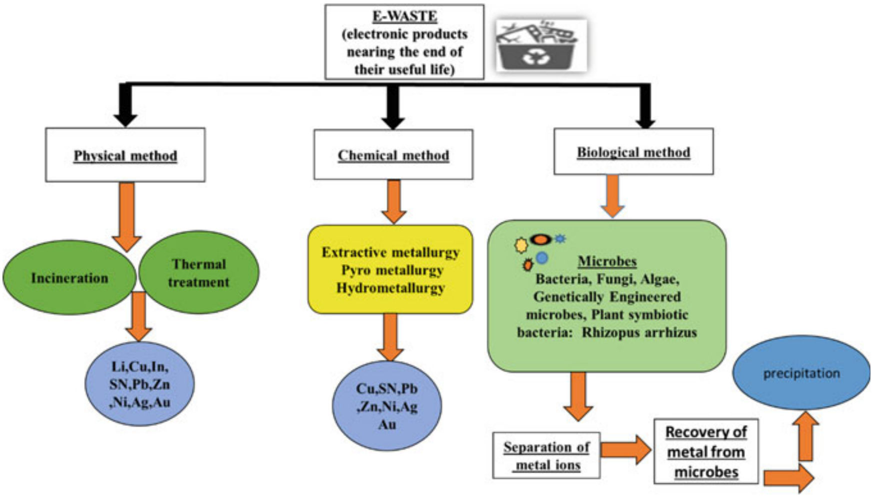



**Fig. 16.1** Overview of the methods used for electronic waste management: recycling of e-waste and extraction of the precious metals, rare earth metals, and metals from scraped waste

## 16.2 Methods to Obtain Suitable Microorganism from the Environment

Isolation of a suitable microorganism from the environment can be divided into two types, "**shotgun**" and **objective** approaches.

### *16.2.1 Shotgun Approach*

**Shotgun approach** involves the collection of samples of microorganisms, biofilms/consortium of bacteria, or other microbial communities directly from flora and fauna, soil, water and waste streams, sewage, or from natural and unusual man-made habitats. This isolated strain then can be screened for desired traits.

### *16.2.2 Objective Approach*

**Objective approach** involves the sampling from specific sites where microorganisms with the desired characteristics are likely to be present. For example, if the desired trait is to degrade or detoxify a specific chemical compound (polyethylene plastic), then microorganism will be sampled from the site where known contaminant (PET

**Table 16.1** Microbes being used in the process of biological e-waste management

| Microorganisms | Leached metals % (mg/g) | References |
|---|---|---|
| Acidophilic consortium (*Acidithiobacillus* and *Gallionella* genera) | Cu: 97% (626 mg/g); Zn: 92%; Al: 88% (34 mg/g) | Zhu et al. (2011) |
| *Acidithiobacillus ferrooxidans* | Cu: 96.8%; Zn: 83.8%; Al: 75.4% | Yang et al. (2014) |
| *Bacillus megaterium* | Cu: 72%; Au: (65 g Au/ton) | Arshadi et al. (2016) |
| *Chromobacterium violaceum*, *Pseudomonas fluorescens* | Au: 69% | Brandl et al. (2008) |
| *Pseudomonas putida* (two-step) | Cu: 98% (164 mg/g); Au: 44% (0.1 mg/g) | Isildar et al. (2016) |
| *Acidithiobacillus ferrooxidans* | Cu: 95% (203 mg/g) | Chen et al. (2015) |
| *Sulfobacillus thermosulfidooxidans* | Cu: 9 Cu: 95% (105 mg/g); Zn: 96% (18 mg/g); Ni: 94% (18 mg/g); Al: 91% (19 mg/g) | Ilyas et al. (2014) |
| *At. ferrooxidans*, *Leptospirillum ferrooxidans*, *At. thiooxidans*, *Acidithiobacillus ferrooxidans* | Cu: 95% (106 mg/g) | Bas et al. (2013) |
| *Acidithiobacillus thiooxidans* | Y: 70% | Beolchini et al. (2012) |
| *At. ferrooxidans*, *At. thiooxidans*, *Aspergillus niger*, *Penicillium simplicissimum* | Cu: 94%; Ni: 89%; Zn: 90% | Liang et al. (2010) |
| *Acidithiobacillus ferrooxidans* | Al: 95% (225 mg/g); Ni: 95% (14 mg/g); Zn: 95% (25 mg/g); Cu: 65% (52 mg/g) | Brandl et al. (2001) |
| *Acidithiobacillus ferrooxidans* | Cu: 100%; Ni: 100% | Arshadi and Mousavi (2014, 2015) |
| *Aspergillus niger* | Cu: 100%; Ni: 100% | Horeh et al. (2018) |
| *Acidithiobacillus ferrooxidans* | Li: 100%; Cu 94%; Co 93.7%, Ni: 87%; Mn: 72%; Cd: 67%; Al: 62%; Ni: 45%; Co: 38% | Bajestani et al. (2014) |
| *Aspergillus niger* | Zn: 100%; Cu: 85.88%; Ni: 80.39% | Faraji et al. (2018) |

plastic) material is present. The isolates may have undergone a selection pressure to metabolize the compound from their niche.

Subsequently, the isolates needed to be screened with enrichment media and maintained as pure cultures with appropriate media and growth conditions. Once isolated as pure cultures, each must be screened for the desired property such as production of a specific chemical and inhibitory compound (Nakayama et al. 1981).

## 16.3 General Mechanisms of Microbial Remediation

Microorganisms capable of utilizing a particular component (heavy metal, plastic, etc.) from the e-waste for their own metabolic needs or converting them into less toxic and easily extractable form. For example, some bacteria can produce specific chemical that leach metals ions from dumped electronic scrap, where others can bind or absorb these metals (Heydarian et al. 2018; Horeh et al. 2018; Sun et al. 2016).

Commonly observed biological mechanisms during remediation or extraction of precious metals from the e-waste are such as (i) Bioaccumulation; (ii) Bioleaching; (iii) Biotransformation; (iv) Biosorption; and (v) Biomineralization (Fig. 16.2).

### 16.3.1 *Bioleaching*

Bioleaching is a process where microbe will produce the enzyme or chemicals that can interact and bind the metal present in waste, and finally, the metal ions can be extracted in liquid form. Two types of bioleaching processes have been reported: direct and indirect leaching. Direct leaching involves the production of organic acids by the microbes that can oxidize the insoluble metals, changing them into liquid ions. Indirect leaching occurs when metal oxidizing bacteria carry out the oxidization of surrounding metals (Baniasadi et al. 2019, Tichy et al. 1998).

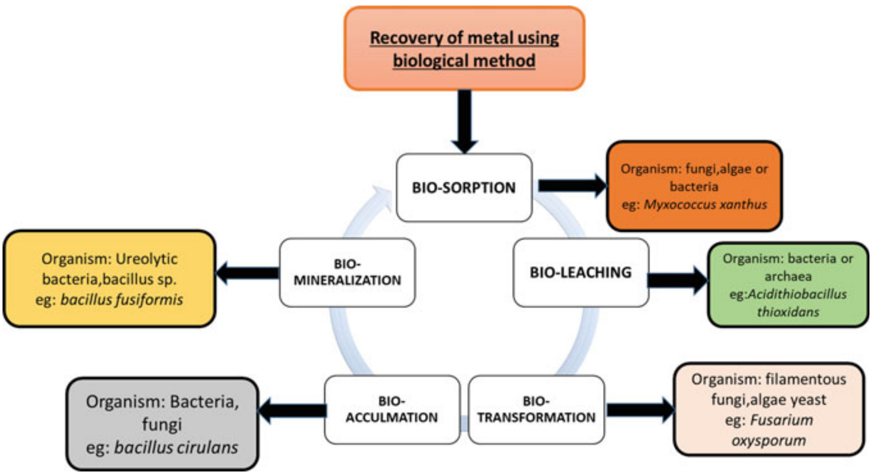



**Fig. 16.2** General mechanisms observed in microbes involved in the process of e-waste management

### 16.3.2 Biosorption

Biosorption is the process where metal ions or contaminants binding to the surface of microbial cell, and there is no active metabolism of contaminant occurs (Volesky and Holan 1995).

### 16.3.3 Bioaccumulation

This process involves the direct absorption of contaminants within the cellular structure of the organism, where absorbed material gets concentrated inside the microbial cells. Active metabolism occurs during bioaccumulation process, where absorbed contaminant undergoes a chemical conversion and produces another compound that is less toxic or undergo sequestration once inside the cell (Prakash et al. 2012; Hou et al. 2006).

### 16.3.4 Biotransformation

Biotransformation happens when a chemical substance gets converted from one form to another chemical form and particularly a toxic metal oxidized, thereby changing its chemical properties (Prakash et al. 2012; Tabak et al. 2005).

### 16.3.5 Biomineralization

It refers to the process which involves microbial induced precipitation where precipitation occurs when metal ions bind to the ligands produced by the microbes (Sherman et al. 2015).

## 16.4 Microbes and Their Biological Significance in E-waste Management

### 16.4.1 Microbes Involve in Recovery of Gold

Large industries use cyanide treatment of e-waste for the extraction of gold. Traditional hydrometallurgy method used liquid cyanide ions that can bind to the gold atom, but the leftover cyanide was another hazard to the environment.

*Chromobacterium violaceum* was identified to be capable of recovering precious metal from the e-waste. It was predicted that dense population of *C. violaceum* produces an enzyme which can convert glycine to hydrogen cyanide, and these cyanide ions can selectively bind to gold atoms present in the solid scrap. Further, the bacteria can convert the unused cyanide to β-cyanoalanine, a nontoxic chemical and clean itself after completion of process (Faramarzi et al. 2004, Sahni et al. 2016). Although the bioleaching process of gold extraction is environment-friendly without any adverse effect, the efficiency is much less as compared to conventional hydrometallurgy and pyrometallurgic methods where the 100% gold recovery can be achieved (Tay et al. 2013; Das et al. 2017).

Further scientist applied genetic engineering approach to create new strains of the bacteria for acceleration of the process and boosting cyanide production. These new strains possessing extra copy of the genes controlling enzyme production along with the promoter sequence, which trigger enzyme production in response to a chemical. These engineered strains generated 68% more cyanide that could recover 25–30% gold (Tay et al. 2013).

One issue was that copper which is present in e-waste that bind cyanide, impeding the recovery of gold. Another problem was preferred pH level for *C. violaceum*, where HCN is evaporated during cyanide formation. Microbial growth gets inhibited due to the mixing of toxic e-waste (Tay et al. 2013).

Scientist used various combinatorial strategies to increase the efficiency of *C. violaceum* in extraction of gold from the electronic scrap. Firstly, copper, the major component, was reduced using nitric oxide, sulfuric acid, and $H_2O_2$. Secondly, the mutant bacteria were isolated those could grow well at higher pH. Thirdly by separately grown microbial culture was used for cyanide production and then waste was mixed with the culture effluent for efficient reaction with gold. Finally, the culture was optimized with ultrasonication for uniform mixing of the nutrient in the media ensuring fast growth of *C. violaceum* with the use of these techniques, ~ 70% of the gold was recovered (Reed et al. 2016; Thompson et al. 2018).

*Delftia acidovorans* is another microbe that is being used in gold extraction from e-waste, and this bacteria releases delftibactin, a chemical that can directly precipitate gold in the form of nanoparticles. *D. acidovorans* can extract about 18% of gold and however with the use of genetic engineering strain can improve to produce abundant delftibactin. In addition, *Pseudomonas putida* (WSC361) can produce cyanide and capable of dissolving 48% of Au in 3 h of incubation period (Johnson 2014) Furthermore, the bacterium *Cupriavidus metallidurans* also refines the gold. Bacterium was identified in 1970s in a metal processing factory. The microbe was working as sponge where biosorption was observed when *C. metallidurans* encased gold and absorbed it through the membrane. The precious metal can be easily recovered by cell disruption.

### 16.4.2 Microbes Recovery of Rare Earth Metals

E-waste also contains rare earth elements here is list of some microbes used to collect these rare earth metals. The microbially produced chemicals recovered up to 49% of the rare earth elements from the catalysts. *Gluconobacter oxydans* can produce gluconic acid which can surround and form a cage around the rare earth metals. Gluconic acid molecules binds, drawing these rare earth metal into solution. That can be easily released by solvent extraction or by changing the pH of microbial surroundings.

*Cellulosimicrobium funkei* is a heterotrophic bacteria used for the bioleaching of gallium arsenide from the semiconductor (Maneesuwannarat et al. 2016). *Tea fungus Kombucha* is used in the recovery of rare metals from fluorescent powder (Hopfe et al. 2017).

Electrodes of liquid crystal display (LCD) contain valuable metals such as indium (In) and strontium (Sr) in the form of indium tin oxide (ITO). ITO is a complex of indium (III) oxide ($In_2O_3$), and tin (IV) oxide ($SnO_2$) constitutes approximately 10–20% $SnO_2$ and 80–90% $In_2O_3$ by weight (Swain & lee 2019). *Acidithiobacillus thiooxidans* adapted to utilize LCD powder at optimum pH, pulp density, and sulfur content of the media with recovery of upto 100% Indium and 10% Strontium from the waste LCD processing (Jowkar et al. 2018). These findings provide an ecofriendly and efficient process of bioleaching of indium metal from discarded liquid crystal displays (LCD) against the chemical leaching process (Fathollahzadeh et al. 2018). *Acidithiobacillus thiooxidans* (DSM 9463) can be used for fast and higher percentage recovery of cerium, neodymium, and europium (> 99%) along with ~ 80% yttrium and lanthanum just in about one week (Johnson 2014).

In addition, *Aspergillus niger* has also been used for bioleaching of more than 99% Yttrium (Y) ~ 80% lanthanum from shredding dust of e-waste (Marra et al. 2018). Now researchers have developed easy method for obtaining valuable earth metals from shredded dust that generates during e-waste recycling. *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, and *Leptospirillum ferrooxidans* are known to play pivotal role in oxidation and solubilization of iron and sulfur from e-waste (Wu et al. 2018). Once solubilized these metal ions can then be easily extracted (Niu et al. 2015).

### 16.4.3 Microbes Involved in Recovery of Metals

The process of recovering base (Cu, Fe, Ni, Pb, Zn) and precious metals (Ag, Au, Co, Pd, Pt) from e-waste might involve a single microbe, a group of microorganisms, or consortiums of microbes (*Acidithiobacillus* spp., *Sulfobacillus* spp., and fungi (*Purpureocillium lilacinum* and *Aspergillus* spp.) (Kumar et al. 2018, Han et al. 2022).

Gluconic acid produced by *A. niger* can result in 94%, 72%, 62%, 45%, and 38% and Cu, Mn, Al, Ni, Co, respectively. Mixed culture of *Leptospirillum ferriphilum* and *Acidithiobacillus thiooxidans* help in bioleaching of Cu, Mn, and Zn from spent batteries (Niu et al. 2015).

Various fungal spp. preferably grows at low pH and temp at the metal ions contamination site. Fungi *Penicillium simplicissimum* produces organic acids such as ethanedioic acid, melic acid, and gluconic acid. These acids facilitate the solubilization of various base metals from e-waste. Considering the power of such fungi, they are helpful in increasing the quality and quantity of the metal extraction from e-waste (Ilyas et al. 2014).

*Aspergillus niger* and *Penicillium simplicissimum* produce gluconic acid that is an excellent chelating agent and can be used during the bio-hydrometallurgical extraction of lithium metals from spent lithium-ion batteries. Gluconic acid helps in dissolving ~ 100% Li, from the e-waste. Several genera and species of microbes synergistically play a prominent role in mobilizations of metals from e-waste. In this regard, four phyla of bacteria have been found in vast majority: Proteobacteria, *Nitrospirae*, *Firmicutes*, and *Actinobacteria*. Moreover, members of archaea like *Sulfolobus*, *Acidianus*, *Metallosphaera*, *Sulfurisphaera* are also involved for metal extraction (Wu et al. 2018, Ilyas et al. 2014). Along with several advantages of using microbes in management of e-waste, there are certain associated disadvantages given in Table 16.2.

**Table 16.2** Advantages and disadvantages for microbial usage in electronic waste management

| Advantages | Disadvantages |
|---|---|
| Easy to grow and inexpensive in maintenance | Growth and bioremediation process gets affected easily by microbial tolerance toward toxic environment of e-waste |
| Environment-friendly and non-hazardous to the environment | The process of bioremediation is usually slower than conventional chemical and physical processes |
| Cannot tolerate harsh conditions such as high temperature, toxic chemicals, extreme pH, and pressure | Availability of limited and expensive molecular toolkits for the improvement of microbes to increase the efficiency of microbes involve in bioremediation processes |
| Once the process begins, the microbes use biochemical transformation or mineralization to permanently remove the contaminants | Process of scaling up the bioremediation is complex, expensive, and time-consuming |

## 16.5 Conclusion

However, bacteria are not the perfect recyclers of e-waste, partly due to huge volume, toxicity, and vivid composition of electronic items. In addition, the microbial process of extracting the desired component is capacitively less than the conventional mechanical methods. Moreover, microorganisms are cost-effective resources for extracting and concentrating the diffuse elements present in the secondary sources.

It presents a huge challenge for the researcher to convince the environmentalist and industrialist to use biological method of e-waste management. However, scientists are already in the path of identifying and using new and known microbes in trial phase that are "restricted to the laboratories": For troubleshooting this and to increase the efficiency and speed of biological extraction/degradation process, "genetic engineering" is the preferred solutions where the particular trait of the microorganism can be engineered using the available technology.

Application of genetically engineered microorganisms GEMs-based bioremediation of metal, toxins or xenobiotic compounds are in the forefront as it is environment-friendly and human-friendly approach. Unfortunately, the information on the genes for the specific microbial properties is not well-developed, thus impeding the process of GEMs improvement. The second main obstacle in the application of GEMs is associated hazards as well as the regulatory affairs. Interestingly, this problem can be troubleshooted by the development and use of "Suicidal Genetically Engineered Microorganisms". In the future, GEMs are going to be one of the most efficient technologies, provided that enormous amount of information can be availed regarding these microbes, their genetic, and biochemical mechanisms. This will allow the scientific community to apply GEMs in situ, that is currently limited to the experimental stage in laboratories.

## References

Ahirwar R, Tripathi AK (2021) E-waste management: a review of recycling process, environmental and occupational health hazards, and potential solutions. Environ Nanotechnol Monit Manage 15:100409

Arshadi M, Mousavi SM (2014) Simultaneous recovery of Ni and Cu from computer-printed circuit boards using bioleaching: statistical evaluation and optimization. Bioresour Technol 174:233–242

Arshadi M, Mousavi SM (2015) Multi-objective optimization of heavy metals bioleaching from discarded mobile phone PCBs: simultaneous Cu and Ni recovery using *Acidithiobacillus ferrooxidans*. Sep Purif Technol 147:210–219

Arshadi M, Mousavi SM, Rasoulnia P (2016) Enhancement of simultaneous gold and copper recovery from discarded mobile phone PCBs using *Bacillus megaterium*: RSM based optimization of effective factors and evaluation of their interactions. Waste Manage 57:158–167

Bajestani MI, Mousavi SM, Shojaosadati SA (2014) Bioleaching of heavy metals from spent household batteries using *Acidithiobacillus ferrooxidans*: statistical evaluation and optimization. Sep Purif Technol 132:309–316

Baniasadi M, Vakilchap F, Bahaloo-Horeh N, Mousavi SM, Farnaud S (2019) Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J Ind Eng Chem 76:75–90

Bas AD, Deveci H, Yazici EY (2013) Bioleaching of copper from low grade scrap TV circuit boards using mesophilic bacteria. Hydrometallurgy 138:65–70

Beolchini F, Fonti V, Dell'Anno A, Rocchetti L, Vegliò F (2012) Assessment of biotechnological strategies for the valorization of metal bearing wastes. Waste Manage 32:949–956

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59:319–326

Brandl H, Lehmann S, Faramarzi MA, Martinelli D (2008) Biomobilization of silver, gold, and platinum from solid waste materials by HCN-forming microorganisms. Hydrometallurgy 94:14–17

Chen S, Yang Y, Liu C, Dong F, Liu B (2015) Column bioleaching copper and its kinetics of waste printed circuit boards (WPCBs) by *Acidithiobacillus ferrooxidans*. Chemosphere 141:162–168

Cucchiella F, D'Adamo I, Koh SCL, Rosa P (2015) Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew Sust Energ Rev 51:263–272

Das S, Natarajan G, Ting Y-P (2017) Bio-extraction of precious metals from urban solid waste. AIP Conf Proc 1805:020004

Faraji F, Golmohammadzadeh R, Rashchi F, Alimardani N (2018) Fungal bioleaching of WPCBs using *Aspergillus niger*: observation, optimization and kinetics. J Environ Manag 217:775–787

Faramarzi MA, Stagars M, Pensini E, Krebs W, Brandl H (2004) Metal solubilization from metal-containing solid materials by cyanogenic *Chromobacterium violaceum*. J Biotechnol 113:321–326

Fathollahzadeh H, Becker T, Eksteen JJ, Kaksonen AH, Watkin ELJ (2018) Microbial contact enhances bioleaching of rare earth elements. Bioresour Technol Rep 3:102–108

Forti V, Baldé CP, Kuehr R, Bel G (2020) The global E-waste monitor 2020: quantities, flows and the circular economy potential 1–119

Han P, Teo WZ, Yew WS (2022) Biologically engineered microbes for bioremediation of electronic waste: wayposts, challenges and future directions. Eng Biol 6:23–34. https://doi.org/10.1049/enb2.12020, https://wileyonlinelibrary.com.

Heydarian A, Mousavi SM, Vakilchap F, Baniasadi M (2018) Application of a mixed culture of adapted acidophilic bacteria in two-step bioleaching of spent lithium-ion laptop batteries. J Power Sources 378:19–30

Hopfe S, Flemming K, Lehmann F, Möckel R, Kutschke S, Pollmann K (2017) Leaching of rare earth elements from fluorescent powder using the tea fungus Kombucha. Waste Manage 62:211–221

Horeh BN, Mousavi SM, Baniasadi M (2018) Use of adapted metal tolerant *Aspergillus niger* to enhance bioleaching efficiency of valuable metals from spent lithium-ion mobile phone batteries. J Clean Prod 197:1546–1557

Hou B, Zhu K, Lu J, Zhao YF (2006) Research on bioremediation of petroleum contaminated soils and its perspectives. Sichuan Environment 6(24):131–140

Ilyas S, Lee J, Kim B (2014) Bioremoval of heavy metals from recycling industry electronic waste by a consortium of moderate thermophiles: process development and optimization. J Clean Prod 70:194–202

Isildar A, van de Vossenberg J, Rene ER, van Hullebusch ED, Lens NL (2016) Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). Waste Manage 57:149–157

Johnson DB (2014) Biomining—biotechnologies for extracting and recovering metals from ores and waste materials. Curr Opin Biotechnol 30:24–31

Jowkar MJ, Horeh NB, Mousavi SM, Pourhossein F (2018) Bioleaching of indium from discarded liquid crystal displays. J Clean Prod 180:417–429

Jujun R, Xingjiong Z, Yiming Q, Jian H (2014) A new strain for recovering precious metals from waste printed circuit boards. Waste Manage 34:901–907

Kaksonen AH, Boxall NJ, Gumulya Y, Khaleque HN, Morris C, Bohu T, Cheng KY, Usher K, Lakaniemi AM (2018) Recent progress in biohydrometallurgy and microbial characterization. Hydrometallurgy 180:7–25

Kumar A, Saini HS, Kumar S (2018) Bioleaching of gold and silver from waste printed circuit boards by *Pseudomonas balearica* SAE1 isolated from an e-waste recycling facility. Curr Microbiol 75:194–201

Liang G, Mo Y, Zhou Q (2010) Novel strategies of bioleaching metals from printed circuit boards (PCBs) in mixed cultivation of two acidophiles. Enzym Microb Technol 47(7):322–326

Maneesuwannarat S, Vangnai AS, Yamashita M, Thiravetyan P (2016) Bioleaching of gallium from gallium arsenide by *Cellulosimicrobium funkei* and its application to semiconductor/electronic wastes. Process Saf Environ Prot 99:80–87

Marra A, Cesaro A, Rene ER, Belgiorno V, Lens PNL (2018) Bioleaching of metals from WEEE shredding dust. J Environ Manag 210:180–190

Nakayama K (1981) Sources of industrial microorganisms. In: Rehm H-J, Reed G (eds) Biotechnology, vol 1. VCH, Weinheim, pp 355–410

Niu Z, Huang Q, Wang J, Yang Y, Xin B, Chen S (2015) Metallic ions catalysis for improving bioleaching yield of Zn and Mn from spent Zn–Mn batteries at high pulp density of 10%. J Hazard Mater 298:170–177

Prakash A, Satyanarayana T, Johri BN (2012) Microorganisms in environmental management: microbes and environment. Springer, Dordrecht

Rawat S, Verma L, Singh J (2020) Environmental hazards and management of E-waste. In: Environmental concerns and sustainable development. Springer, pp 381–398

Reed DW, Fujita Y, Daubaras DL, Jiao Y, Thompson VS (2016) Bioleaching of rare earth elements from waste phosphors and cracking catalysts. Hydrometallurgy 166:34–40

Sahajwalla V, Gaikwad V (2018) The present and future of e-waste plastics recycling. Curr Opin Green Sustain Chem 13:102–107

Sahni A, Kumar A, Kumar S (2016) Chemo-biohydrometallurgy—a hybrid technology to recover metals from obsolete mobile SIM cards. Environ Nanotechnol Monit Manage 6:130–133

Sherman VR, Yang W, Meyers MA (2015) The materials science of collagen. J Mech Behav Biomed Mater 52:22–50. https://doi.org/10.1016/j.jmbbm.2015.05.023

Sun M, Wang Y, Hong J, Dai J, Wang R, Niu Z, Xin B (2016) Life cycle assessment of a biohydrometallurgical treatment of spent Zn–Mn batteries. J Clean Prod 129:350–358

Swain B, Lee CG (2019) Commercial indium recovery processes development from various e-(industry) waste through the insightful integration of valorization processes: a perspective. Waste Manage 87:597–611

Tabak HH, Lens P, van Hullebusch ED, Dejonghe W (2005) Developments in bioremediation of soils and sediments polluted with metals and radionuclides 1. Microbial processes and mechanisms affecting bioremediation of metal contamination and influencing metal toxicity and transport. Rev Environ Sci Biotechnol 4(3):115–156

Tay SB et al (2013) Enhancing gold recovery from electronic waste via lixiviant metabolic engineering in *Chromobacterium violaceum.* Sci Rep 3:2236

Thompson VS et al (2018) Techno-economic and life cycle analysis for bioleaching rare-earth elements from waste materials. ACS Sustain Chem Eng 6:1602–1609

Tichy R, Rulkens WH, Grotenhuis JTC, Nydl V, Cuypers C, Fajtl J (1998) Bioleaching of metals from soils or sediments. Water Sci Technol 37(8):119–127

Volesky B, Holan ZR (1995) Biosorption of heavy metals. Biotechnol Prog 11(3):235–250

Wu W, Liu X, Zhang X, Zhu M, Tan W (2018) Bioleaching of copper from waste printed circuit boards by bacteria-free cultural supernatant of iron–sulfur oxidizing bacteria. Bioresour Bioprocess 5(10):1–13. https://doi.org/10.1186/s40643-018-0196-6

Yang Y, Chen S, Li S, Chen M, Chen A, Liu B (2014) Bioleaching waste printed circuit boards by *Acidithiobacillus ferrooxidans* and its kinetics aspect. J Biotechnol 173:24–30

Zeng X, Mathews JA, Li J (2018) Urban mining of E-waste is becoming more cost-effective than virgin mining. Environ Sci Technol 52(8):4835–4841

Zhu N, Xiang Y, Zhang T, Wu P, Dang Z, Li P, Wu J (2011) Bioleaching of metal concentrates of waste printed circuit boards by mixed culture of acidophilic bacteria. J Hazard Mater 192:614–619

# Chapter 17
# Recent Trends in Biomining Microorganisms for Solid Waste Management

**Pragati Srivastava**

**Abstract** Today, the world is severely afflicted by boundless waste generated by different categorical anthropogenic activities unlike mining, industrial waste, e-waste, etc. Its improper handling may cause deleterious effects on the environment. The constituents of the waste generated contain harmful toxic polycyclic aromatics which pose a direct threat to the environment as well as the human race. Heavy metal discharge from the solid waste accumulated in the dumping site gets cumulated in the soil and gets absorbed by the plants leading to biomagnifications in the food chain and substantially reaching the human body, leading to compromised health. An environmentally sound, economic and cost-effective approach 'microbial biomining' can be a powerful strategy for solid waste management. They transform toxic solid waste into nontoxic form and are sufficiently capable of catalyzing mineral dissolution. It can be an absolute solution for mineral beneficiation to overcome environmental problems.

**Keywords** E-waste · Biomining · Solid waste management · Microbial biominners

## 17.1 Introduction

Referring to the population's structure, which is growing rapidly, the necessity for improved technology to meet a person's everyday needs keeps replacing the older technology and automatically generates waste in a vast quantity (Vyas et al. 2022). Industrial garbage, municipal waste, and electronic waste are all having detrimental effects on the environment. Its management is the biggest challenge across the world. Electronic waste, rubbish dump, domestic waste, malleable waste produced from plastics and metals, wood, toppling construction sites all contribute in the generation of solid wastes (Das and Ghosh 2022). Extraction and recovery of valuable metals

P. Srivastava (✉)
Department of Microbiology, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263145, India
e-mail: prags.cbsh@gmail.com

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_17

with the help of microorganisms from solid waste and minerals can be a powerful strategy for solid waste management. Biomining is used for the recovery of several metals like copper, nickel, cobalt, zinc, uranium, and precious metals like gold and silver (Urbina et al. 2019). Presently, biomining is also implemented in the recovery of metals from electronic waste such as voltaic substances like spend batteries, electrical appliances like refrigerator, television air conditioners, sound boxes, laptops, motherboards, which is serving as the fastest-growing waste around the globe. Extremophiles are microorganisms that thrive in an acidic pH range of 2.0–4.0 and aid in metal dissolution through acid secretion. Some known examples are *Leptospirillum ferrooxidans*, *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Sulfolobus* spp. *Penicillium* spp. and *Aspergillus niger* fungal species are intensively studied for the biomining process (Kumar et al. 2022). Biomining microorganisms play a crucial role by forming an association with the inorganic component of the solid waste and help in the recovery of metals, producing a minimum release of toxic effluents into the environment and are considered as a green technology. Biomining consists of two major steps for the recovery of metals from their respective sources. The first step involves bioleaching, which is escorted by thermophiles and chemolithotrophs that oxidize sulphur, where oxidation of metal sulphides at acidic pH takes place into metal ions (Pattanaik et al. 2020), followed by a conditioning step of bio-oxidation. In bio-oxidation, microorganisms interact with a mineral matrix containing the target metal, allowing them to be exposed to the oxidation slag (Jerez 2012). In bio-oxidation, the metal remains in the more concentrated form (Hoque and Philip 2011).

Metals are extracted by the action of ferric ion or acid during microbial solubilization, which involves both chemical and biological processes. Microorganisms are in charge of creating these leaching agents. It is known that a wide range of lithotrophic and organotrophic bacteria mediate these activities. Since the beginning of life, a significant part is played by the microorganisms in the production of minerals and the disintegration of the earth's crust (Gao et al. 2021). In the past, leaching of copper was done using microorganisms' having natural capacity for mineral breakdown without anyone even realizing that this process was mediated by microorganisms; it was purely empirical at the time. According to the noted figures, 5% of the world's gold was produced via biomining and copper production was up to 15% (Sana et al. 2021). The recuperation of precious metals made possible by biomining will allow for the reclamation of solid wastes, as well as the opportunity to address public health and environmental quality issues related to pollution caused by solid wastes. It also emphasizes the regulatory bodies' duty to ensure that the biomined site has an appropriate lining system and design so that any further processing and municipal sewage wastewater treatment activities may be carried out with a minimal danger to the environment and public health (Mohan and Joseph 2020).

## 17.2 History of Biomining

Mining is as ancient as the civilization has existed. Specific metals and their compounds have been used since ages to date for many significant cultural periods; thus, the discovery of metals has exerted an influence on the development of civilization. Agriculture and mining both were considered as the primary initiative of the human civilization. The magnifying infrastructure, fertilizer industry, and electronic industry all rely on mining. Apart from its so many outputs, mining is considered to be detrimental for environment and human health because of its aftereffects to the ecosystem weather its water, air, or land resources (García-Balboa et al. 2022). It includes deforestation, loss of wildlife, land degradation, acid mine drainage, air pollution, ground water contamination, surface water contamination, siltation of water bodies and agricultural lands, and much more (Watling 2014). The growing infrastructure and swift economy have build up peer pressure on metallurgical sector to overcome the metal demand. The ore grade is deteriorated with span of time which worsens the situation. Looking at the after effects of the process a sustainable approach for retraction of metals, a tool for bioremediation is required for the solid waste management (Martínez-Bellange et al. 2022).

Microbial biominners came into existence for the extraction of metals from solid wastes (low-grade ores, mine waste dumps, mine tailings, sewage water, landfills, and electronic wastes) by the use of native microorganisms, and the process is defined as biomining (Nayak 2022). A German physician and mineralogist by occupation Georgius Agricola (1494–1555) has stated in his book *de re metallica* the method of copper extraction. The recovery of metal copper from ores appears to have begun at least 100–200 BC in China, according to Rossi, and it is also likely to have been used in Europe in the second century, according to his book bio-hydrometallurgy (Sana et al. 2021). Identification of *T. ferrooxidans* as the causative agent of acid mine drainage (AMD) and the description of bacterial participation in copper leaching set stage for revolutionizing biomining. Later, *T. ferrooxidans* was changed to *A. ferrooxidans*. The ability of the chemoautotrophic acidophilic iron oxidizing bacteria to keep iron in an oxidizing state and to draw energy indirectly from the sulphide minerals for the oxidation of sulphide copper ore to solubilize copper in a highly acidic environment was recognized. Leaching of copper run-of (Dump leaching) began in the USA in the middle of the 1960s, ushering in the contemporary era of biomining (Johnson 2018). In Canada in the 1970s, residual uranium extraction led to in-situ bioleaching of uranium (Wadden and Gallent 1985).

The interaction between the microorganisms and inorganic substances found in dumping site can be extremely important. The process of rock weathering enables the liberation of metals from minerals, and the reduction and oxidation of metals are all processes that depend heavily on the abundance of microorganisms in nature. The geochemical cycle of inorganic substances in nature also heavily relies on these microbial processes. These microbiological methods' key benefits for end users are their simplicity of usage and minimal need for process controls. Technical waste treatment applications may benefit from adapting these microbiological concepts and procedures. As a closed loop process with little effluent generation, the technique is also assumed to be a environment-friendly technique (Hoque and Philip 2011).

## 17.3 Mechanism Involved

The mechanism basically involved in the process is mineral sulphides oxidation to the target metal ions and sulphate, and reaction is governed under the influence of microorganism, aerobically where $O_2$ serve as the terminal electron acceptor (Sand et al. 1995; Donati et al. 2016). Reaction involved in the process:

(i) $MS_{(S)} + 2O2_{(g)} \rightarrow MSO_{4(ac)}$.

Acidophilic microorganisms with the ability to oxidize iron (II) and/or sulphur compounds in accordance with the following equations catalyse this reaction.

(ii) $2Fe^{2+}{}_{(ac)} + 1/2O_{2(g)} + 2H^{+}{}_{(ac)} \rightarrow 2Fe^{3+}{}_{(ac)} + H_2O$.
(iii) $0.125S_{8(s)} + 1\ 1/2O_{2(g)} + H_2O \rightarrow H_2SO_{4(s)}$.

Only protons and iron (III) can dissolve metal sulphides during bioleaching procedures. Microorganisms exclusively play the role of replenishing iron (III) and/or protons in these currently established methods.

## 17.4 Microorganism Involved in Biomining

The genus *Acidithiobacillus* contains the most extensively researched leaching bacteria. Also, certain mediocre thermophile *A. caldus* and acidophilic mesophiles *Acidithiobacillus ferrooxidans* and *A. thiooxidans* which fall amongst gram-negative $\gamma$-proteobacteria are also included (Schippers 2007; Donati et al. 2016; Chen et al. 2022). The bacteria attack the sulphur particle through a process known as "pitting", in which some bacteria are still tightly bound to the cavities while others have left the surface, leaving the compartment empty. This process has been described as a "model biomining microorganism" (Olson et al. 2003; Rawlings 2005). When cells of biomining bacteria colonize wider areas of a surface, they create biofilm, which is very similar to a monolayer.

*Leptospirillum* species are regarded as significant biomining bacteria. Additionally, a few gram-positive bioleaching bacteria belonging to the genera Acidimicrobium, Ferromicrobium, and Sulfobacillus have been reported. Sulphur and iron can be oxidized by well-known biomining archaeons, mostly from the genera *Sulfurisphaera* (II), *Metallosphaera*, *Acidianus,* and *Sulfolobus.* Recently identified and characterized are two mesophilic iron (II) oxidizing archaeons from the Thermoplasmales, *Ferroplasma acidiphilium*, and *F. acidarmanus* (Carmona-Gutierrez et al. 2022). A variety of diverse microbes collaborate to extract dissolved metal values from ores through oxidative processes. Below is a quick summary of the microbiological characteristics of a few other well-known biomining bacteria.

### *17.4.1* Acidithiobacillus ferrooxidans

*A. ferrooxidans* is a rod-shaped, gram-negative bacillus that can be found as a single cell, in pairs, or chains but does not produce endospores. It measures 1–1.5 m in length and 0.5 m in diameter (Jiménez-Paredes et al. 2021). Along with other microbes, *A. ferrooxidans* plays a significant part in bio-hydrometallurgical processes. The oxidation of ferrous ions and reduced sulphur provides these bacteria with their energy; in the first case, the build up of ferric ions as a by-product can impede it. Extracellular polymeric substances (EPS) are recognized to play a significant part in adapting and tolerating a variety of inhibiting circumstances (Saavedra et al. 2020).

### *17.4.2* Acidithiobacillus caldus

The single polar flagellum on the outer cell wall of the short, rod-shaped gram-negative bacterium *A. caldus*, exhibiting traits of gram-negative cell wall, allows it to move. It often comes in pairs and measures 1 by 1–2 m in length (Hallberg and Lindström 1994). Similar to *A. thiooxidans,* this organism can oxidize reduced sulphur compounds, but it cannot oxidize ferric iron. It has 16S rRNA sequence homology to *A. thiooxidans* and is moderate thermophiles (45 °C). These microbial biominners are considered as a “weed” and mixotrophic growth is reported under glucose or yeast presence (Qi et al. 2022).

### *17.4.3* Leptospirillum

Based on 16S rRNA sequencing, they are classified as Nitrospira. They are gram-negative chemolithotrophs and are considered as extremophiles which are acid tolerant *Leptospirillum* spp. Only ferrous iron can be used by them as an electron donor; reducing sulphide compounds cannot be utilized by them. They have a strong propinquity for ferrous iron (Valdez-Nuñez et al. 2022). Jeong and Choi (2020) recently reported a bioaugmentation study where 90% of $Zn^{2+}$, $Hg^{2+}$, $Cd^{2+}$, and $Cu^{2+}$ ions were extracted from the biofilm and the major subjugated populations were *Leptospirillum ferrooxidans*, *Acidothiobacillus thiooxidans*, *At. ferrooxidans*, *Acidiphilium cryptum*, and they could function as the main ferrous ion oxidizers under the existence of *A. caldus* or *A. thiooxidans,* which can oxidize sulphur. *Leptospirilli* have been classified into two species: *L. ferrooxidans* and *L. thermoferrooxidans.*

The likelihood of *Leptospirillum* species is at least four. The genome DNA-DNA hybridization between the two G + C groups of *Leptospirillum ferrooxidans* is reported to be at or below 11%. These two G + C groups are 49%-51% and 55–56%, while the *L. ferrooxidans* strain belongs to the 49–51% G1C group, a different species, *L. ferriphilum*, could be identified in the higher G + C group (Coram and Rawlings 2002). It was discovered that several *L. ferriphilum* isolates could grow at 45 °C. It was discovered that all isolates from South African commercial bio-oxidation facilities operating at temperatures of 40 °C and higher were *L. ferriphilum.* At 7.5 M oxidation, $Fe^{3+}$ ions at a rate of 1954 mg/l/h was profoundly exhibited by polystress-resistant bacterium *L. ferriphilum* under the influence of 3.75 g/L Cu, 0.5 g/L Cd, 92 g/L Zn, 0.2 g/L Pb, 154 g/L of $SO_4{}^{2-}$, 5.5 g/L of $Cl^{-1}$ (Natarajan 2018; Liu and Zhou 2022).

### *17.4.4* Metallosphaera

They are aerobic, iron-, and sulphur-oxidizing chemolithotrophs capable of growing on complex organic materials like yeast extract but cannot utilize carbohydrates (Wang et al. 2020). There have been numerous reports of *Metallosphaera sedula* growing at pH 1.0–4.5 and oxidizing various sulphide minerals at 80–85 °C. The most effective organisms for bioleaching of chalcopyrite ores may be those that resemble *Metallosphaera* (Panyushkina et al. 2022).

### *17.4.5* Acidianus

At 70 °C and pH of 1.5–2.0, the thermophilic chemolithoautotrophic archaeon grows. According to Kölbl et al. (2022), *Acidianus brierleyi* can either thrive autotrophically by oxidizing ferrous iron or sulphur or heterotrophically by using complex organic substrates. The obligatory chemolithotrophic bacteria *Acidianus infernus* and *Acidianus ambivalens* can grow either aerobically or anaerobically via the oxidation or reduction of inorganic sulphur compounds. The ideal temperature and pH for *Acidianus infernus* are 90 °C and 2.0, respectively (Omokawa et al. 2022).

### *17.4.6* Acidithiobacillus ferrivorans

Acquired from settings affected by metal mines, *Acidithiobacillus ferrivorans*, sp. nov., is a facultatively anaerobic, psychrotolerant acidophile (Hallberg et al. 2010). *At. ferrivorans* and *At. ferrooxidans* differ in terms of their pH and temperature properties despite sharing many physiological aspects (Lam et al. 2022).

### *17.4.7* Acidithiobacillus ferriphilus

It is an extreme acidophilic, facultatively anaerobic iron–sulphur metabolizer (Guzman et al. 2022). It is a gold mill tailings associated acidophile. A single plasmid and 2489 putative protein-coding units can be found in the circular genome of *Acidithiobacillus ferriphilus* GT2. Functional investigation reveals the ability to fix $N_2$ and $CO_2$ and to oxidize iron, decrease sulphur compounds.

It is recognized that a vast number of heterotrophic fungus, heterotrophic bacteria, chemolithoautotrophic bacteria, and archaebacteria mediate the process of biomining. The most often used chemoautotrophic bacteria for biomining are *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, and *Acidithiobacillus thiooxidans*. The most frequently utilized heterotrophic bacteria for metal solubilization are *Bacillus licheniformis*, *Bacillus polymyxa*, and *Pseudomonas putida*, while the most frequently used fungus are *Aspergillus niger* and *Penicillium simplicissimum* (Zoungrana et al. 2022). It is also known that mesophilic and acidophilic archaebacteria of the genera *Ferroplasma*, as well as thermophilic archaebacteria of the genera *Sulfolobus*, *Acidianus*, *Metallosphaera*, and *Sulfurisphaera*, facilitate metal leaching. In order to extract metals from low-grade ores, mining waste and tailings, dumps of municipal solid waste, and e-waste even when the metals are present in extremely low concentrations without hurting the environment and ecology, the best technology now available is microbial mediated leaching (Kanekar and Kanekar 2022). Applications of certain biomining microorganisms are given in Table 17.1, and Fig. 17.1 depicts the major steps involved in solid waste management.

## 17.5 Implementation of Genomics and Metagenomics for Microbial Biominners

The reviewing of the composition and data operation of genetic constituents present in an organism's DNA is referred to as genomics. Utilizing genomics, one may calculate diversity in the genetic constituent and examine evolution adaptively, upgradation with new genes and designing models for metabolic activity. Prophesying action of microbes that how will they react to their surroundings. Many biomining bacteria' whole genome sequencing results have recently been uploaded to the NCBI database. There are typically several genotypes for each type of biomining microorganism, which reflects the genetic diversity of the organism. Assembly levels of a few strains of biomining microorganisms are available, and the data signifies that most biomining microorganisms have an incomplete assembly level. As a result, future genetic research will need to be augmented with data that is more thorough and complete. Microbial biominners that are sequenced, its comparative genomics analysis could help in divulging the adaptive evolution. Such biomining microorganisms as *L. ferriphilum*, *A. caldus*, *S. thermosulfidooxidans*, and *A. thiooxidans*

**Table 17.1** Application of biomining

| S. No. | Application of biomining | Metals recovered | Microbial miners | References |
|---|---|---|---|---|
| 1 | Bioengineering surfaces for metal recovery from aqueous solution | Cu | *Gandoderma lucidum* | Urbina et al. (2019) |
| 2 | Metal recovery from e-waste | Al, Cu, Pb, Ni, Sn, and Zn | *Thiobacillus ferrooxidans*, *Aspergillus Niger* and *Penicillium simplicissimu* | García-Balboa et al. (2022) and Peter et al. (2022) |
| 3 | Metal recovery from coal fly ash | Cr, Pb, Cu, Zn | *Anabena variabilis*, *Tolypothrix tenius* and *Aulosira fertilissimia* | Kaur and Goyal (2018) |
| 4 | Metal recovery from coal fly ash | Fe, Al, Zn, V, Ba, Mn, Pb, Ce | *Candida Bombicola*, *Phanerochaete chrysosporium* and *Cryptococcus* | Park and Liang (2019) |
| 5 | Use of synthetic agonists of quorum sensing *N*-acyl homoserine lactone pathway | Cu and Au | *Pseudomonas fluorescens*; *Acidithiobacillus ferrooxidans* | Caicedo et al. (2022) |
| 6 | Metal recovery from e-waste | Cr, Pb, Cu, Zn | *Thiobacilli* sp, *Pseudomonas* sp., *Aspergillus* sp., *Penicillium* sp. | Chakraborty et al. (2022) |
| 7 | Metal recovery from fresh municipal solid waste | Cu and Au | *Pseudomonas fluorescens*; *Acidithiobacillus ferrooxidans* | Choudhury et al. (2022) |
| 8 | Biomining of low-grade bauxite from molasses medium | Bauxite | *P. simplicissimum* | Shah et al. (2022) |
| 9 | Multi-metal extraction from printed circuit boards (PCBs) and tantalum capacitor scrap | Zn, Fe, Al and Ni | A mixed consortium of acidophiles and heterotrophic fungal strains: (*Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans* and *Acidithiobacillus thiooxidans*), (*Aspergillus niger*) | Sikander et al. (2022) |
| 10 | Bioleaching of typical electronic waste—printed circuit boards (WPCBs) | Au, Ag and Pd | *Chromobacterium violaceum*, *Pseudomonas* sp., and *Bacillus megaterium*) and *fungi* (e.g., *Aspergillus niger*, *Penicillium simplicissimum*) | Ji et al. (2022) |

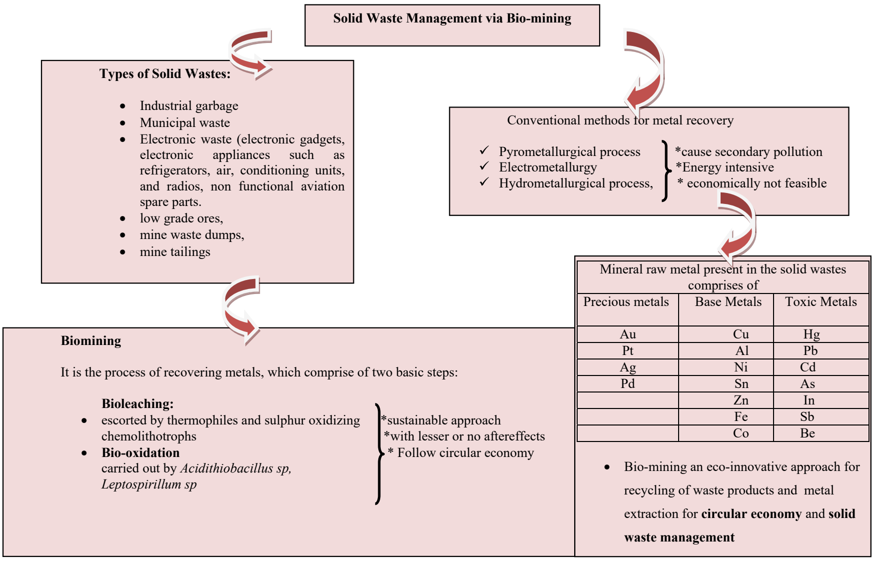



**Fig. 17.1** Steps involved in solid management via biomining

have been researched using this approach, for instance. These findings emphasize flow of genetic events comprising gain in genes, loss in genes, and its rearrangement that are related to intra-specific variations and adaptive evolution to extreme environments (e.g., horizontal gene transfer and duplication of genes). Some elements unlike insertion sequences, mobile genetic elements, integrative conjugative plasmids, and genome island may reveal the process of gene turnover (Zhang et al. 2016; Liu et al. 2022).

These novel findings help to refine the interrelation between models designed for studying metabolic reactions and make out some unique metabolic properties of biomining bacteria. There are several main carbon- and nitrogen-based metabolic pathways documented in a variety of well-known biomining bacteria. In *A. ferrooxidans,* ATCC 23270 carbon is metabolize via Calvin Bashan Bensen (CBB), Embden Meyerhoff Parnas pathway (EMP), Pentose phosphate pathway (PPP), and nitrogen metabolism via nitrogen fixation and ammonium uptake, respectively (Valdés et al. 2008; Liu et al. 2022). Additionally, complete cell models of *A. ferrooxidans* ATCC 23270 and projection of inorganic ion assimilation and absorption regulatory models for have been developed. It has been possible to pinpoint certain genes and proteins involved in iron sulphur oxidation using models of the $Fe^{2+}$ and sulphur oxidation electron transport routes in *A. ferrooxidans* (Zhang et al. 2018). There are published models for the carbon uptake, nitrogen metabolism, and sulphur oxidation of various strains of *A. thiooxidans.*

## 17.6 Implementation of All-Omics in the Study of Microbial Biominners

Conjugating all the multi-omics technologies can enable us to generate comprehensive data on complex biological system, such as microbial biominners, rather than single involvement of omics analysis. The 3-omics, i.e. genomics, proteomics, and transcriptomics, have illustrated adaptive strategy of major microbe involved in biomining *Leptospirillum ferriphilum* growing in chalcopyrite, identification of nitrogenase cluster for $N_2$ fixation that was earlier unidentified (Christel et al. 2018). By using genomic and transcriptome analyses, it was possible to determine how *A. ferrivorans* YL15 may respond to conditions such as a pH that is incredibly acidic, high metal ion concentrations, UV radiation, low temperatures, and the introduction of foreign genetic elements (Peng et al. 2017). Transcriptomic and proteomic study provided the first comprehensive insight of *A. ferrooxidans's* aerobic and anaerobic hydrogen metabolism at low pH (Kucera et al. 2020). Additionally, proteomics can provide specific information that transcriptomics cannot, while also identifying information that transcriptomics could overlook.

## 17.7 Bioengineering Surfaces for Metal Recovery from Aqueous Solutions

Conventional extraction procedures are inefficient and require energy-intensive processes to recycle e-waste that contains heterogeneous materials and trace amounts of metals. Urban biomining, also known as the application of a biological strategy to resource extraction from e-waste, permits metal retrieval at ambient conditions with less detrimental environmental consequences and minimal energy requirements than current technologies. Microbial surface adsorption can aid in the recovery of metals from e-waste-containing aqueous solutions (Liu et al. 2022).

The surface's functional groups will bind many cations with high affinity, limiting selectivity (Navarrete et al. 2011). Metal cofactors are not easily replaced from their cognate metallo-proteins by competing ions in the intracellular milieu, and all cellular fumids contain a range of metal ions at variable quantities. In the light of this, a biological strategy for metal adsorption based on peptides should be much focused. The metal coordination number and molecular shape of a ligand's cognate metal, which are shared characteristics between the two, are thought to be crucial aspects in determining specificity. The major coordination sphere, which is defined as the molecules that are directly attached to the metal, is where a metalloprotein should bind a metal cofactor with amino acids in order to optimize the molecular geometry and coordination number of the cognate metal (Urbina et al. 2019; Tavakoli et al. 2021).

## 17.8 Biomining as a New Aspect of Circularity of Waste Management

The "circular economy" approach of waste management, which includes not just managing trash but also its reuse and recycling, might help in the development of new companies and jobs while lowering emissions and enhancing the efficient use of natural resources (including energy, water, and materials). Biomining adheres to the core values of the circular economy by optimizing the recovery of recyclable materials. The ratio of soil to trash and excavation depth both affects how effective biomining is. The highest efficiency of biomining is implied by the depth of the excavation and the lowest soil-to-waste ratio (Bir et al. 2022). The most efficient resource recovery can be acquired only when the recovery of trash, which comprises recyclable, combustible, and non-combustible components, is taken into consideration. In the frame of reference of biomining, it puts into practise the core ideas of a circular economy model that uses sustainable waste management through reuse, recycling, and recovery, which is a shift from a linear economy, i.e. take-make-waste and accountable production of materials, and can satisfy the needs of raw materials for small-scale industries, such as small manufacturing industries, glass industries, plastic industries, etc., which can be advantageous with regard to environmental sustainability (Xavier et al. 2021).

## 17.9 Conclusion and Future Perspectives

Technology-based treatments which are economically viable and environment friendly are needed to address the harmful environmental effects of trash accumulation. The philosophy of "looking at waste as a resource and recycling it to retrieve the value of the waste" has significantly changed how solid waste is managed (SWM). The core of technical eco-innovations is automation of waste separation, retrieval, network optimization, digital information apps (increased efficiency by 40–85%), and modern techniques. The regulatory framework, which includes rule changes, new policies, plans, and smart city missions, is in charge of putting "technology advancements" into practice on a practical level and has demonstrated positive effects on society. The increase in bio-recovery efficiency of precious metals is essential for improving scaling-up potential because the majority of the discovered microbial technologies are created in laboratories. Future research focuses on high-performance methods for important metal recovery by microbial processes, as well as novel microorganisms is of concern. The intricacy and distinctive inter-specific interactions, as well as the varied chemical profiles and inventiveness that accompany the evolution of many organisms, particularly within consortia and signal transmission, are other untapped areas in terms of research. It should be highlighted that little is known about a crucial process called "quorum sensing" (QS), which is regulated by cell-to-cell communication processes and is evident in gram-negative bacteria's participation in bioleaching step of biomining.

## References


Bir T, Banerjee S, Dutta A (2022). Legacy waste characterization: bio-mining solution for landfills and resource recovery towards circularity. In: International conference on chemical, bio and environmental engineering. Springer, Cham, pp 635–650

Caicedo JC, Villamizar S, Orlandoni G (2022) The use of synthetic agonists of quorum sensing *N*-acyl homoserine lactone pathway improves the bioleaching ability in *Acidithiobacillus* and *Pseudomonas bacteria.* PeerJ 9(10):e13801

Carmona-Gutierrez D, Kainz K, Zimmermann A et al (2022) A hundred spotlights on microbiology: how microorganisms shape our lives. Microbial Cell 9(4):72

Chakraborty SC, Zaman M, Uz W et al (2022) Metals extraction processes from electronic waste: constraints and opportunities. Environ Sci Pollut Res 27:1–9

Chen J, Liu Y, Diep P et al (2022) Genetic engineering of extremely acidophilic *Acidithiobacillus species* for biomining: progress and perspectives. J Hazard Mater 26:129456

Choudhury AR, Boyina LP, Kumar DL et al (2022) Biomined and fresh municipal solid waste as sources of refuse derived fuel. In: Circular economy in municipal solid waste landfilling: biomining & leachate treatment. Springer, Cham, pp 235–252

Christel S, Herold M, Bellenberg S et al (2018) Multi-omics reveals the lifestyle of the acidophilic, mineral-oxidizing model species *Leptospirillum ferriphilum* T. Appl Environ Microbiol 84(3):e02091–17

Coram NJ, Rawlings DE (2002). Molecular relationship between two groups of the genus *Leptospirillum* and the finding that *Leptospirillum ferriphilum* sp. nov. dominates South African commercial biooxidation tanks that operate at 40 °C. Appl Environ Microbiol 68(2):838–845

Das AP, Ghosh S (2022) Role of microorganisms in extenuation of mining and industrial wastes. Geomicrobiol J 39(3–5):173–175

Donati ER, Castro C, Urbieta MS (2016) Thermophilic microorganisms in biomining. World J Microbiol Biotechnol 32(11):1–8

Gao X, Jiang L, Mao Y et al (2021) Progress, challenges, and perspectives of bioleaching for recovering heavy metals from mine tailings. Adsorpt Sci Technol 7:2021

García-Balboa C, Martínez-Alesón García P, López-Rodas V et al (2022) Microbial biominers: sequential bioleaching and biouptake of metals from electronic scraps. MicrobiologyOpen 11(1):e1265

Guzman MS, Reed D, Fujita Y et al (2022) Complete genome sequence of *Acidithiobacillus ferriphilus* GT2, isolated from gold mill tailings. Microbiol Resour Announc 11(2):e01089–21

Hallberg KB, Lindström EB (1994) Characterization of *Thiobacillus caldus* sp. nov., a moderately thermophilic acidophile. Microbiology 140(12):3451–3456

Hallberg KB, González-Toril E, Johnson DB (2010) *Acidithiobacillus ferrivorans*, sp. nov.; facultatively anaerobic, psychrotolerant iron-, and sulfur-oxidizing acidophiles isolated from metal mine-impacted environments. Extremophiles 14(1):9–19

Hoque ME, Philip OJ (2011) Biotechnological recovery of heavy metals from secondary sources—an overview. Mater Sci Eng C 31(2):57–66

Jeong SW, Choi YJ (2020) Extremophilic microorganisms for the treatment of toxic pollutants in the environment. Molecules 25(21):4916

Jerez CA (2012) The use of extremophilic microorganisms in the industrial recovery of metals. In: Extremophiles: sustainable resources and biotechnological implications, vol 2, pp 319–334

Ji X, Yang M, Wan A et al (2022) Bioleaching of typical electronic waste—printed circuit boards (WPCBs): a short review. Int J Environ Res Public Health 19(12):7508

Jiménez-Paredes AE, Alfaro-Saldaña EF, Hernández-Sánchez A et al (2021) An autochthonous *Acidithiobacillus ferrooxidans* metapopulation exploited for two-step pyrite biooxidation improves Au/Ag particle release from mining waste. Mining 1(3):335–350

Johnson DB (2018) The evolution, current status, and future prospects of using biotechnologies in the mineral extraction and metal recovery sectors. Minerals 8(8):343

Kanekar PP, Kanekar SP (2022) Acidophilic microorganisms. In: Diversity and biotechnology of extremophilic microorganisms from India. Springer, Singapore, pp 155–185

Kaur R, Goyal D (2018) Heavy metal accumulation from coal fly ash by cyanobacterial biofertilizers. Part Sci Technol 36(4):513–516

Kölbl D, Memic A, Schnideritsch H et al (2022) Thermoacidophilic bioleaching of industrial metallic steel waste product. Front Microbiol 13:864411

Kucera J, Lochman J, Bouchal P, Pakostova E, Mikulasek K, Hedrich S, Janiczek O, Mandl M, Johnson DB et al (2020) A model of aerobic and anaerobic metabolism of hydrogen in the extremophile *Acidithiobacillus ferrooxidans*. Front Microbiol 11:610836

Kumar M, Kochhar N, Kavya IK et al (2022) Perspectives on the microorganism of extreme environments and their applications. Curr Res Microbial Sci 21:100134

Lam EJ, Bernardo-Sánchez A, Sokoła-Szewioła V (2022) Editorial for special issue "risk assessment, management and control of mining contamination". Minerals 12(8):992

Liu R, Zhou H (2022) Growth in ever-increasing acidity condition enhanced the adaptation and bioleaching ability of *Leptospirillum ferriphilum*. Int Microbiol 17:1

Liu M, Li Z, Chen Z et al (2022) Simultaneous biodetection and bioremediation of $Cu^{2+}$ from industrial wastewater by bacterial cell surface display system. Int Biodeterior Biodegradation 1(173):105467

Martínez-Bellange P, von Bernath D, Navarro CA et al (2022) Biomining of metals: new challenges for the next 15 years. Microb Biotechnol 15(1):186–188

Mohan S, Joseph CP (2020) Biomining: an innovative and practical solution for reclamation of open dumpsite. In: Recent developments in waste management: select proceedings of recycle 2018. Springer, Singapore, pp 167–178

Natarajan KA (2018) Biotechnology of metals: principles, recovery methods and environmental concerns. Elsevier

Navarrete JU, Borrok DM, Viveros M et al (2011) Copper isotope fractionation during surface adsorption and intracellular incorporation by bacteria. Geochim Cosmochim Acta 75(3):784–799

Nayak NP (2022) Microorganisms and their application in mining and allied industries. Mater Today Proc 72:2886–2891

Olson GJ, Brierley JA, Brierley CL (2003) Bioleaching review part B. Appl Microbiol Biotechnol 63(3):249–257

Omokawa H, Kurosawa N, Sakai HD (2022) Complete genome sequence of *Acidianus* sp. strain HS-5, isolated from the Unzen hot spring in Japan. Microbiol Resour Announc 11(2):e01159-21

Panyushkina A, Muravyov M, Fomchenko N (2022). A case of predominance of *Alicyclobacillus tolerans* in microbial community during bioleaching of pentlandite-chalcopyrite concentrate. Minerals 12(4):396

Park S, Liang Y (2019) Bioleaching of trace elements and rare earth elements from coal fly ash. Int J Coal Sci Technol 6(1):74–83

Pattanaik A, Samal DP, Sukla LB, Pradhan D (2020) Advancements and use of OMIC technologies in the field of bioleaching: a review

Peng T, Ma L, Feng X et al (2017) Genomic and transcriptomic analyses reveal adaptation mechanisms of an *Acidithiobacillus ferrivorans* strain YL15 to alpine acid mine drainage. PLoS ONE 12(5):e0178008

Peter D, Shruti Arputha Sakayaraj L, Ranganathan TV (2022) Recovery of precious metals from electronic and other secondary solid waste by bioleaching approach. Biotechnol Zero Waste Emerg Waste Manage Tech 7:207–218

Qi Y, Shangguan X, He J, Chen L, Jin J, Liu Y, Qiu G, Yu R, Li J, Zeng W, Shen L et al (2022) Expression, purification, characterization and direct electrochemistry of two HiPIPs from *Acidithiobacillus caldus* SM-1. Anal Biochem 650:114724

Rawlings DE (2005) Characteristics and adaptability of iron-and sulfur-oxidizing microorganisms used for the recovery of metals from minerals and their concentrates. Microb Cell Fact 4(1):1–5

Saavedra A, Aguirre P, Gentina JC (2020) Biooxidation of iron by *Acidithiobacillus ferrooxidans* in the presence of D-galactose: understanding its influence on the production of EPS and cell tolerance to high concentrations of iron. Front Microbiol 23(11):759

Sana S, Neelam D, Gupta V et al (2021) An overview: application of microorganisms in bio-mining of metals (review article). Int J Pharm Biol Sci 11(1):01–08. https://doi.org/10.21276/ijpbs.2021.11.1.1

Sand W, Gerke T, Hallmann R et al (1995) Sulfur chemistry, biofilm, and the (in) direct attack mechanism—a critical evaluation of bacterial leaching. Appl Microbiol Biotechnol 43(6):961–966

Schippers A (2007) Microorganisms involved in bioleaching and nucleic acid-based molecular methods for their identification and quantification. In: Microbial processing of metal sulfides. Springer, Dordrecht, pp 3–33

Shah SS, Palmieri MC, Sponchiado SR et al (2022) A sustainable approach on biomining of low-grade bauxite by *P. simplicissimum* using molasses medium. Braz J Microbiol 53(2):831–843

Sikander A, Kelly S, Kuchta K et al (2022) Chemical and microbial leaching of valuable metals from PCBs and tantalum capacitors of spent mobile phones. Int J Environ Res Public Health 19(16):10006

Tavakoli HZ, Bahrami-Bavani M, Miyanmahaleh Y et al (2021) Identification and characterization of a metal-resistant Acidithiobacillus ferrooxidans as important potential application for bioleaching. Biologia 76(4):1327–1337

Urbina J, Patil A, Fujishima K, Paulino-Lima IG, Saltikov C, Rothschild LJ et al (2019) A new approach to biomining: bioengineering surfaces for metal recovery from aqueous solutions. Sci Rep 9(1):1

Valdés J, Pedroso I, Quatrini R et al (2008) *Acidithiobacillus ferrooxidans* metabolism: from genome sequence to industrial applications. BMC Genom 9(1):1–24

Valdez-Nuñez LF, Ayala-Muñoz D, Sánchez-España J, Sánchez-Andrea I et al (2022) Microbial communities in peruvian acid mine drainages: low-abundance sulfate-reducing bacteria with high metabolic activity. Geomicrobiol J 24:1–7

Vyas S, Prajapati P, Shah AV et al (2022) Opportunities and knowledge gaps in biochemical interventions for mining of resources from solid waste: a special focus on anaerobic digestion. Fuel 1(311):122625

Wadden D, Gallant A (1985) The in-place leaching of uranium at Denison Mines. Can Metall Quart 24(2):127–134

Wang P, Li LZ, Qin YL et al (2020) Comparative genomic analysis reveals the metabolism and evolution of the thermophilic archaeal genus *Metallosphaera*. Front Microbiol 11:1192

Watling HR (2014) Review of biohydrometallurgical metals extraction from polymetallic mineral resources. Minerals 5(1):1–60

Xavier LH, Giese EC, Ribeiro-Duthie AC, Lins FA et al (2021) Sustainability and the circular economy: a theoretical approach focused on e-waste urban mining. Resour Policy 74:101467

Zhang X, She S, Dong W et al (2016) Comparative genomics unravels metabolic differences at the species and/or strain level and extremely acidic environmental adaptation of ten bacteria belonging to the genus *Acidithiobacillus*. Syst Appl Microbiol 39(8):493–502

Zhang S, Yan L, Xing W et al (2018) *Acidithiobacillus ferrooxidans* and its potential application. Extremophiles 22(4):563–579

Zoungrana A, Hasnine MD, Yuan Q (2022) Landfill mining: significance, operation and global perspectives. In: Circular economy in municipal solid waste landfilling: biomining & leachate treatment. Springer, Cham, pp 25–45

# Chapter 18
# Plant–Bacteria Interaction in the Recovery of Metals from Electronic Waste

**Guadalupe Díaz-Domínguez, Bárbara Paulet Domínguez-Capitaine, María Esther Díaz-Martínez, and Rosalba Argumedo-Delira**

**Abstract** Waste electrical and electronic equipment (WEEE) is considered a secondary source of metals, and biotechnological alternatives are currently being sought for its recovery in an environmental-friendly way. Therefore, the potential of *Medicago sativa* L. in the phytoextraction of Au, Ag, Pd, Cu, and Si from computer printed circuit boards (PCBs) with and without *Pseudomonas tolaasii* inoculation and the phytoextraction of Au, Ag, Pd, Cu, and Si from *Lens culinaris* from cell phone PCB with and without *Rhizobium tropici* inoculation under hydroponic conditions was evaluated. PCB obtained from obsolete computers and cell phones were cut to reduce their size. The seeds of *M. sativa* L. and *L. culinaris* were then germinated for 15 days. Subsequently, *P. tolaasii* was cultured in nutrient agar and *R. tropici* in ELMARC medium; then, a bacterial suspension of each bacterium was prepared at a concentration of $10^8$ colony-forming units (CFUs). *M. sativa* L. and *L. culinaris* plants were then transplanted into a pot with modified Long Ashton nutrient solution. Then, 1 g of computer PCB were added to the *M. sativa* L. plants and 6 mL of *P. tolaasii* ($10^8$ CFU), while 1 g of cell phone PCB and 6 mL of *R. tropici* ($10^8$ CFU) were added to the *L. culinaris* plants. After 20 days in the greenhouse, the plants were harvested to determine their biomass in the aerial part and roots and the concentration of Au, Ag, Pd, Cu, and Si using an ICP-OES optical emission spectrometer. The results indicate that the plant–bacteria interaction is affected by the presence of PCB. Cu from PCB of computer and cell phones is the metal that showed the greatest accumulation in the biomass of both plants. The highest accumulation of Cu (73%) was found in the *M. sativa* L. treatments without bacterial inoculation, while

---

G. Díaz-Domínguez · B. P. Domínguez-Capitaine · M. E. Díaz-Martínez · R. Argumedo-Delira (✉)
Instituto de Química Aplicada, Universidad Veracruzana, Luis Castelazo Ayala S/N, Col. Industrial Animas, 91190 Xalapa, Veracruz, Mexico
e-mail: rargumedo@uv.mx

G. Díaz-Domínguez · B. P. Domínguez-Capitaine
Facultad de Ciencias Químicas, Universidad Veracruzana, Xalapa, México

M. E. Díaz-Martínez
Facultad de Ciencias Agrícolas, Universidad Veracruzana, Xalapa, México

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_18

the accumulation of Cu (27%) by *L. culinaris* was favored by the inoculation of *R. tropici*. In addition, bacterial inoculation slightly improved trace Pd phytoextraction and trace Au bioleaching for *M. sativa* treatments with computer PCB. Meanwhile, the *L. culinaris* treatments that were not inoculated with the *R. tropici* accumulated Au (11%) and Si (10%) from cell phone PCB in their biomass. These results show the potential that plant–bacteria interaction could have for the selective recovery of metals from PCB of computers and cell phones if the appropriate association is found and the conditions favor a high phytoextraction of the metal of interest. Hence, alternative technologies to the existing ones are currently required for the recovery of metals from electronic waste that are friendly to the environment and that help provide metals to the existing market.

**Keywords** *Pseudomonas* · *Rhizobium* · Metals · Printed circuit boards · Lentil · Alfalfa

## 18.1 Introduction

Technological progress and the globalization of the market have contributed to the increase in the production of electrical and electronic equipment, accelerating their acquisition and renewal, causing the useful life of these equipment to be shorter, and therefore, they are discarded (Chakraborty et al. 2022a; Vishwakarma et al. 2022). Electronic waste includes PCB, which are the basis of the electronics industry since they are an essential part of most electrical and electronic equipment (Duan and Zhu 2022). Components mounted on PCB are generally chips, integrated circuits, connectors, and capacitors (Huesgen 2022). Computer PCB is made with a single layer of fiberglass, cellulose paper, or phenolic coating and with a copper layer made up of 45% metals, 28% ceramics, and 27% polymers (Yamane et al. 2011; Chakraborty et al. 2022b). While the PCB used in cell phones are composed of a multiple layer of epoxy resin, fiberglass and covered by a layer of copper, they are composed of 63% metals, 24% ceramics, and 13% polymers (Kaya 2019).

Various treatments based on hydrometallurgical, pyrometallurgical, and biological processes have been used for the recovery of metals from PCBs from computers and cell phones (Fernandes Andrade et al. 2022; Kumari and Samadder 2022). Hydrometallurgical processes consist mainly of acid or alkaline leaching of the finely divided solid material of PCB; subsequently, the leachates of the metals of interest are isolated and concentrated (Cui and Zhang 2008; Krishnan et al. 2021). Meanwhile, pyrometallurgical processes include incineration, smelting, sintering, and gas-phase reactions at high temperatures (Faraji et al. 2022). However, pyrometallurgical processes have some disadvantages such as the generation of combustion dust and dioxins (Priya and Hait 2017; Islam et al. 2020), while hydrometallurgical processes generate highly corrosive and toxic wastewater (Rajesh et al. 2022). The biological processes for the recovery of metals from PCB involve the use of bacteria, fungi, and plants (Argumedo-Delira et al. 2020). The most used bacteria are acidophilic bacteria such as *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Thiobacillus thiooxidans*, *Thiobacillus ferrooxidans*, *Sulfobacillus thermosulfidooxidans* (Brandl et al. 2001; Ilyas et al. 2022; Pirsaheb et al. 2022; Silva et al. 2022) and cyanogenic bacteria such as *Pseudomonas aeruginosa*, *Chromobacterium violaceum*, *Bacillus megaterium* (Natarajan and Ting 2014; Alshehri 2018; Merli et al. 2022). Filamentous fungi of the genera *Aspergillus*, *Penicillium*, *Fusarium*, *Trichoderma* (Díaz-Martínez et al. 2019; Yaashikaa et al. 2022). Plants such as *Lolium perenne* L. and *Medicago sativa* L. (Díaz-Martínez et al. 2018). Although the reports found in the literature on the biological recovery of metals from PCB are promising, more research is still needed to implement these methodologies in industrial processes that can help in the recovery of metals from electronic waste in a sustainable and environmental-friendly way.

Therefore, it is important to explore the plant–bacteria interaction for the recovery of metals from PCB as a biological alternative. Since it has been reported that bacteria inhabit the surface and within many organs of most plants that lead to positive, neutral, or negative relationships with their hosts (Partida-Martínez and Heil 2011; Orlikowska et al. 2017), the positive effects of bacteria for plants vary according to specific characters of bacteria and plants (genotypes), in addition to the interactions between bacteria and plants which are affected by biotic and abiotic factors (Agler et al. 2016). The benefits provided by bacteria to their host plants are the production of growth hormones (phytohormones and 1-aminocyclopropane-1-carboxylic acid deaminase, ACC), the absorption of nutrients (solubilization of phosphorus, the fixation of nitrogen, and iron sequestration), tolerance to abiotic and biotic stress, resistance to pathogens, and production of useful secondary metabolites (Glick 2020; Trivedi et al. 2020).

Regarding the tolerance of plants to abiotic stress caused by metals, it has been reported that plants inoculated with bacteria improve the absorption and accumulation of metals in different parts of the plant without influencing its growth (Ashraf et al. 2017). Bacteria have also been reported to increase the biomass production of plant hosts exposed to different metals (Franco-Franklin et al. 2021). This interaction has been used for the phytoremediation of soils contaminated with metals and in the phytoextraction of metals within phytomining (Kidd et al. 2017; Kong and Glick 2017). Meanwhile, the bacterial mechanisms reported within the interaction with plants subjected to metal stress consist of transforming metals into bioavailable and soluble forms through the action of siderophores, organic acids, biosurfactants, biomethylation, and redox processes (Ullah et al. 2015). Considering the above, the present study aimed to evaluate the potential of *M. sativa* L. in the phytoextraction of metals from computer PCB with and without *P. tolaasii* inoculation, and the phytoextraction of metals by *L. culinaris* from cell phone PCB with and without *R. tropici* inoculation under hydroponic conditions.

## 18.2 Materials and Methods

### *18.2.1 Collection and Dismantling of Obsolete Computers and Cell Phones*

Obsolete computers and cell phones were collected, which were dismantled to obtain the printed circuit board with the help of screwdrivers and tweezers. Subsequently, the circuits present in the PCB were removed; then, the PCB was cut into pieces of 0.5 cm × 0.5 cm to facilitate handling. Then, 1 g of the computer and cell phone PCBs were separately digested with aqua regia (3:1 $HCl/HNO_3$) at 108 °C for 4 h. Subsequently, the solutions obtained were filtered under gravity with filter paper and adjusted to 25 mL. The dissolved samples were analyzed in an optical emission spectrometer ICP-OES (Varian® Mod. 725-ES) to quantify Au, Ag, Pd, Cu, and Si present in PCB.

### *18.2.2 Germination of* M. sativa *L. and* L. culinaris *Seeds and Transplanting to Pots*

*Medicago sativa* L. and *L. culinaris* seeds were disinfected in 3% sodium hypochlorite (NaClO) for 3 min; then, the seeds were rinsed six times with distilled water. Subsequently, the seeds of the plants were placed in a container with hydrogen peroxide ($H_2O_2$) for 3 min. The seeds were then rinsed six times with distilled water. The seeds were then placed in a container with ethanol ($CH_3CH_2OH$) for 3 min and subsequently rinsed 6 times with distilled water. The seeds were then placed in containers with cotton moistened with distilled water for germination at room temperature (20–25 °C) for 15 days. Afterward, the plants that had homogeneity in their height (~ 10 cm) were selected and transplanted into pots made with 200 mL of polyethylene terephthalate (PET) bottles disinfected with 10% sodium hypochlorite. The PET pots where the *M. sativa* L. and *L. culinaris* plants were established contained 55 mL of Long Ashton modified nutrient solution (Fig. 18.1).

### *18.2.3 Preparation of Bacterial Inoculant*

The bacterium *P. tolaasii* was isolated from the rhizosphere of the potato, while *R. tropici* was isolated from lentil nodules, and both strains were provided by the

**Fig. 18.1** *Medicago sativa* L. treatments with computer PCB and inoculated with *P. tolaasii*

Soil Microbiology Laboratory of the Postgraduate in Edaphology of the Campus Montecillo Postgraduate College in the state of Mexico. Both bacteria have promoted plant growth of various plants (data not shown). *P. tolaasii* was grown in Petri dishes with nutrient agar (BD Bioxon®), while *R. tropici* was grown in Petri dishes with ELMARC medium, and both bacteria were incubated for 3 days at 28 °C. After this time, bacterial suspensions were prepared at a concentration of $10^8$ colony-forming units (CFUs) according to the McFarland scale.

### *18.2.4 Treatments of Plants with PCB and Growing Conditions*

The treatments were established as follows: (1) Long Ashton modified nutrient solution, (2) Long Ashton modified nutrient solution + plant, (3) PCB + Long Ashton modified nutrient solution, (4) PCB + Long Ashton modified nutrient solution + plant, and (5) PCB + Long Ashton modified nutrient solution + plant + bacteria (Table 18.1); each of the treatments had four repetitions. About 1 g of PCB was added to the PCB treatments, while 6 mL of the bacterial suspension ($1 \times 10^8$ CFU) was added to the bacterial treatments. Finally, all the treatments were placed inside another disinfected 1 L PET bottle to avoid contamination and were established in a greenhouse for 20 days at room temperature (20–28 °C).

**Table 18.1** Treatments with *M. sativa* L. and *L. culinaris* in Long Ashton nutrient solution and PCB with and without bacterial inoculation

| Treatments | |
|---|---|
| 1 | Long Ashton modified nutrient solution |
| 2 | Long Ashton modified nutrient solution + *Medicago sativa* L. |
| | Long Ashton modified nutrient solution + *Lens culinaris* |
| 3 | Computer PCB + Long Ashton modified nutrient solution |
| | Cell phone PCB + Long Ashton modified nutrient solution |
| 4 | Computer PCB + Long Ashton modified nutrient solution + *Medicago sativa* L. |
| | Cell phone PCB + Long Ashton modified nutrient solution + *Lens culinaris* |
| 5 | Computer PCB + Long Ashton modified nutrient solution + *Medicago sativa* L. + *P. tolaasii* |
| | Cell phone PCB + Long Ashton modified nutrient solution + *Lens culinaris* + *R. tropici* |

### 18.2.5 Determination of Ag, Au, Cu, Pd, and Si in Plant Biomass

After 20 days, the *M. sativa* L. and *L. culinaris* plants were harvested. The plants were dried at 60 °C for 48 h and ground in a mortar to determine the dry weight of the dry biomass (aerial part and root). Subsequently, this biomass was taken to be digested with aqua regia (3:1 $HCl/HNO_3$) at 108 °C for 4 h. The obtained solution was filtered and adjusted to 10 mL. The dissolved samples were analyzed in an ICP-OES optical emission spectrometer (Varian® Mod. 725-ES) to quantify the phytoextraction of metals (Ag, Au, Cu, Pd, and Si). For the *M. sativa* L. and *L. culinaris* plants, metal bioleaching was determined by removing the PCB fragments from computers from the nutrient solution by gravity filtration, then 1 mL of concentrated nitric acid was added to the solution obtained, and then, metals (Ag, Au, Cu, Pd, and Si) were analyzed in an optical emission spectrometer ICP-OES (Varian® Mod. 725-ES). While in the case of the treatments inoculated with bacteria, the bioleaching of metals was determined by centrifugation of the treatments at 3300 rpm for 10 min, after this time, the supernatant was filtered and 1 mL of concentrated nitric acid was added to analyze metals (Ag, Au, Cu, Pd, and Si) in an optical emission spectrometer ICP-OES (Varian® Mod. 725-ES).

### 18.2.6 Statistical Analysis

For biomass and phytoextraction of metals from PCB with and without bacterial inoculation and metal bioleaching, a completely randomized design was used, using analysis of variance (ANOVA) and the comparison of means test (Tukey, $\alpha = 0.05$), with the statistical program SAS Institute, 2021.

## 18.3 Results and Discussion

All treatments for *M. sativa* L. plants showed an increase in the pH (on average 7.8) of the initial nutrient solution (6.1), and this may be due to the reduction of intracellular nitrate to ammonium by the plants combined with the co-transport of protons during the consumption of sugars (Hageman 1984), since *M. sativa* L. plants are sensitive to acidity and their optimum growth pH is between 6.5 and 7.5 (McCauley et al. 2009). Likewise, the increase in the pH of the nutrient solution can also be attributed to the presence of PCB, an effect that was reported by Brandl et al. (2001). This same behavior was observed in *L. culinaris* treatments, plants that require a pH between 6 and 8 (Abraham 2015). Regarding the biomass of the plants (aerial part and root) expressed in dry weight, it was found that the treatments with *M. sativa* L. and computer PCB had a positive effect on the biomass in the aerial part compared to the biomass of *M. sativa* L. But, when the bacteria are inoculated in the treatments with computer PCB + *M. sativa* L., it is observed that the biomass of the aerial part decreases (Fig. 18.2). In the case of the biomass of the root of *M. sativa* L., the same behavior that was observed for the biomass of the aerial part was presented, and it was found that the treatment of *M. sativa* L. with *P. tolaasii* had the highest biomass of the aerial part (Fig. 18.3). The positive effect on the biomass of *M. sativa* L. when exposed to PCB has been reported by Díaz-Martínez et al. (2018) for hydroponic crops, and this behavior was also presented in this study.

In the case of *L. culinaris*, the biomass of the aerial part decreases 13.6% in the treatments exposed to PCB from cell phones compared to the treatments with *L. culinaris* (Fig. 18.4). However, the treatments of *L. culinaris* exposed to PCB and with and without inoculation of *R. tropici* did not present statistical differences for the biomass of the aerial part of the plants, while for the biomass of the aerial part and the root, the best treatments were where *L. culinaris* and *R. tropici* were found

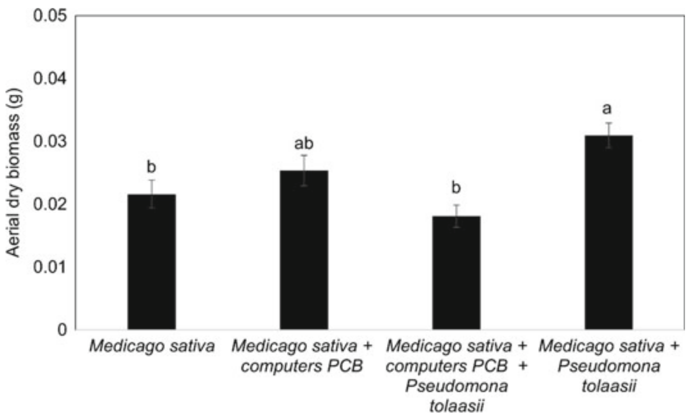



**Fig. 18.2** Biomass of the aerial part of the treatments of *M. sativa* L. with computer PCB. Mean ± standard error, $n = 4$

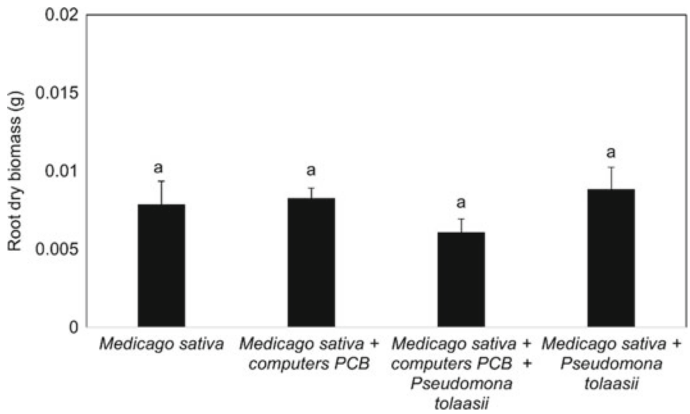



**Fig. 18.3** Biomass of the roots of the treatments of *M. sativa* L. with computer PCB. Mean ± standard error, $n = 4$

(Fig. 18.5). In both legumes, it was expected that the inoculation of the bacteria would increase the biomass of the aerial part and of the root in the plants that were exposed to PCB. However, a negative effect was found for the biomass of the aerial part of the PCB + plant + bacteria treatments when compared to the plant + bacteria treatments. This behavior may be related to the toxicity that PCB may have for the symbiosis between the bacteria and the legumes under study, since without the electronic waste, the plants inoculated with the bacteria had the highest biomass of the aerial part and of the root. It has been reported that elevated levels of metals in soils can affect the growth of bacteria and host legumes as well as affect the symbiosis between legumes and bacteria, due to increased production of ROS (Stambulska et al. 2018; Stambulska and Bayliak 2020), which may be related to the results found.

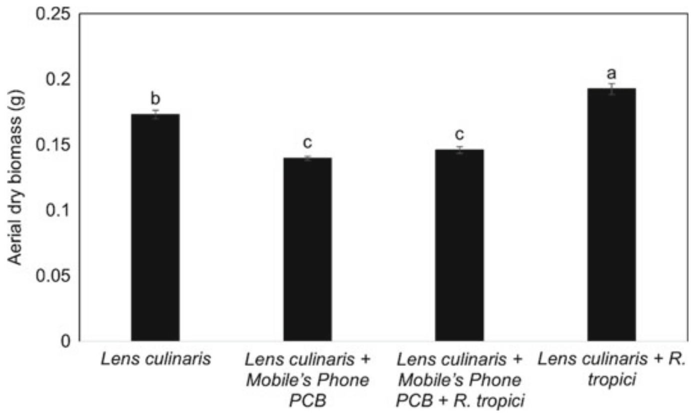



**Fig. 18.4** Biomass of the aerial part of the treatments of *L. culinaris* with cell phone PCB. Mean ± standard error, $n = 4$

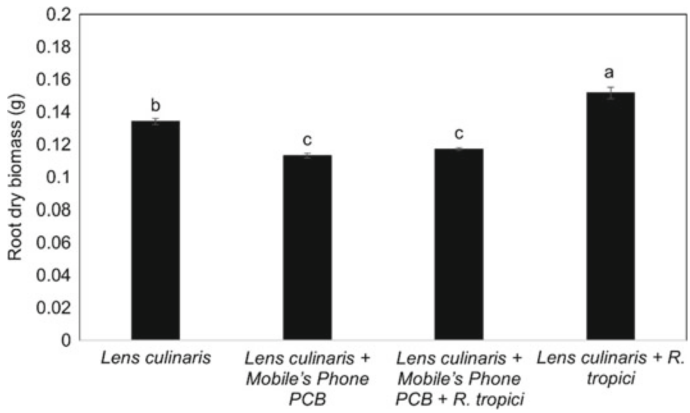



**Fig. 18.5** Biomass of the roots of the treatments of *L. culinaris* with cell phone PCB. Mean ± standard error, $n = 4$

In the phytoextraction of metals, it was found that *M. sativa* L. accumulated more Cu (73%) than any other metal from computer PCB. In addition, no statistical differences were found between the *M. sativa* L. treatments and the *M. sativa* L. + *P. tolaasii* treatments for Cu phytoextraction (Fig. 18.6). The results indicate that *P. tolaasii* inoculation did not help Ag phytoextraction, but slightly improved Pd phytoextraction as well as Au bioleaching (Fig. 18.7).

With respect to the phytoextraction of metals by *L. culinaris*, Cu from cell phone PCB was also the metal that the plant accumulates in the highest proportion in its biomass. In this case, there is greater phytoextraction of Cu (27%) in the treatments

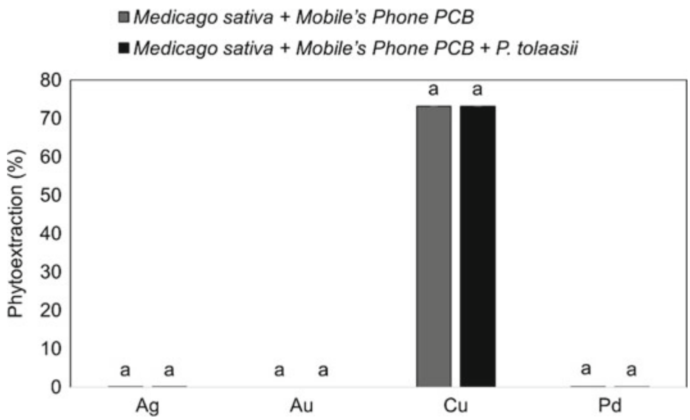



**Fig. 18.6** Copper, silver, and gold phytoextraction for treatments with *M. sativa* L. exposed to computer PCB. Mean ± standard error, $n = 4$

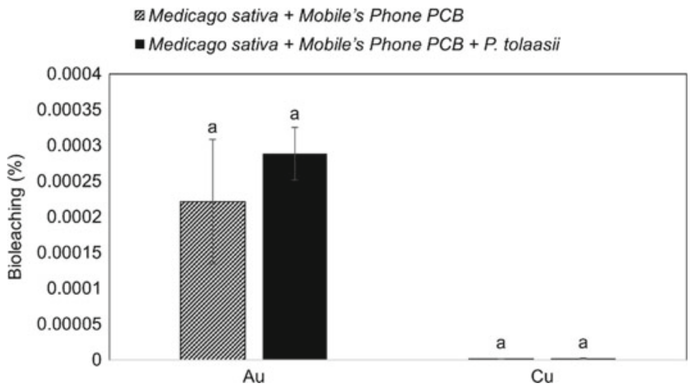



**Fig. 18.7** Copper and gold bioleaching for treatments with *M. sativa* L. exposed to computer PCB. Mean ± standard error, $n = 4$

that are inoculated with *R. tropici* (Fig. 18.8). Meanwhile, the *L. culinaris* treatments that were not inoculated with *R. tropici* had higher phytoextraction of Au (11%) and Si (10%). Similarly, the inoculation of *R. tropici* slightly improved Cu bioleaching (Fig. 18.9).

The phytoextraction of Cu in both plants may be since Cu is one of the metals that is found in greater quantity by weight in the PCB of computers (20 wt%) and cell phones (35 wt%), which possibly contributed to its greater bioavailability for both plants (Yamane et al. 2011). It could also be due to the ability of both plants to interact with various metals and their ability to accumulate them in the aerial part and root (Rahman et al. 2012; Raklami et al 2021). For example, it has been reported that *M. sativa* L. plants have been used for the phytoremediation of soils

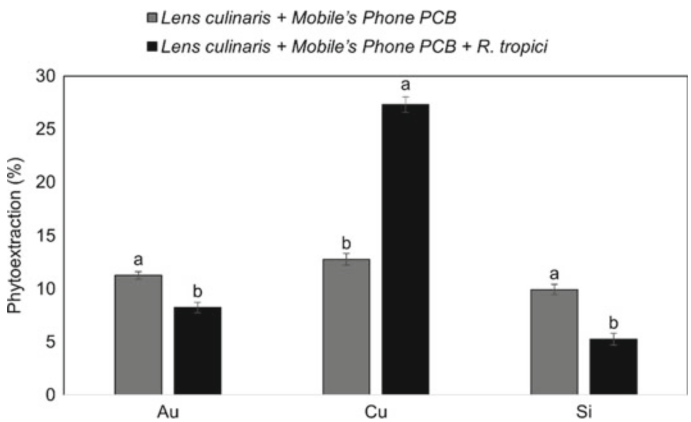



**Fig. 18.8** Copper, gold, and silicon phytoextraction for treatments with *L. culinaris* exposed to cell phone PCB. Mean ± standard error, $n = 4$

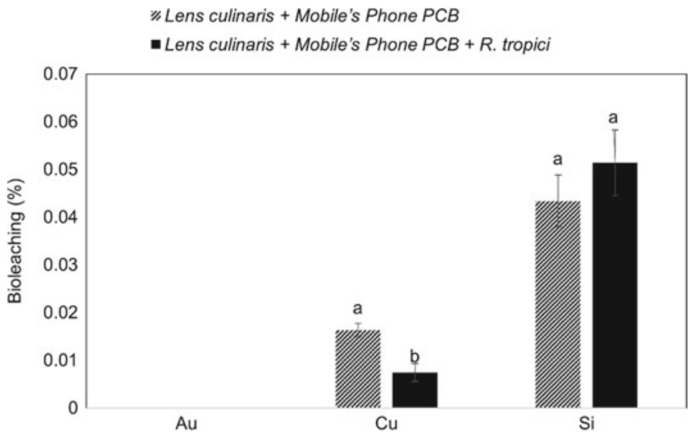



**Fig. 18.9** Copper, gold, and silicon bioleaching for treatments with *L. culinaris* exposed to cell phone PCB. Mean ± standard error, $n = 4$

contaminated with metals and mine tailings (where Cu is present), due to their high biomass productivity, high tolerance to metals, and its great capacity to absorb metals (Tabasi et al. 2017; Chen et al. 2022). In the case of sites contaminated with metals, it has been found that *M. sativa* L. presents the maximum Cu content in the roots, 35.81 mg kg$^{-1}$ (Sękara et al. 2005); this behavior is not observed in the experiments with PCB, since the maximum Cu content is found in the aerial part. On the other hand, under in vitro conditions, it has been reported that *M. sativa* L. is affected in the germination process and in its growth when exposed to concentrations higher than 20 mg L$^{-1}$ of Cu, while when *M. sativa* L. was exposed to a concentration of 5 mg L$^{-1}$, there was a 59% stimulation in shoot growth (Aydinalp and Marinova 2009), indicating that the concentration of Cu is a factor that determines the toxicity of Cu for *M. sativa* L. In the case of PCB, the toxic effect toward alfalfa plants was shown after 20 days of exposure (data not shown), but this effect cannot be attributed to a specific metal or material, but to all the components of computer PCB. Meanwhile, *L. culinaris* has been reported as a Cu hyperaccumulating plant with an accumulation rate of 1.19 mg g$^{-1}$ (Rahman et al. 2012). As reported for *M. sativa* L., Cu toxicity for *L. culinaris* depends on the concentration of this element, and for the germination of *L. culinaris* seeds, Cu at a concentration of 25 mg L$^{-1}$ has a toxic effect (Iqbal et al. 2018).

Regarding the inoculation of *P. tolaasii* in *M. sativa* L. plants exposed to computer PCB, only minimal effects were found on Pd phytoextraction and Au bioleaching. Although it has been reported that *M. sativa* L. accumulates high amounts of Au (III) in its biomass independently of pH (Gardea-Torresdey et al. 2002), in this study, no accumulation of this element was found, even though bioleached traces were found in the treatments of *M. sativa* L. + computer PCB + *P. tolaasii*, while for Cu, there were no statistical differences between the treatments of *M. sativa* L. + PCB with and without *P. tolaasii* inoculation. The result found for Cu contrasts with that reported by Chen et al. (2018) since they report that the inoculation of *Sinorhizobium meliloti* (rhizobia) significantly increased the amount of Cu in the inoculated plants compared to the non-inoculated plants and report that the amount of Cu was higher in the roots than in the shoots, while the co-inoculation of *Paenibacillus mucilaginosus* (PGPR) and *Sinorhizobium meliloti* (rhizobia) in *M. sativa* L. decreased the accumulation of Cu (48.6%) in the shoots compared to the treatments without inoculation (Ju et al. 2020). In the case of *R. tropici* inoculation to *L. culinaris* plants exposed to cell phone PCB, a significant effect was found for Cu phytoextraction, since the content of this metal in plant biomass doubled. This information coincides with what is reported for the rhizobia-legume association, since rhizobia increase the tolerance and accumulation of metals in plants (Akhtar et al. 2018; Fagorzi et al. 2018).

## 18.4 Conclusions

In this study, it was found that the plant–bacteria relationship is affected by the presence of PCB from computers and cell phones, in terms of biomass production (aerial part and root) of legumes, while the relationship between *L. culinaris* and *R. tropici* could be important for the phytoextraction of Cu since the plant accumulated a greater amount of Cu from cell phone PCB than in the treatments without bacterial inoculation. Con lo cual se infiere que la interacción planta-bacteria puede ser relevante para la recuperación de algunos metales a partir de PCB, ya que se encontró que dicha interacción tiene preferencia por algunos metales. However, more research is needed to find the relationships between plants and bacteria that can selectively recover metals of commercial importance from PCB in higher percentages.

## References

Abraham R (2015) Lentil (*Lens culinaris* medikus) current status and future prospect of production in Ethiopia. Adv Plants Agric Res 2:1–9. https://doi.org/10.15406/apar.2015.02.00040

Agler MT, Ruhe J, Kroll S et al (2016) Microbial hub taxa link host and abiotic factors to plant microbiome variation. PLoS Biol 14:e1002352. https://doi.org/10.1371/journal.pbio.1002352

Akhtar N, Hussain A, Riaz A et al (2018) Biremediation of heavy metal stress by Rhizobium chickpea symbiosis. J Agric Res 56:27–34

Alshehri ANZ (2018) Microbial recovery of gold metal from untreated and pretreated electronic wastes by wild and mutated cyanogenic *Bacillus megaterium*. Am J Microbiol Res 6:14–21. https://doi.org/10.12691/ajmr-6-1-3

Argumedo-Delira R, Díaz-Martínez ME, Gómez-Martínez MJ (2020) Microorganisms and plants in the recovery of metals from the printed circuit boards of computers and cell phones: a mini review. Metals 10(9):1120. https://doi.org/10.3390/met10091120

Ashraf MA, Hussain I, Rasheed R et al (2017) Advances in microbe-assisted reclamation of heavy metal contaminated soils over the last decade: a review. J Environ Manag 198:132–143. https://doi.org/10.1016/j.jenvman.2017.04.060

Aydinalp C, Marinova S (2009) The effects of heavy metals on seed germination and plant growth on alfalfa plant (*Medicago sativa*). Bulg J Agric Sci 15:347–350

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59:319–326. https://doi.org/10.1016/S0304-386X(00)00188-2

Chakraborty SC, Qamruzzaman M, Zaman MWU et al (2022a) Metals in e-waste: occurrence, fate, impacts and remediation technologies. Process Saf Environ Prot 162:230–252. https://doi.org/10.1016/j.psep.2022.04.011

Chakraborty SC, Zaman MWU, Hoque M et al (2022b) Metals extraction processes from electronic waste: constraints and opportunities. Environ Sci Pollut Res 29:32651–32669. https://doi.org/10.1007/s11356-022-19322-8

Chen J, Liu YQ, Yan XW et al (2018) Rhizobium inoculation enhances copper tolerance by affecting copper uptake and regulating the ascorbate-glutathione cycle and phytochelatin biosynthesis-related gene expression in *Medicago sativa* seedlings. Ecotoxicol Environ Saf 162:312–323. https://doi.org/10.1016/j.ecoenv.2018.07.001

Chen L, Beiyuan J, Hue W et al (2022) Phytoremediation of potentially toxic elements (PTEs) contaminated soils using alfalfa (*Medicago sativa* L.): a comprehensive review. Chemosphere 293:133577. https://doi.org/10.1016/j.chemosphere.2022.133577

Cui J, Zhang L (2008) Metallurgical recovery of metals from electronic waste: a review. J Hazard Mater 158:228–256. https://doi.org/10.1016/j.jhazmat.2008.02.001

Díaz-Martínez ME, Argumedo-Delira R, Sánchez-Viveros G et al (2018) Lead phytoextraction from printed circuit computer boards by *Lolium perenne* L. and *Medicago sativa* L. Int J Phytoremediat 20:432–439. https://doi.org/10.1080/15226514.2017.1365339

Díaz-Martínez ME, Argumedo-Delira R, Sánchez-Viveros G et al (2019) Microbial bioleaching of Ag, Au and Cu from printed circuit boards of mobile phone. Curr Microbiol 76:536–544. https://doi.org/10.1007/s00284-019-01646-3

Duan H, Zhu X-N (2022) Recent advances in recovering technology for recycling gold from waste printed circuit boards: a review. Energy Sources A Recovery Util Environ Eff 44:1640–1659. https://doi.org/10.1080/15567036.2022.2056271

Fagorzi C, Checcucci A, DiCenzo GC et al (2018) Harnessing rhizobia to improve heavy-metal phytoremediation by legumes. Genes 9:542. https://doi.org/10.3390/genes9110542

Faraji F, Golmohammadzadeh R, Pickles CA (2022) Potential and current practices of recycling waste printed circuit boards: a review of the recent progress in pyrometallurgy. J Environ Manage 316:115242. https://doi.org/10.1016/j.jenvman.2022.115242

Fernandes Andrade D, Castro JP, Garcia JA et al (2022) Analytical and reclamation technologies for identification and recycling of precious materials from waste computer and mobile phones. Chemosphere 286:131739. https://doi.org/10.1016/j.chemosphere.2021.131739

Franco-Franklin V, Moreno-Riascos S, Ghneim-Herrera T (2021) Are endophytic bacteria an option for increasing heavy metal tolerance of plants? A meta-analysis of the effect size. Front Environ Sci 8:603668. https://doi.org/10.3389/fenvs.2020.603668

Gardea-Torresdey JL, Tiemann KJ, Parsons JG et al (2002) Characterization of trace level Au (III) binding to alfalfa biomass (*Medicago sativa*) by GFAA. Adv Environ Res 6:313–323. https://doi.org/10.1016/S1093-0191(01)00064-8

Glick BR (2020) Introduction to plant growth-promoting bacteria. In: Beneficial plant-bacterial interactions. Springer, Cham, pp 1–37. https://doi.org/10.1007/978-3-030-44368-9_1

Hageman RH (1984) Ammonium versus nitrate nutrition of higher plants. In: Hauck RD (ed) Nitrogen in crop production, Wiley, pp 67–84. https://doi.org/10.2134/1990.nitrogenincropproduction.c4

Huesgen T (2022) Printed circuit board embedded power semiconductors: a technology review. PEDC (in press). https://doi.org/10.1016/j.pedc.2022.100017

Ilyas S, Srivastava RR, Kim H et al (2022) Biotechnological recycling of hazardous waste PCBs using *Sulfobacillus thermosulfidooxidans* through pretreatment of toxicant metals: process optimization and kinetic studies. Chemosphere 286:131978. https://doi.org/10.1016/j.chemosphere.2021.131978

Iqbal MZ, Nayab S, Shafiq M et al (2018) Effects of copper on seed germination and seedling growth performance of *Lens culinaris* medik. J Plant Dev Sci 25:85. https://doi.org/10.33628/jpd.2018.25.1.85

Islam A, Ahmed T, Awual MdR et al (2020) Advances in sustainable approaches to recover metals from e-waste—a review. J Clean Prod 244:118815. https://doi.org/10.1016/j.jclepro.2019.118815

Ju W, Jin X, Liu L et al (2020) Rhizobacteria inoculation benefits nutrient availability for phytostabilization in copper contaminated soil: drivers from bacterial community structures in rhizosphere. Appl Soil Ecol Appl 150:103450. https://doi.org/10.1016/j.apsoil.2019.103450

Kaya M (2019). Printed circuit boards (PCBs). In: Electronic waste and printed circuit board recycling technologies. The minerals, metals & materials series. Springer, Cham. https://doi.org/10.1007/978-3-030-26593-9_2

Kidd PS, Alvarez-Lopez V, Becerra-Castro C et al (2017) Potential role of plant-associated bacteria in plant metal uptake and implications in phytotechnologies. Adv Bot Res 83:87–126. https://doi.org/10.1016/bs.abr.2016.12.004

Kong Z, Glick BR (2017) The role of plant growth-promoting bacteria in metal phytoremediation. Adv Microb Physiol 71:97–132. https://doi.org/10.1016/bs.ampbs.2017.04.001

Krishnan S, Zulkapli NS, Kamyab H et al (2021) Current technologies for recovery of metals from industrial wastes: an overview. Environ Technol Innov 22:101525. https://doi.org/10.1016/j.eti.2021.101525

Kumari R, Samadder SR (2022) A critical review of the pre-processing and metals recovery methods from e-wastes. J Environ Manage 320:115887. https://doi.org/10.1016/j.jenvman.2022.115887

McCauley A, Jones C, Jacobsen J (2009) Soil pH and organic matter. In: Nutrient management modules, vol 8, #4449-8. Montana State University Extension Service, Bozeman, Montana

Merli G, Becci A, Amato A (2022) Recovery of precious metals from printed circuit boards by cyanogenic bacteria: optimization of cyanide production by statistical analysis. J Environ Chem Eng 10:107495. https://doi.org/10.1016/j.jece.2022.107495

Natarajan G, Ting Y-P (2014) Pretreatment of e-waste and mutation of alkali-tolerant cyanogenic bacteria promote gold biorecovery. Bioresour Technol 152:80–85. https://doi.org/10.1016/j.biortech.2013.10.108

Orlikowska T, Nowak K, Reed B (2017) Bacteria in the plant tissue culture environment. Plant Cell Tiss Organ Cult 128:487–508. https://doi.org/10.1007/s11240-016-1144-9

Partida-Martínez LP, Heil M (2011) The microbe-free plant: fact or artifact? Front Plant Sci 2:100. https://doi.org/10.3389/fpls.2011.00100

Pirsaheb M, Zadsar S, Hossini H et al (2022) Bioleaching of carbide waste using spent culture of *Acidithiobacillus* bacteria: effective factor evaluation and ecological risk assessment. Environ Technol Innov 28:10280. https://doi.org/10.1016/j.eti.2022.102801

Priya A, Hait S (2017) Comparative assessment of metallurgical recovery of metals from electronic waste with special emphasis on bioleaching. Environ Sci Pollut Res 24:6989–7008. https://doi.org/10.1007/s11356-016-8313-6

Rahman MM, Jakaria SM et al (2012) Phytormediation of copper toxicity in soil by various corn and vegetables of Bangladesh. AJASE 1:14–22

Rajesh R, Kanakadhurga D, Prabaharan N (2022) Electronic waste: a critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environ Challenges 7:100507. https://doi.org/10.1016/j.envc.2022.100507

Raklami A, Oubane M, Meddich A et al (2021) Phytotoxicity and genotoxicity as a new approach to assess heavy metals effect on *Medicago sativa* L.: role of metallo-resistant rhizobacteria. Environ Technol Innov 24:101833. https://doi.org/10.1016/j.eti.2021.101833

Sękara A, Poniedziałek M, Ciura J et al (2005) Zinc and copper accumulation and distribution in the tissues of nine crops: implications for phytoremediation. Pol J Environ Stud 14:829–835

Silva J, Días R, Cardoso V et al (2022) Biolixiviation of metals of computers printed circuit boards by *Acidithiobacillus ferrooxidans* and metals bioremoval by mixed culture subjected to a magnetic field. Res Sq 1–25. https://doi.org/10.21203/rs.3.rs-1734157/v1

Stambulska UY, Bayliak MM (2020) Legume-rhizobium symbiosis: Secondary metabolites, free radical processes, and effects of heavy metals. In: Mérillon JM, Ramawat K (eds) Co-evolution of secondary metabolites. Reference series in phytochemistry. Springer, Cham. https://doi.org/10.1007/978-3-319-96397-6_43

Stambulska UY, Bayliak MM, Lushchak VI (2018) Chromium (VI) toxicity in legume plants: modulation effects of rhizobial symbiosis. Bio Med Res Int 2018:1–13. https://doi.org/10.1155/2018/8031213

Tabasi S, Hassani H, Azadmehr R (2017) Phytoextraction-based process of metal absorption from soil in mining areas (tailing dams) by *Medicago sativa* L. (Alfalfa) (case study: Sarcheshmeh porphyry copper mine, SE of Iran). J Min Environ 8(3):419–431. https://doi.org/10.22044/jme.2017.897

Trivedi P, Leach JE, Tringe SG et al (2020) Plant–microbiome interactions: from community assembly to plant health. Nat Rev Microbiol 18:607–621. https://doi.org/10.1038/s41579-020-0412-1

Ullah A, Heng S, Munis MF et al (2015) Phytoremediation of heavy metals assisted by plant growth promoting (PGP) bacteria: a review. Environ Exp Bot 117:28–40. https://doi.org/10.1016/j.envexpbot.2015.05.001

Vishwakarma S, Kumar V, Arya S et al (2022) E-waste in information and communication technology sector: existing scenario, management schemes and initiatives. Environ Technol Innov 27:02797. https://doi.org/10.1016/j.eti.2022.102797

Yaashikaa PR, Priyanka B, Kumar SP et al (2022) A review on recent advancements in recovery of valuable and toxic metals from e-waste using bioleaching approach. Chemosphere 287:132230. https://doi.org/10.1016/j.chemosphere.2021.132230

Yamane LH, de Moraes VT, Espinosa DCR et al (2011) Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers. Waste Manage 31:2553–2558. https://doi.org/10.1016/j.wasman.2011.07.006

# Chapter 19
# E-waste Management: Prospects and Strategies

**Ashish Chalana, Kalpana Singh, Shashank Sharma, Vikas Bhardwaj, and Rakesh Kumar Rai**

**Abstract** For the past few years, the e-waste problem has taken over on a larger scale, so we are now forced to rethink how to tackle this e-waste problem. So, people start thinking about the e-waste management concept and trying to develop new methods by which we can reduce e-waste. The present chapter highlights the scenario of e-waste in India and other parts of the globe. It also exhibits the trends of e-waste in India through a comparison with other countries. The study reveals that electronic equipment such as computers, mobile, and telephones are identified as the principal e-waste generators in India. A report suggests that computers contributed to 70% of the total e-waste generated in India, while telecommunication equipment accounted for 12%. Among cities, Mumbai is one of the biggest hubs and ranked number one on the list as it generates an estimated 120,000 tons of e-waste annually. Approximately 70% of heavy metals found in landfills are accounted for by e-waste. In light of this, this chapter also offers suggestions to deal with the challenges, conventional e-waste management methods, eco-friendly e-waste management methods, and problems of e-waste.

**Keywords** Conventional e-waste method · Eco-friendly e-waste management · Recycles

A. Chalana (✉) · S. Sharma (✉)
Department of Chemistry and Biochemistry, Sharda School of Basic Science and Research, Sharda University, Greater Noida, Uttar Pradesh, India
e-mail: ashish.chalana@sharda.ac.in

S. Sharma
e-mail: shashank.enviro@gmail.com

K. Singh
Lloyd Institute of Management and Technology, Greater Noida, Uttar Pradesh, India

V. Bhardwaj
Department of Applied Sciences, JMIT Radaur, Yamunanagar, Haryana, India

R. K. Rai
Department of Chemistry, Indian Institute of Technology Tirupati (IIT Tirupati), Tirupati, Andhra Pradesh 517506, India

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_19

## 19.1 Introduction

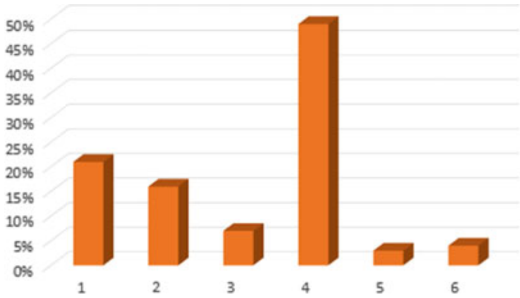
According to the Basel agreement, “wastes” are defined as substances or things that are disposed of or are intended to be disposed of in accordance with national regulations. E-waste is one of the many different sorts of trash that exists. The phrase “electronic garbage,” or simply “e-waste,” refers to a variety of electric and electronic devices that are no longer useful to their owners. New technologies are rapidly superseding millions of analog appliances, leading to their disposal in prescribe landfills despite potentially adverse impacts on the environment. The management of municipal solid waste (MSW), particularly electronic trash, or e-waste, is one of the most significant issues pertaining to human activities. It has tremendous impact on the environment (Cervantes et al. 2018). Traditional and environmental-friendly e-waste management is complex (Cervantes et al. 2018). In reality, it involves each individual as well as several waste management organizations and businesses firms (Achillas et al. 2013; Juul et al. 2013; Soltani et al. 2015). As a result, the reduction of the social and environmental effects of waste-related consequences depends on a number of factors. Local governments are often in charge of waste management, but they often have few resources, particularly in areas where there are not many wealthy residents (Chu et al. 2019). The capacity of the authorities for waste management planning, contracting, operational monitoring, and other related tasks is negatively impacted by this. Additionally, a majority of municipalities have inter-municipal government collaboration in existence. This has an adverse effect on the government’s capacity for e-waste management planning, contracting, operational monitoring, and other related tasks. Additionally, only a small number of cities have inter-municipal government cooperation in place; as a result, its influence on waste collection and sorting is generally limited. Instead, shared resources are typically used for e-waste sorting, recycling, e-waste transfer, disposal, and city cleaning (Kaza et al. 2018). Therefore, municipal waste management presents a scattered picture at several geographic scales, both globally and locally. Latest findings indicate that the European Union’s 27 member states’ performance in the management of e-waste or e-garbage has rapidly converged since the Waste Framework Directive of 2008 was enacted into national law; nonetheless, as far as convergence is concerned, the objective of this work is to contribute to the analysis of municipal waste management with an emphasis on quantitative aspects of solid waste selection and subsequent delivery to waste treatment facilities. We are particularly curious to know if detailed information on waste sorting and treatment might assist identify relatively homogeneous groupings of municipalities based on characteristics of regional waste management methods.

### 19.1.1 Global E-waste Problem

E-waste is the most rapidly expanded municipal waste across the globe, and more than 50 MT of e-waste is produced globally every year. Developing countries will experience rapid industrial and economic growth along with the enormous amount of e-waste generation that will be cause for serious concern (Castigliego et al. 2021), due to their growing population and the anticipated increase in sales of electronic products in these nations. According to the UN Environment Program (UNEP), if e-waste recycling was left to the informal sector, countries like China, India, Brazil, Mexico, and others would see increasing environmental damage and health issues. The two countries with the highest percentages of e-waste production throughout this decade are the EU (30%) and the USA (28%). According to the Inventory Assessment Manual, the overall amount of e-waste produced in the EU is projected to be between 14 and 15 kg per person or between 5 and 7 MT annually, whereas India and China contribute less than 1 kg. E-waste makes up 6 million tons of solid garbage annually in Europe. In the EU, the generation of e-waste is anticipated to increase by 3–5% year. The combination of a consumer-focused business strategy, rapid product obsolescence, and technological e-waste can be categorized according to its physical and chemical components. Table 19.1 lists the classification of its qualities in the references. The variations in the physical and chemical composition may result from data collected over a longer period of time. As technology advances, the composition of e-chemical waste may change. A study done to evaluate the chemical makeup of dynamic RAM (DRAM) between 1991 and 2008 predicted that from 2008 to 2020, DRAM would have a steady level of gold and silver, a drop in palladium concentration of 80%, and an increase in copper content of 75%. The physical composition of the world's e-waste will vary due to changes in technology and modular design, although precious metals will increase as a result of the decline in DRAM modules. ICT metals might be steady (Charles et al. 2017). Although technology may cause changes in the physical composition of the world's e-waste, its overall chemical composition is projected to remain steady. In Europe, EU Directives have established waste policies and aimed to address waste challenges throughout the past 20 years. Due to these rules, municipal waste management in Europe has moved up the waste hierarchy. The Waste Framework Directive 2008/98/EC, which places an emphasis on trash avoidance, planning for reuse, recycling, and other forms of recovery, leaves disposal as the least desirable alternative. In recent decades, waste management in the EU has greatly improved (Bourguignon 2018). In the USA, for governments and the corporate sector, top priorities are to limit the impact of municipal solid waste (MSW) on social and ecological systems. In order to limit the quantity of garbage that is burned or dumped, several communities are implementing zero-waste (ZW) initiatives, which encourage responsible material creation, consumption, reuse, and recovery (Phillips et al. 2011) (Fig. 19.1). As a result of worries about the carbon footprint of waste treatment options like landfilling or combustion, officials have pushed for increased measures to divert from green (Castigliego et al. 2021). E-waste management is particularly crucial to cities, which stand to gain from the shift away from trash as being resourceful and wasteful is a burden (Zaman et al. 2020). Understanding past trash generation patterns and potential trends can be helpful. Such strategies are developed by policymakers in a thorough manner (Ayeleru et al. 2018). Forecasts can be used to later evaluate the probable effects of ZW acts. Such efforts to encourage e-waste avoidance often involve system boundaries, which are often required for this strategy in terms of both process and time (Bakas et al. 2017; Castigliego et al. 2019) (Fig. 19.2).

**Table 19.1** Composition of e-waste

| Constituents | Vats and Singh (2014) | Realff et al. (2004) | Kong et al. (2012) | Hossain et al. (2015) |
|---|---|---|---|---|
| Metal (%) | 60.20 | 49 | 13 | 39.50 |
| Copper (%) | – | – | 7 | 20.10 |
| Iron (%) | – | – | – | 8.10 |
| Tin (%) | – | – | – | 4 |
| Nickel (%) | – | – | – | 2 |
| Lead (%) | – | – | – | 2 |
| Aluminum (%) | – | – | – | 2 |
| Zinc (%) | – | | – | 1 |
| Silver (%) | – | – | – | 0.20 |
| Gold (%) | – | – | – | 0.10 |
| Palladium (%) | – | – | – | 0.01 |
| Plastics (%) | 15.20 | 33 | 21 | 30.30 |
| Metal-plastic mixture (%) | 5 | | – | – |
| Cables (%) | 2 | | – | – |
| Screens (CRT and LCD) (%) | 11.90 | 12 | – | – |
| PCB (%) | 1.70 | – | – | – |
| Other (%) | 1.40 | 1 | – | – |
| Pollutants (%) | 2.70 | – | – | – |
| Wood (%) | – | 5 | – | |
| Refractory oxides (%) | – | – | – | 30.20 |




| | |
|---|---|
| 1 | Consumer electronics |
| 2 | Small house hold appliances |
| 3 | IT and telecommunication |
| 4 | Large household appliances |
| 5 | Lighting equipment's |
| 6 | Electronic and electrical tools |

**Fig. 19.1** Classification of waste electronic managements

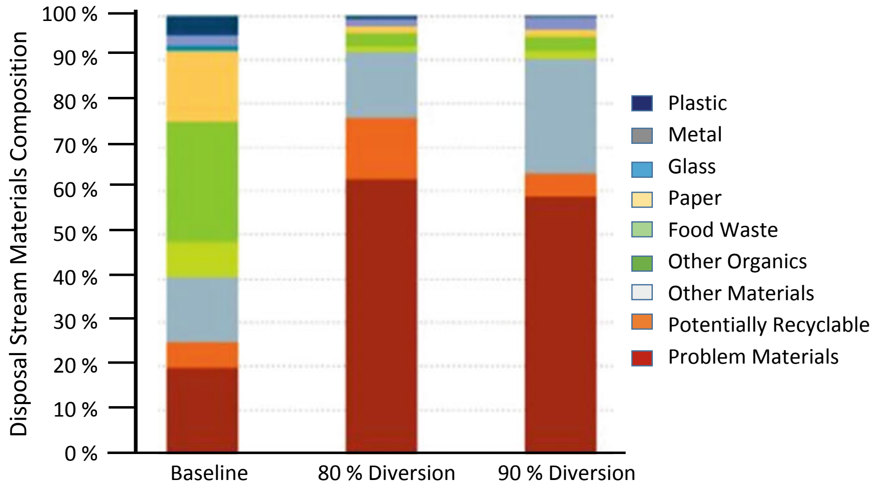



**Fig. 19.2** The bar diagram shows the disposal of various waste materials by Boston's Disposal stream management

## *19.1.2 E-waste Problem in India*

Environmental factors and human health are closely related to each other, so e-waste contamination in food chains and direct exposure in recycling regions can both have a negative influence on health. Table 19.2 lists the majority of studies related to health and the environment. The percentage of various Constituents of E-waste mentioned by Vats and Singh (2014) and Hossain et al. (2015) are metals 60.20%, 49%,13%, Copper at 7% of 39.50% 10.10% Iron, 8.10% Tin, 4% Nickel, 2% Lead, 2% Aluminum, 1% Zinc, 0.20% Silver, 0.10% Gold, and 0.01% Palladium, Plastics 15.20%, 33%, 21%, 30.3% Metal-plastic hybrid 5%, Cables 10%, Screens (CRT and LCD) 11.90% 12% PCB 1.70% Others 1.40% 1% Pollutants Refractory oxides: 5% Wood, 2.80% 30.20% respectively which is being released in the environment. According to recent UN estimates, e-waste from outdated computers would increase by 400% in China and by 500% in India compared to 2007 levels by 2020. Additionally, by 2020, India's and China's levels of electronic waste from abandoned mobile phones would both be around seven and 18 times larger than they were in 2007 (Fig. 19.3). Such forecasts underline the urgent need to solve the e-waste issue in developing nations like India where the recycling process is still not fully managed. A report from the Electronics' Sector Association of India estimated (ELCINA 2009) with an astounding overall e-waste output in India. It is being reported that there was 4.34 lakh tons of e-waste was being generated by the end of 2009 (Wang and Wang 2019). CPCB calculated that the e-waste generated will be more than 0.8 MT by 2012 (Ganguly 2016). Approximately eight states provide 70% of the total amount of e-waste produced in the nation, whereas around more than 60% of India's total e-waste is produced in 65 cities. A thorough study conducted in 2005 (Jog 2008) documented the breakdown of WEEE generation in India by state. Figure 19.3 displays India's regional breakdown of e-waste production. Maharashtra is the top-ranking state among the top ten producers of e-waste, followed by Tamil Nadu, Andhra Pradesh, Uttar Pradesh, West Bengal, Delhi, Karnataka, Gujarat, Madhya Pradesh, and Punjab. The percentage of e-waste creation in different states is depicted in Fig. 19.3. Mumbai is first among the top ten cities that produce the most e-waste, followed by Delhi, Bengaluru, Chennai, Kolkata, Ahmedabad, Hyderabad, Pune, Surat, and Nagpur. Research is carried out by Greenpeace International Considering Environmental Issues (Ganguly 2016) (contamination from e-waste CRT storage to recycle from the Brijgang and Kantinagar regions in India's New Delhi). The investigation revealed abnormally high hazardous metal concentrations in soil samples collected from various storage locations, including Ni (0.4%), Pb (1.5%), and dust containing Zn (2.1%), Ba (0.3%), and Cd (310 mg/kg), as shown in Table 19.2. Lead values were 1580 mg/kg in the soil samples.

**Table 19.2** Sample analysis of e-waste showing speciation of different heavy metals

| Metals | Powder in CRT (mg/kg) | Soil (mg/kg) | Dust (mg/kg) | Dust/soil (mg/kg) |
|---|---|---|---|---|
| Ag | 52 | Less than 2 | 10 | 155 |
| Ba | 3850 | 277 | 2610 | 193 |
| Cd | 16,800 | 54.5 | 310 | 16.4 |
| Cr | 11 | 20 | 86 | 21 |
| Cu | 74 | 61 | 439 | 82 |
| Pb | 494 | 1580 | 14,600 | 1370 |
| Ni | 121 | 47 | 3900 | 157 |
| Zn | 273,000 | 964 | 21,100 | 506 |
| Yt | Less than one | 171 | 10,500 | 67 |

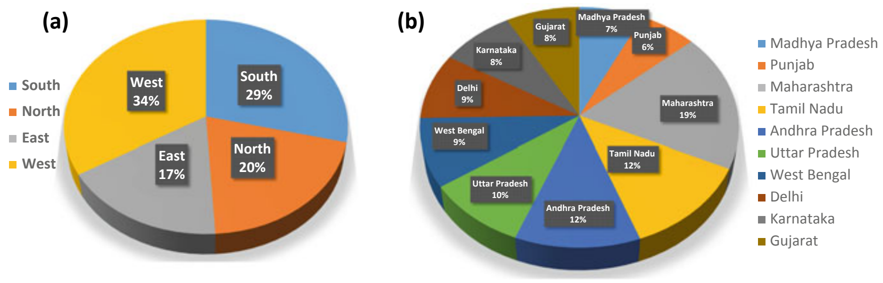



**Fig. 19.3** E-waste generation in India. **a** Region-wise generation of e-waste **b** generation of e-waste in top ten states in India

## 19.2 Industrial Waste Treatment Techniques, Methods, Impact on the Environment, and Health Problem

### *19.2.1 Organic Chemicals Industries*

Depending on the product they produce, such as plastics, bulk organic compounds, insecticides, resins, or synthetic fabrics, organic chemicals release a variety of pollutants. Organic compounds that can be discharged include solvents like toluene, vinyl chloride, chloroform, benzene, phenols, xylene, and naphthalene. The impacts of biodegradable wastewater treatment systems can be assessed using biochemical oxygen demand (BOD), which is the overall measurement of various organic contaminants. BOD can also be utilized as regulatory criteria in various discharge permits. The metal contaminants are lead, zinc, copper, chromium, and nickel (Sajid et al. 2019; Mustansar 2022).

### *19.2.2 Battery Manufacturing*

Batteries are made by companies that also produce large-scale units for trucks, cars, and other motor vehicles, as well as portable equipment (such as power equipment) and small electronics' products. Pollutants produced in battery manufacturing facilities include lead, zinc, iron, cadmium, copper, cobalt, chromium, nickel, mercury, manganese, grease and oil, and cyanide (reuse) (Sloop et al. 2020; Melchor-Martínez et al. 2021).

### 19.2.3 Electric Power Plants

The majority of industrial wastewater is produced by fossil fuel power plants, especially coal-fired ones. Electric power plant wastewater frequently contains metals like mercury, chromium, cadmium, and lead as well as selenium, nitrogen compounds (nitrates and nitrites), and arsenic (Islam et al. 2020; Jiang et al. 2019).

The wastewater flow includes fly ash, bottom ash, flue-gas mercury control, and flue-gas disinfection. The wastewater treatment facility typically receives the pollutants that are captured by air pollution control facilities, such as wet scrubbers. Treatment technologies are needed for ash ponds, several types of surface implantation, and coal-fired facilities (Sun et al. 2022; Masoomi et al. 2020). In these ash ponds, wastewater is separated from big particles using gravity. Technology does not handle dissolved pollutants. Additional pollution reduction tools may be utilized at the power plant depending on the trash it produces. These are chemical rainfall, dry ash management, active sludge processing, closed-loop ash reuse, evaporation–crystallization processes, and biofuel treatment. The treatment of flu-gas desulfurization wastewater has become extremely efficient thanks to ion exchange (IE) technology in electrodialysis and membrane systems, enabling certain permitted authorities, like the US Environmental Protection Agency, to set emission limits. Similar treatment methods are used for other high-quality industrial effluents (Lv et al. 2022; Gurreri et al. 2020).

## 19.3 Constituents of E-waste

Some computer parts are recycled for use in the production of new computer goods, while others are just metals that are recycled for use in a variety of industries like construction, jewelry, and household cutlery. Carbon, aluminum, iron, beryllium, silicon, plastics, thermosetting, copper, tin, lead, polyvinyl chlorides (PVCs), epoxy resin, PCBs, and fiberglass make up the majority of the substances (Mmereki et al. 2016). The following elements are found in small amounts in e-waste: tantalum, silver, yttrium, vanadium, titanium, thorium, terbium, selenium, ruthenium, palladium, rhodium, platinum, niobium, nickel, germanium, gallium, manganese, lithium, indium, gold, europium, cobalt, boron, antimony, americium, bismuth. Almost all electronics require copper (in the form of wire and printed circuit board tracks) and tin and lead (in the form of solder); however, lead-free solder is gaining popularity (Grant et al. 2013).

## 19.4 The Impact of E-waste on the Environment

Many ecosystems in underdeveloped countries have been impacted by the dumping of electronic waste. The body, groundwater, air, soil, marine, and terrestrial creatures, both wild and domestic, as well as the food and drinking water consumed by people and animals, are all depleted of atmospheric and liquid water (Caravanos et al. 2013). According to studies carried out in Guiyu, China, the levels of carcinogen in the rice paddy and duck ponds were higher than the cadmium, nickel, lead, and copper for agriculture international guidelines. Heavy metals have been reported to be present in road dust (more than 100 times copper and 300 times more than in the control village's road dust), and air dioxin has also been observed (a type of pre-measured 100 times the level). Further research revealed that the soil at Ghana's Agglucos e-waste dump contained 18,125 ppm lead (Takyi et al. 2020).

Sports areas and non-sports areas must adhere to the US EPA criteria for lead levels in soil, which are 400 ppm and 1200 ppm, respectively. At the Ghana Agglocy e-waste dump, scrap workers burn electronic parts and car horn wire to reclaim copper, polluting the environment with lead, furan, and dioxin (Rene et al. 2021) (Table 19.3).

## 19.5 Recycling of E-waste

Recycling is crucial for managing e-waste. If effectively implemented, it should greatly minimize the amount of dangerous compounds in the environment and the energy required from natural resources. However, the local government must assist it and promote community awareness and education. Reusing circuit boards that were printed from electrical trash is the most challenging task. The traditional ways of using common metals like iron, aluminum, copper, etc., involve mechanical separations and shredding but are less effective because the printed circuit boards are enclosed with precious metals like silver, platinum, tin, gold, etc. Melting circuit boards and using open-pit acid leaching to remove copper wires from burnt cable sheets and precious metals are further methods of processing electronic trash (Ganesan et al. 1964). Electronics that are properly reused or disposed of assist prevent health issues, greenhouse gas emissions, and unemployment. For the purpose of recycling printed circuit boards, another technique, such as cryogenic dissociation, has been investigated. The downcycling process is replaced by the regeneration and recycling of more environmentally and socially responsible alternatives. Because they contain mercury, cadmium, and lead, many sizes of coin cells and buttons with a 2–9 v battery are reused in a few nations.

**Table 19.3** E-harmful waste's effects on the environment and on human health

| Component of e-waste | Electric appliances that contain them | Negative effects on health |
|---|---|---|
| Sulfur | A component in lead–acid batteries | Sulfuric acid is created when sulfur, air, and water are combined. The primary reason for acid rain is this. Deforestation brought on by acid rain also impacts aquatic life. It has an impact on lung and respiratory system health. Asthma and chronic bronchitis are also caused by it |
| Polyvinyl chloride (PVC) | PVC is frequently used in electrical wiring insulation as well as in electronic device handles, light fixtures, switches, and other components | PVC harms the immune system, disrupts hormones, and increases the risk of cancer. One of the plastics that harms the environment the most is PVC |
| Perfluorooctanoic acid (PFOA) | Discovered in kitchenware, such as PTFE-coated non-stick cookware | It may result in testicular and kidney cancer |
| Mercury | Old computers, paint, thermostat switches, tilt switches, fluorescent tubes, and other mechanical devices all contain it | The hazardous methylmercury that results from mercury emission penetrates the food chain. The substance will get into the bloodstream and may harm the brain |
| Lead | Found in batteries, solders, photovoltaics, and metal alloys | Lead exposure can harm the kidneys and raise blood pressure in adults. Low birth weight, early birth, and miscarriage are risks for pregnant women |
| Hexavalent chromium | Cr(VI) is a component of metal coatings that create corrosion-resistant metal | Both plants and animals can be poisoned by hexavalent chromium in various ways. It is both corrosive and carcinogenic, functioning as a potent oxidizing agent |
| Cadmium | Used as a corrosion resistance coating and semiconductor device | Cadmium inhalation can result in cancer, lung damage, fever, and muscle ache |

(continued)

**Table 19.3** (continued)

| Component of e-waste | Electric appliances that contain them | Negative effects on health |
|---|---|---|
| Brominated flame retardants (BFRs) | Most electronics' polymers use them as flame retardants, comprised PBBs, PBDE, octa-, deca-, and penta-BDE | Thyroid issues, liver issues, and delayed nervous system development are all negative health effects. The effects on humans, animals, and the environment are comparable |
| Beryllium oxide | Used to insulate heat | Skin ulcers, nasal irritation, and skin burning |
| Americium | Radioactive materials | Americium is a substance that causes cancer |
| Brominated flame retardants (BFRs) | Most electronics' polymers use them as flame retardants, comprised PBBs, PBDE, octa-, deca-, and penta-BDE | Thyroid issues, liver issues, and delayed nervous system development are all negative health effects. The effects on humans, animals, and the environment are comparable |

## 19.6 Handling and Management of E-waste

A few industrialized nations use automatic shredding machinery after manually disassembling the items into their component parts (metal frames, circuit boards, plastics, and power supply). One of the advantages of the method is the ability of humans to recognize and save working and repairable elements, such as cables, chips, RAM, transistors, and other components (Vermeşan et al. 2020). The drawback is that countries with the lowest standards of health and safety offer workers at lower rates. The materials for shredding are transported by a hopper into a simple mechanical separator, where the metal fractions and component plastic are separated using screening and granulating machinery and sold to smelters or plastic recyclers. These recycling machines have a dust collection system and are entirely enclosed. Glass, non-ferrous and ferrous metals, and plastic are separated using eddy currents, Trommel screens, and magnets before being transferred to a smelter for further separation. Scrubbers and screens are used to catch some pollutants. CRT glass is repurposed into lead ammunition, car batteries, wheel weights, and wheel weights, or it is given to foundries to use as a fluxing agent when processing raw lead ore. Palladium, gold, tin, silver, and copper are among the precious metals that are sold to smelters for recycling. Harmful smoke and gases are captured, contained, and treated in order to lessen the risk to the environment and its effects. These methods allow for the secure reclamation of all significant computer building materials. The used e-waste management procedure is described in Table 19.4, along with how it affects the environment.

**Table 19.4** Environmental effects of processing different types of e-waste

| Component of e-waste | Process used | Potential risk to the environment |
|---|---|---|
| Computer wires | Both burning and stripping | Environmentally harmful polycyclic aromatic hydrocarbons are emitted |
| Plastic from devices like radios, TVs, printers, displays, and keyboards | Melting and shredding | Dioxins, heavy metals, hydrocarbons, and other pollutants are released into the environment along with plastic |
| Chips and the additional gold-plated parts | Using acid to burr and strip | During the process, heavy metals, tin, lead, polycyclic aromatic hydrocarbons, and acid are emitted |
| Computer wires | Burning and stripping | Environmentally harmful polycyclic aromatic hydrocarbons are emitted |
| Printed circuit board | Acid bath, de-soldering, and burning | Glass dust is emitted into the environment together with lead, tin, cadmium, and mercury |
| Cathode ray tubes | Breaking and dumping | In this procedure, heavy metals like phosphor, barium, lead, and others are discharged into the environment |

### *19.6.1 Conventional Techniques*

Landfilling: It is one of the most often employed e-waste disposal techniques in India. On these flat surfaces, trenches are dug, and earth is removed from them. After that, waste is buried there and then covered with a substantial layer of dirt.

Incineration: The garbage is burned completely and under control at high temperatures (900–1000 °C) in incinerators that have been specifically developed for the purpose. For recycling, certain factories extract the iron from the slag. Some organic materials that are harmful to the environment are transformed into less dangerous molecules through incineration.

Recycling: Recycling is the process of disassembling, or removing, various components of electronic waste that contain hazardous materials like PCBs and mercury. It also involves separating plastics, removing CRTs, separating ferrous and non-ferrous metals, and recycling printed circuit boards, hard drives, floppy drives, compact disks, mobile phones, fax machines, printers, CPUs, memory chips, connecting wires, and cables.

### 19.6.2 Green Approach

**Approaches for bioremediation**: The term "bioremediation" refers to a broad notion that encompasses all procedures used to restore an environment that has previously been contaminated to its original state (Das and Dash 2014). Metals from electronic waste products can be mobilized via microbiological techniques. In the presence of electronic garbage, bacteria like *thiobacillus*, *thiooxidans*, and *T. ferrooxidans* as well as fungi like *Aspergillus niger* and *Penicillium simplicissimum* will grow (Gouma et al. 2014; Wang et al. 2014; Jin and Fallgren 2014; Mala et al. 2014). Metals were mobilized due to the production of inorganic and organic acids. Al, Ni, Pb, and Zn were all mobilized by both fungi to greater than 95% and Cu and Su by 65%, respectively. More than 90% of the Cu, Zn, Ni, and Al that were available could be leached by *thiobacillius*. Sn probably precipitated as SnO, whereas Pb precipitated as $PbSO_4$.

### 19.6.3 Phytoremediation for Electronic Waste

Phytoremediation could be a practical, cost-effective alternative to engineering-based methods. Phytoremediation, which uses plants to remediate soil, sediment, and water, has been used successfully on sites that have been contaminated with PCBs and other organic contaminants, a dangerous metal found in e-waste (Liu et al. 2014). Arbuscular mycorrhizal fungi (AMFs) significantly enhance the growth of PAH-degrading bacteria and increase peroxidase activities in soil in the context of multi-component bioremediation, which also include polycyclic aromatic hydrocarbon (PAH)-degrading bacteria like *Acinetobacter* sp., *Glomus mosseae*, and ryegrass *Lolium multiflorum* (Hutchinson et al. 2003; Nan Xiao et al. 2015). The dissipation of phenanthrene (PHE) and pyrene (PYR) from soil is greatly speed up when ryegrass interacts with AMF or PAH-degrading bacteria. AMF, plants, and PAH-degrading bacteria may work together to create a multi-component phytoremediation system for soil that has been contaminated with PAHs (Xiao et al. 2015; Chen et al 2009). Comparing the ability of four plant species (rice, alfalfa, ryegrass, and tall fescue) to clean up soil has been contaminated with PCBs in Taizhou, one of China's largest e-waste recycling facilities. After 120 days, rhizosphere soil showed higher PCBs' removal percentages of 25.6–28.5% compared to non-rhizosphere (10.4–16.9%) and unplanted controls (7.3%) such that it can be utilized to effectively neutralize dangerous components like PCBs.

## 19.7 Conclusion

Recent technological developments like the internet of things (IoT) and cloud computing have the potential to "dematerialize" the industries that manufacture electronic devices. A rise in cutting-edge product tracking and creative service and take-back business models may result in global value chains and the circular economy. Efficiency in electronic materials, e-waste recycling infrastructure, and scaling up the quantity and amount of recovered materials needed to meet the need of electronics' supply chains are all crucial. Millions of high-quality jobs might be created around the world if the right policy mix is put in place and the industry is managed properly. A fresh vision is necessary for the consumption and manufacture of electrical and technological items. Electronic waste is typically presented as a post-consumer concern; however, the problem is that it encompasses the entire lifecycle of the electronic gadgets that everyone uses. To reduce e-waste, it is vital for policymakers, consumers, raw material producers, miners, traders, investors, manufacturers, and designers to work together. Additionally, they increase the physical and financial usefulness of items and their capacity for recycling, reuse, and repair. They also maintain the value of the system.

The demand for new materials' sources and ongoing technological improvement drives the export of e-waste to emerging nations. Currently, this is creating millions of jobs worldwide (the GOOD), assisting in achieving some SDGs from the 2030 Agenda for Sustainable Development (SDGs), such eradicating poverty in poor nations. This "driver" facilitates complex human activities, both official and informal, yet poor e-waste management has a negative impact on the environment's "state change" (the BAD), which has a bad "impact" on human welfare as a result (the UGLY). In the absence of effective management practices, the BAD and the UGLY will overwhelm the GOOD, a trend that is at odds with the SDGs.

The report also shows that rich nations must shoulder the burden of transferring technology, sharing knowledge, and investing in cutting-edge facilities so that emerging nations can deal with the environmental problem. Furthermore, rather than only being applied as a theoretical notion, the circular economy application should be made for specific environmental issues. Environmental issues cannot be solved by exporting them.

## References

Achillas C, Moussiopoulos N, Karagiannidis A, Banias G, Perkoulidis G (2013) The use of multi-criteria decision analysis to tackle waste management problems: a literature review. Waste Manage Res 31(2):115–129

Ayeleru OO, Okonta FN, Ntuli F (2018) Municipal solid waste generation and characterization in the City of Johannesburg: a pathway for the implementation of zero waste. Waste Manage 79:87–97. https://doi.org/10.1016/j.wasman.2018.07.026

Bakas I, Laurent A, Clavreul J, Bernstad Saraiva A, Niero M, Gentil E, Hauschild MZ (2017) LCA of solid waste management systems

Bourguignon D (2018) Circular economy package: four legislative proposals on waste

Caravanos J, Clarke EE, Osei CS, Amoyaw-Osei Y (2013) Exploratory health assessment of chemical exposures at E-waste recycling and scrapyard facility in Ghana. J Health Pollut 3(4):11–22. https://doi.org/10.5696/2156-9614-3.4.11

Castigliego JR, Walsh MJ, Pollack A, Cleveland CJ (2019) Carbon free Boston: waste technical report. Boston University Institute for Sustainable Energy, Boston, MA, USA. Available at http://sites.bu.edu/cfb/technical-reports

Castigliego JR, Pollack A, Cleveland CJ, Walsh MJ (2021) Evaluating emissions reductions from zero waste strategies under dynamic conditions: a case study from Boston. Waste Manage 126:170–179

Cervantes DET, Martínez AL, Hernández MC, de Cortazar ALG (2018) Using indicators as a tool to evaluate municipal solid waste management: a critical review. Waste Manage 80:51–63

Charles RG, Douglas P, Hallin IL, Matthews I, Liversage G (2017) An investigation of trends in precious metal and copper content of RAM modules in WEEE: implications for long term recycling potential. Waste Manage 60:505–520

Chen D, Bi X, Zhao J, Chen L, Tan J, Mai B, Sheng G, Pu J, Wong M (2009) Pollution categorization and diurnal variation of PBDES in the atmosphere of e-waste dismantling region. Environ Pollut 157:1051–1057

Chu Z, Wang W, Zhou A, Huang W-C (2019) Charging for municipal solid waste disposal in Beijing. Waste Manage 94:85–94

Das S, Dash HR (2014) Microbial bioremediation: a potential tool for restoration of contaminated areas. In: Microbial biodegradation and bioremediation, pp 1–21

ELCINA (2009) Study on status and potential for E-waste management in India. February [online] from http://toxicslink.org/dn.php?section=1andid=37andatn=0 (Accessed January 2014)

Ganesan R, Ramesh B, Teja C (2021) Awareness of reuse reduce recycle & dispose of E-waste in Chennai. J Phys Conf Ser 7. https://doi.org/10.1088/1742-6596/1964/7/072006

Ganguly R (2016) E-waste management in India–an overview. Int J Earth Sci Eng 9(2):574–588

Gouma S, Fragoeiro S, Bastos AC, Magan N (2014) Bacterial and fungal bioremediation strategies, pp 301–323

Grant K, Goldizen FC, Sly PD, Brune M-N, Neira M, van den Berg M, Norman RE (2013) Health consequences of exposure to e-waste: a systematic review. Lancet Global Health 1(6):e350–e361. https://doi.org/10.1016/S2214-109X(13)70101-3

Gurreri L, Tamburini A, Cipollina A, Micale G (2020) Electrodialysis applications in wastewater treatment for environmental protection and resources recovery: a systematic review on progress and perspectives. Membranes 10(7):1–93. https://doi.org/10.3390/MEMBRANES10070146

Hossain MS, Al-Hamadani SM, Rahman MT (2015) E-waste: a challenge for sustainable development. J Health Pollut 5(9):3–11

Hussain MC, Hait S (2022) Advanced organic waste management: sustainable practices and approaches

Hutchinson JM, Whiteley, HE, Smith CD, Connors L (2003) The developmental progression of comprehension-related skills in children learning EAL. J Res Reading 26(1):19–32

Islam A, Ahmed T, Awual MR, Rahman A, Sultana M, Aziz AA, Monir MU, Teo SH, Hasan M (2020) Advances in sustainable approaches to recover metals from e-waste—a review. J Clean Prod 244:118815. https://doi.org/10.1016/j.jclepro.2019.118815

Jiang B, Adebayo A, Jia J, Xing Y, Deng S, Guo L, Liang Y, Zhang D (2019) Impacts of heavy metals and soil properties at a Nigerian e-waste site on soil microbial community. J Hazard Mater 362:187–195. https://doi.org/10.1016/j.jhazmat.2018.08.060

Jin S, Fallgren PH (2014) Feasibility of using bio electro chemical systems for bioremediation

Jog S (2008) Ten states contribute 70% of e-waste generated in India. Financ Exp

Juul N, Münster M, Ravn H, Söderman ML (2013) Challenges when performing economic optimization of waste treatment: a review. Waste Manage 33(9):1918–1925

Kaza S, Yao L, Bhada-Tata P, Van Woerden F (2018) What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications

Kong S, Liu H, Zeng H, Liu Y (2012) The status and progress of resource utilization technology of e-waste pollution in China. Proc Environ Sci 16:515–521

Liu H, Meng F, Tong Y, Chi J (2014) Effect of plant density on phytoremediation of polycyclic aromatic hydrocarbons contaminated sediments with *Vallisneria spiralis*, pp 380–385

Lv Y, Wu S, Liao J, Qiu Y, Dong J, Liu C, Ruan H, Shen J (2022) An integrated adsorption- and membrane-based system for high-salinity aniline wastewater treatment with zero liquid discharge. Desalination 527:115537. https://doi.org/10.1016/j.desal.2021.115537

Mala JGS, Sujatha D, Rose C (2014) Inducible chromate reductase exhibiting extracellular activity in *Bacillus methylotrophicus* for chromium

Masoomi I, Kamata H, Yukimura A, Ohtsubo K, Schmid MO, Scheffknecht G (2020) Investigation on the behavior of mercury across the flue gas treatment of coal combustion power plants using a lab-scale firing system. Fuel Process Technol 201:106340. https://doi.org/10.1016/j.fuproc.2020.106340

Melchor-Martínez EM, Macias-Garbett R, Malacara-Becerra A, Iqbal HMN, Sosa-Hernández JE, Parra-Saldívar R (2021) Environmental impact of emerging contaminants from battery waste: a mini review. Case Stud Chem Environ Eng 3:100104. https://doi.org/10.1016/j.cscee.2021.100104

Mmereki D, Li B, Baldwin A, Hong L (2016) E-waste in transition—from pollution to resource. InTech. https://doi.org/10.5772/61332

Phillips PS, Tudor T, Bird H, Bates M (2011) A critical review of a key waste strategy initiative in England: zero waste places projects 2008–2009. Res Conserv Recyc 55(3):335–343

Realff MJ, Raymond M, Ammons JC (2004) E-waste: an opportunity. Mater Today 7(1):40–45

Rene ER, Sethurajan M, Ponnusamy VK, Kumar G, Dung TNB, Brindhadevi K, Pugazhendhi A (2021) Electronic waste generation, recycling and resource recovery: technological perspectives and trends. J Hazard Mater 416:125664. https://doi.org/10.1016/j.jhazmat.2021.125664

Sajid M, Syed JH, Iqbal M, Abbas Z, Hussain I, Baig MA (2019) Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-waste) from major cities in Pakistan. Waste Manage (NY, NY) 84:394–401. https://doi.org/10.1016/J.WASMAN.2018.11.026

Sloop S, Crandon L, Allen M, Koetje K, Reed L, Gaines L, Sirisaksoontorn W, Lerner M (2020) A direct recycling case study from a lithium-ion battery recall. Sustain Mater Technol 25:e00152. https://doi.org/10.1016/j.susmat.2020.e00152

Soltani A, Hewage K, Reza B, Sadiq R (2015) Multiple stakeholders in multi-criteria decision-making in the context of municipal solid waste management: a review. Waste Manage 35:318–328

Sun Z, Ma A, Zhao S, Luo H, Xie X, Liao Y, Liang X (2022) Research progress on petroleum coke for mercury removal from coal-fired flue gas. Fuel 309:122084. https://doi.org/10.1016/j.fuel.2021.122084

Takyi SA et al (2020) Micronutrient-rich dietary intake is associated with a reduction in the effects of particulate matter on blood pressure among electronic waste recyclers at Agbogbloshie, Ghana. BMC Public Health 20(1):1–14. https://doi.org/10.1186/S12889-020-09173-8/TABLES/4

Vats MC, Singh SK (2014) E-waste characteristic and its disposal. Int J Ecol Sci Environ Eng

Vermeşan H, Tiuc AE, Purcar M (2019) Advanced recovery techniques for waste materials from IT and telecommunication equipment printed circuit boards. Sustainability 12(1):74. https://doi.org/10.3390/SU12010074

Wang X, Wang L (2019) Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. Int J Prod Res

Wang Y, Peng B, Yang Z, Chai L, Liao Q, Zhang Z, Li C (2014) Bacterial community dynamics during bioremediation of Cr(V1)-contaminated soil

Xiao N, Liu R, Jin C, Dai Y (2015) Efficiency of five ornamental plant species in the phytoremediation of polycyclic aromatic hydrocarbon (PAH)-contaminated soil. Ecol Eng 75:384–391

Zaman A, Huang F, Jiang M, Wei W, Zhou Z (2020) Preparation, properties, and applications of natural cellulosic aerogels: a review. Energy Built Environ 1(1):60–76

# Chapter 20
# Role of Biotechnological Approaches for the Valorization of Precious Metals from E-waste

**Rashmi Upadhyay and Perumalla Janaki Ramayya**

**Abstract** The speedy e-waste volume is getting produced globally. Concurrently, various recycling technologies, i.e., chemical along with mechanical methods are well studied, although the biological approach is the majorly an imperative method. Biological approach turns to be superior to current pyrometallurgical processes which are deemed to be energy-intensive, imperfect as well as non-selective. Henceforth, this chapter provides elaborated knowledge about valorization/extraction of precious metals from electronic waste. It outlines biotechnological processes as a promising alternative to the present industrial best available technologies. These technologies include bioleaching from biosorption, bioelectrochemical, and various matrices' systems.

**Keywords** E-waste · Bioleaching · Precious metals · Metal recovery

## 20.1 Introduction

The increased quantity of electronic and electrical products is increasingly becoming a waste stream globally (Awasthi et al. 2019a, b; Awasthi and Li 2017a, b). According to the UN global e-waste reports, the quantity of electronic garbage produced in 2019 was 53.6 Mt which presents 21% of the e-waste produced over the previous five years. The reports also predict that e-waste generation will reach 74 Mt globally by 2030. Statistics on the biggest global producers of e-waste is depicted in Fig. 20.1. Almost, 20% e-waste is collected officially and recycled formally (Baldé et al. 2017). The various reports suggested that developed countries transfer their e-waste to the many other countries such as Malaysia, Thailand, Nigeria, Ghana, Indonesia (Wong et al. 2007; Huisman et al. 2015; Odeyingb et al. 2017) (Fig. 20.2).

R. Upadhyay (✉)
International Rice Research Institute (IRRI, India Office), 1st Floor, Office Block, NASC Complex, DPS Marg, PUSA, New Delhi 110012, India
e-mail: rashmiupadhyay123@gmail.com

P. J. Ramayya
Breeding Modernization, International Rice Research Institute (IRRI, India Office), 1st Floor, Office Block, NASC Complex, DPS Marg, PUSA, New Delhi 110012, India



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_20

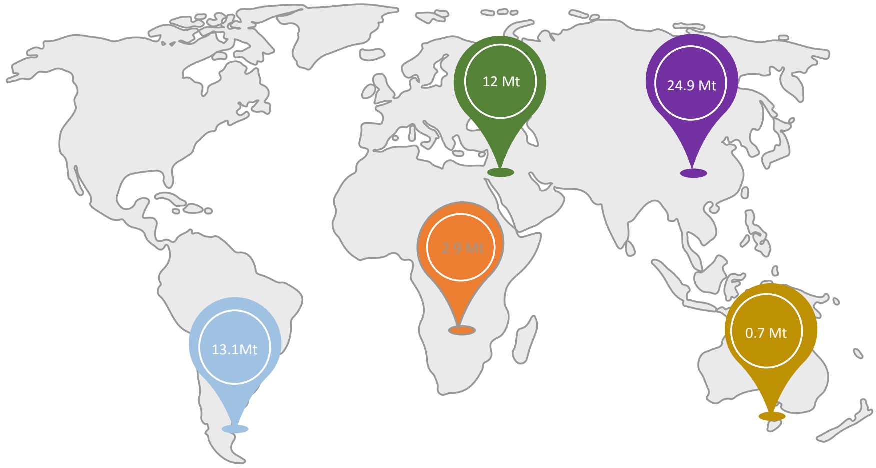



**Fig. 20.1** Study areas. Data compiled from various UN reports, Abalansa et al. (2021)

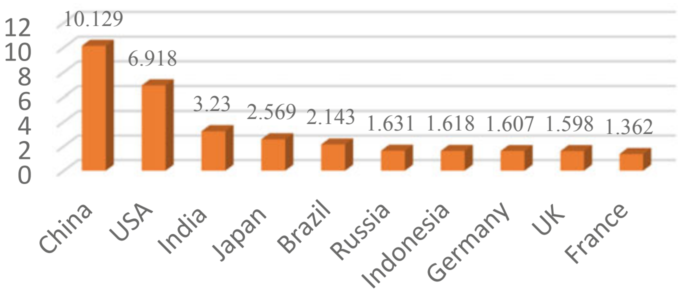



**Fig. 20.2** Statistics on the biggest producers of e-waste. Data compiled from various UN reports, Abalansa et al. (2021)

However, once these countries cease to do so, the e-waste recycling is going to become a new challenge for many well-developed countries. However, management of e-waste is not regulated well, majorly in various developing nations (Awasthi et al. 2016; Duan et al. 2016; Li et al. 2015a, b). Since inappropriate recycling techniques are now very prevalent in developing nations, many dangerous elements and substances, like heavy metals, are released, having a harmful effect on the environment and the general public's health (Awasthi et al. 2019a, b; Song and Li 2014).

But, valuable metals like copper, gold, and rare earth elements (REEs) including neodymium (Nd), indium (In), yttrium (Y), and gallium (Ga) could be found in significant quantities in e-waste (Awasthi et al. 2019a, b; Maneesuwannarat et al., 2016; Pourhossein and Mousavi 2018; Vats and Singh 2015). There is increasing interest in e-waste as an substitute material for recovery of important metals, owing to its greater content of valuable metals. According to few statistics, there is approximately 10–1000 g gold/ton e-waste which is much greater when compared with the mineral ore. Henceforth, e-waste is also called as "urban mine" (Davis and Heart. 2008).

Furthermore, the presence of significant levels of metals poses a very problem because under the erroneous management, they might be released into the environment. However, this feature also offers a chance to move toward a circular strategy based on the maxim "resource-product-regenerated resource", where waste is turned into a resource. The previous linear management strategy, in which a product becomes garbage to be disposed of, has moved toward a circular approach to address this two-fold criticality.

E-waste is recycled majorly by applying technologies that include chemical leaching techniques and mechanical separation (Awasthi et al. 2016; Awasthi and Li 2017a, b; Kaya 2016; Pant and Singh 2013). Nonetheless, these recycling processes are having several impediments. In most recent times, biotechnological approaches (bioleaching) is being considered as an effective technology for commercial exploitation of precious metals from electronic waste and low-graded ores. Therefore, this chapter furnishes an elaborative information regarding extracting precious metals from e-waste. Moreover, the main objective of this chapter is to present outlook on environment-friendly processes in order to recover valuable resource materials and metals from e-waste.

## 20.2 Bioprocessing of E-waste for Valuable Metals' Recovery

### *20.2.1 Valuable Metal Content of E-waste*

Principal sources of critical metals, such a platinum group metals (PGMs), rare earth elements (REEs), are not equally distributed across the world. Monopoly of few major producing nations in export of REE results in scarcity of resources which are frequently associated with (a) the demand of an increasing world population competing for a better standard of living and (b) geopolitical issues that include political instability of reserve hosting countries and export restrictions. The European Commission (EC) has listed 27 critical metals in accordance to their risk in shortage of supply and their economic importance. Among them, a greater number is essential composition of electrical and electronic equipment (EEE). However, these are essentially important to make transition economy that is low-carbon and green economy.

EEE components like printed circuit boards, permanent magnets, lithium–ion, nickel metal hybrid (NiMH), and nickel–cadmium (Ni–Cd) batteries, lamp phosphors, liquid crystal displays (LCDs), light-emitting diodes (LEDs), and hard disk drives (HDDs) are therefore crucial secondary sources of critical metals (Binnemans et al. 2013; Ueberschaar and Rotter 2015). Numerous influential industries from a variety of manufacturing enterprises, particularly those in the electric vehicle, renewable energy, and consumer electronics sectors, are now aware of the difficulties posed by the scarcity and insufficiency of raw materials. This emphasizes how crucial it is to develop cutting-edge (bio) methods for extracting essential raw materials from WEEE.

### *20.2.2 Biotechnology for Extracting Precious Metals from E-waste*

Biotechnology provides a well-defined pathway for extracting Au, Ag, As, Mn, Mo, W, V, Ni, Cu, and Zn from primary ores (Morin et al. 2006). Moreover, 5% Au and 15% Cu and trace amount of Ni and Zn are obtained using microorganisms. Bioleaching is a proven technology for processing low-graded ores. There is rising interest both commercially and academically in bioprocessing of waste for better metal recovery. The biomining of principal minerals is better understood and detailed by Mahmoud et al. (2017), Brierley and Brierley (2013). Waste materials such as post-consumer anthropogenic discarded materials on contrary reveal dissimilarities to primary materials as several metals are found in their zero valence elemental state in electronic and electrical equipment's waste often alloyed with other metals (Bloodworth 2014).

### *20.2.3 Bioleaching/Biometallurgical Technique*

The amalgation of biotechnology and hydrometallurgical process by applying biocatalysts such as enzymes and microorganisms has developed into another metallurgical process known as biometallurgy (bioleaching) for recycling of e-waste (Wang and Chen 2009). In bioleaching process, there is conversion of metallic compounds into their water-soluble states by using variety of microorganisms, and those are mainly (a) chemolithoautotrophs' prokaryotes (Ilyas et al. 2007), (b) heterotrophic bacteria, (c) fungi. Some of the studies of bioleaching approaches for valorization of precious metals are depicted in Table 20.1.

**Table 20.1** Studies based on biotechnological approaches for metal removal from e-waste (Awasthi et al. 2019a, b)

| Microorganisms | Experimental condition | Leached metals % (mg/g PCB) | References |
|---|---|---|---|
| *Pseudomonas putida* (two-step) | Temperature: 30 °C; pH: 8.0–9.2 | Cu: 98% (164 mg/g), Au: 44% (0.1 mg/g) | Işıldar et al. (2016) |
| *Acidithiobacillus ferrooxidans* | Temperature: 30 °C; pH: 2.0 | Cu: 95% (203 mg/g) | Chen et al. (2015) |
| *Sulfobacillus thermosulfidooxidans* | Temperature: 45 °C; pH: 2.0 | Cu: 95% (105 mg/g), Al: 91% (19 mg/g), Zn: 96% (18 mg/g), Ni: 94% (18 mg/g) | Ilyas and Lee (2014) |
| *At. ferrooxidans, Leptospirillum ferrooxidans, At. thiooxidans* | Temperature: 25 °C; pH: 1.7 | Cu: 95% (106 mg/g) | Bas et al. (2013) |
| *Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, Leptospirillum ferrooxidans* | Temperature: 30 °C; n/a; 10% (CRT fluorescent powder) | Y: 70% | Beolchini et al. (2012) |
| *Acidophilic consortium (genera Acidithiobacillus and Gallionella)* | Temperature: 30 °C; pH: 2.0 | Cu: 97% (626 mg/g), Al: 88% (34 mg/g), Zn: 92% (28 mg/g) | Zhu et al. (2011) |
| *At. ferrooxidans, At. thiooxidans* | Temperature: 28 °C; pH: 1.5–3.5 | Cu: 94%; Ni: 89%; Zn: 90% | Liang et al. (2010) |
| *Chromobacterium violaceum, Pseudomonas fluorescens, Pseudomonas plecoglossicida* | Temperature: 30 °C; pH: 7.2–9.2 | Au: 69% | Brandl et al. (2008) |
| *Sulfobacillus thermosulfidooxidans, acidophilic isolate* | Temperature: 45 °C; pH: 2.0 | Cu: 89% (76 mg/g), Ni: 81% (16.2 mg/g), Zn: 83% (66.4 mg/g) | Ilyas et al. (2007) |
| *Aspergillus niger, Penicillium simplicissimum* | Temperature: 30 °C; pH: 3.5 | Cu: 65% (52 mg/g), Al: 95% (225 mg/g), Ni: 95% (14 mg/g), Zn: 95% (25 mg/g) | Brandl et al. (2001) |
| *Acidithiobacillus ferrooxidans* | Initial pH: 3; initial $Fe^{3+}$: 8.4 g/L; pulp density 20 g/L, particle size: 95 µm | Cu: 100%; Ni: 100% | Arshadi and Mousavi (2014) |

(continued)

**Table 20.1** (continued)

| Microorganisms | Experimental condition | Leached metals % (mg/g PCB) | References |
|---|---|---|---|
| *Acidithiobacillus ferrooxidans* | Initial pH of 1, initial $Fe^{3+}$ concentration of 4.18 g/L, pulp density of 8.5 g/L, and particle size of 114.02 lm (#100 mesh) | Cu: 100%; Ni: 100% | Arshadi and Mousavi (2015) |
| *Bacillus megaterium* | Mobile phone PCBs; initial pH: 10, pulp density: 8.13 g/L, glycine: 10 g/L | Cu: 72%; Au: (65 g Au/ton) | Arshadi et al. (2016) |
| *Aspergillus niger* | Spore suspension: 1 mL (approximately $10^7$ spores/mL); pulp density: 1% (w/v); shaking speed: 130 rpm; temperature: 30 °C; incubation period: 30 days | Li: 100%; Cu: 94%; Mn: 72%, Al: 62%; Ni: 45%; Co: 38% | Horeh et al. (2018) |
| *Acidithiobacillus ferrooxidans* | Initial pH: 1; particle size: 62 μm; initial $Fe^{3+}$: 9.7 g/L | Ni: 87%, Cd: 67%, Co: 93.7% | Bajestani et al. (2014) |
| *Aspergillus niger* | Room temperature; rotation speed 120 rpm; pulp densities (0.5–20 g/L); incubation: 30 days | Zn: 100%; Ni: 80.39%; Cu: 85.88% | Faraji et al. (2018) |
| *Acidithiobacillus ferrooxidans* | pH: 2.25; initial Fe(II): 9 g/L, metal concentrates: 12 g/L, inoculation quantity: 10%; particle size: 0.178–0.250 mm, incubated 78 h, and for Zn (183 h) | Cu: 92.57%; Al: 85.24%; Zn: 95.18% | Yang et al. (2017) |

## *20.2.4 Microorganisms for Bioleaching*

### 20.2.4.1 Bioleaching by Chemolithotrophic Autotrophs

A diverse range of chemolithotrophic bacteria, e.g., *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans* are well known for mobilizing metals from the e-waste and are most extensively studied mesophilic microorganisms in bioleaching communities. They utilize carbon dioxide as carbon source, ferrous ion as inorganic compounds, and sulfur as an energy source (Peiravi et al. 2017).

#### 20.2.4.2 Bioleaching by Heterotrophs

Heterotrophic bioleaching serves as a promising approach for metal recovery from secondary raw materials such as rare earth elements, and those are slags, coal, ashes, and fluorescent powders (Das and Das 2013). Heterotrophic microorganism can bear high pH and complex metals in the solution. Archaea, bacteria, and fungi are part of heterotrophic bioleaching (Burgstaller and Schinner 1993). Li et al. (2014) used *Chromobacterium violaceum*, a cyanide generating bacterium to leach out gold from wasted printed circuit boards with yeast, peptone, and glycine. They reported that gold leaching efficiency is influenced by various factors like dissolved oxygen, particle size, metals, and nutriment, particularly various metal ions acting as a catalyst in the process of metabolism. A homemade oxygenator was used to supply the oxygen for bacterial respiration and leaching efficiency of gold increased substantially. All the stimulating effects are clearly visible from the total amount of cyanide generated, which is equivalent to the optimum leaching efficiency. The amalgation of oxygen supplement, added nutrients, and the pre-treatment by bio-oxidation has made gold bioleaching efficiency to reach to 70.6%, which was much greater than the earlier reports. Heterotrophic bioleaching of valuable/critical metals from e-waste has been targeted on organic acid and cyanide generating microorganisms. Cyanogenic bioleaching focuses on valuable metals and platinum group metals, i.e., Au, Ag, Pt, Pd, Rh, and Ru. Critical metals, such as Co, Ga, Ge, Li, Sb, and W, are bioleached from secondary sources by chelation technique.

#### 20.2.4.3 Bioleaching by Heterotrophic Bacteria

Bioleaching of precious metals is carried out by Pseudomonas strains, i.e., *P. aeruginosa, P. fluorescens, and P. putida.* These microbes are found ubiquitously, basically in soils and solubilize metals owing to several metabolic products (Kaksonen et al. 2014). The bioleaching from primary ores of Cu, Au, Ag, Pt, and Zn by several *Pseudomonas* species (Kucuker et al. 2016) and electrical and electronic equipment's waste (Gadd 2009) has been reported. The two-step heterotrophic/autotrophic bio recovery strategy was applied to recover Cu and Au by Işıldar et al. (2016). Heterotrophic bioleaching of rare earth metals from waste materials has been exhibited. The two bacterial strains, those are *Acinetobacter* and *Pseudomonas* spp., and strain of fungus associated to Penicillium and Talaromyces were selected along with the bacterium *Gluconobacter oxydans* for phosphor powders' leaching and fluid catalytic cracking catalysts. Powders of phosphorous and the rare earth elements' efficiency of leaching were highest that is of 2%. Total rare elements of 49% were leached out from the fluid catalytic cracking catalyst utilizing cell-free culture supernatants of *G. oxydans* (Das and Das 2013).

In the initial step, complete leaching of the base metals from the dust was carried out by *Acidithiobacillus thiooxidans* under acidic conditions. At this step, europium, cerium, and neodymium were recovered at high percentages. Additionally, La and

Y were recovered with an yield of 80%. In the next step, *Pseudomonas putida*, a cyanide-producing bacteria was recovered at 48% of Au in 3 h by *A. thiooxidans*.

#### 20.2.4.4 Bioleaching by Fungus

Bioleaching by fungal redoxolysis accomplishes at a relatively increased pH, i.e., near to neural or alkaline (Xu and Ting 2004). Majorly studied microbes in bioleaching of metals by fungus from waste material are *Penicillium simplicissimum* and *Aspergillus niger* (Lee and Pandey 2012). Fungal strains of *Aspergillus niger*, *Aspergillus terreus* ML3-1, and *Paecilomyces species* were used for solubilizing rare earth elements (Brisson et al. 2016). Comparison with experiments by abiotic leaching demonstrated the useful effect of microorganism presence. Narayanasamy et al. (2017) reported the recovery of precious metals from electronic waste PCBs by bioleaching using acidophilic fungi. They concluded that the acidophilic *A. niger* DDNS1 can be utilized as a potent biological agent for the purpose of leaching of precious metals and degrade toxic metals from e-waste PCBs. The results also suggested that biodegradation and bioleaching are the effective methods for recycling and recovery of e-waste metals for both environment and economic perspectives. The two-step bioleaching procedure was carried in organic acid-forming conditions for the highest mobilization of metals.

## 20.3 Bioleaching of Printed Circuit Boards (PCBs)

Among all the e-wastes, printed circuit boards (PCBs) carry hazardous and valuable metals (Willner et al. 2015). Printed circuit boards (PCBs) are the brains of many electronic devices. They are the integral part of electrical and electronic equipment's constituting about 3% of total weight of electronic scrap. The precious heterogenous metals in PCBs include copper (19.19%), aluminum (7.06%), nickel (5.35%), iron (3.56%), tin (2.03%), lead (1.01%), and also, the precious metals silver and gold (0.2%) (Yoo et al. 2009).

The PCBs are valuable junk at the end of their useful lives because they contain precious metals like Au, Ag, and Pd as well as base metals like Cu and Zn (25 and 2 wt%, respectively) (250, 1000, and 110 ppm, respectively). Pyrometallurgy and hydrometallurgy are the two approaches that industries utilize to recover metals from PCBs most frequently. Dioxins and furans are produced as a result of pyrometallurgical techniques, which also often have significant operating costs. Low-cost hydrometallurgy requires a lot of chemical agents yet uses little energy. As an alternative, bio-hydrometallurgy frequently complies with sustainability principles necessary for the growth of a circular economy and is cost-effective, easy, and ecologically beneficial.

With the inculcation of current biotechnological approaches, they have obtained major prominence in PCBs' exploitation since they can be more promising approach than the chemical techniques. Researchers have found that the method of extracting Cu and Zn from PCBs by using the fungal strain *Aspergillus niger* is sustainable. For the bioleaching of PCBs, fungus such as *A. niger* that was isolated in laboratory from ambient samples was utilized.

The YPD broth, which contains 1.5% agar and contains 10 g/L yeast extract (Y), 20 g/L peptone (P), and 20 g/L D-glucose (D), was used for the fungus inoculation inside of sterile Petri dishes with a 100 mm diameter. Additionally, Rifampicin, a 100 mg/L antibiotic, was added to this medium. The PCB addition at various fermentation durations and the addition of two oxidizing agents ($Fe^{3+}$ or $Mn^{7+)}$ were both tested using the bioleaching methods. The ideal circumstances were found.

The addition of PCBs after 14 days, the use of $Fe^{3+}$ as an oxidizing agent, and pulp density of 2.5% (w/v) were determined to be the ideal conditions. After 21 days of fermentation, extraction efficiency of 60% and 40% for Cu and Zn, respectively, was achieved. By employing milk whey as a substrate for fungal growth and the ensuing synthesis of citric acid, which was then used as a bioleaching agent, the process eco-design was further improved. In Fig. 20.3, the bioleaching of PCB waste is shown. Culture of microbes produces metabolites that is utilized as an leaching agent. This method is utilized for the removal of precious metals from the e-waste systematic, generally in the form of precipitation.

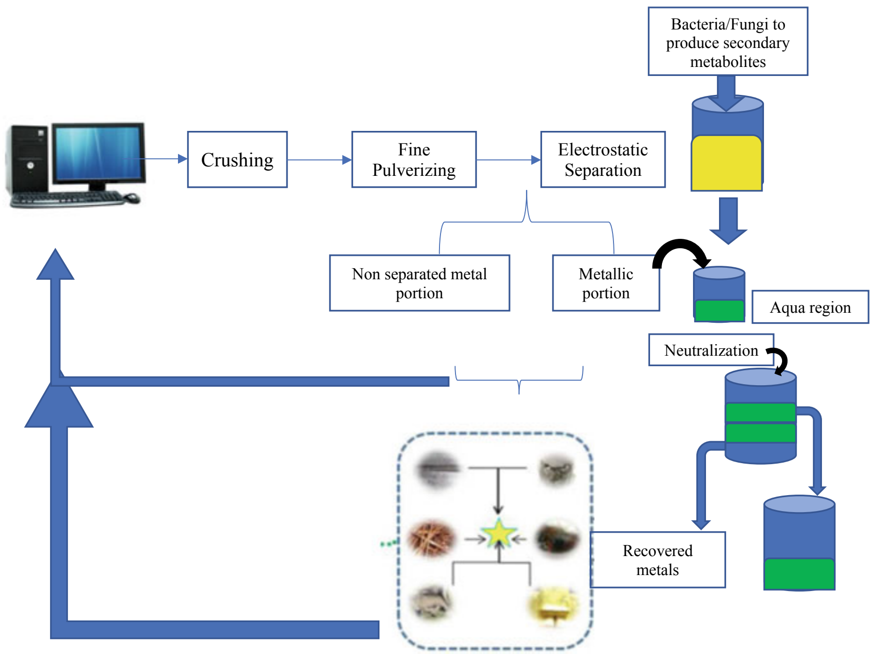



**Fig. 20.3** Metabolites of microbes for removal of metals from e-waste (e.g., PCBs)

## 20.4 Bioleaching Reactions

The mechanism bioleaching of copper using PCBs by *A. ferrooxidans* is predicted as same as involving metal sulfides in terms of involving indirect leaching carried by the biogenic sulfuric acid (Ilyas et al. 2010). The basic bit part of the microorganisms in the entire process involves oxidized elemental sulfur ($S^0$) to sulfuric acid ($H_2SO_4$). Elemental sulfur cannot be seen available in waste PCBs and add up outside the leaching media. Externally supplied ferrous iron ($Fe^{2+}$) serves as an electron donor and is introduced to the leaching media. Bacteria oxidize it to ferric iron ($Fe^{3+}$). Equations are given below:

$$S^0 + 1.5O_2 + H_2O \rightarrow 2H^+ + SO_4^{2-}$$
$$5Fe^{2+} + O_2 + 2H \rightarrow 4Fe + 2OH$$

$Fe^{3+}$ acts as an oxidizing agent in the bioleaching reaction to speed up the leaching reaction. Copper is liberated from the waste material by biogenic ferric iron and sulfuric acid. A combined acidolysis and redoxolysis bioleaching mechanism for metal dissolution from waste material is what this translates into. Equations are given below:

$$Cu^0 + 2Fe^{3+} \rightarrow Cu^{2+}+2Fe^{2+}$$
$$Cu^0 + H_2SO_4 + 0.5O_2 \rightarrow Cu^{2+} + SO_4^{2-} + H_2O$$

Bioleaching rate greatly depends on the ferrous ion, pH, and rate of oxidation from ferrous to ferric (Oguchi et al. 2012). Biogenic $Fe^{3+}$ concentration is correlated with leaching rate and the extraction efficiency (Hussein et al. 2004). Barmettler et al. (2016) submitted that the interactions between microbes and rare earth metals have not yet been completely investigated, and the bioleaching process is described in terms of acidolysis, redoxolysis, and complexolysis.

## 20.5 Biometallurgical Versus Hydrometallurgical and Pyrometallurgical Processes

Bioleaching has distinct advantage over traditional metallurgical processes that includes low operational cost, relatively lower energy requirement, relatively simple, increase efficiency in effluent detoxification, economical and eco-friendly nature (Wang et al. 2013). Traditional metallurgical processes, i.e., hydrometallurgical and pyrometallurgical methods for extracting metals are less time taking and rapid in comparison to bioleaching process. Nonetheless, investment cost and considerable energy requirement, accompanied toxicity, and low metal recovery from e-waste increase the redundancy of aforesaid methods. Bioleaching offers substantial advantage of higher metal extraction rate from the low-grade, depleted ores, and the complex resources by involving the active bioagents.

## 20.6 Bioelectrochemical, Biosorption, and Bioprecipitation Processes for Precious Metal Recovery

As part of these recovery strategies, bio-based technologies are recognized as a cost-effective solution to concentrate components from diluted leachates and wastewater, and recovery of valuable elements may help to lower the cost of waste treatment. Bio-based strategies work for dilute waste streams along with an input of low energy. Henceforth, bioelectrochemical systems, bioprecipitation, and biosorption processes are now being incorporated into the novel hydro, bio, and hybrid metallurgical systems.

### *20.6.1 Biosorption*

The method known as "biosorption" enables the binding of various metal ions from an aqueous solution using microbial biomass or their metabolites (Sheel and Pant 2018). The leaching and recovery of precious metals like platinum, palladium, and gold from used PCBs are the main application of the biosorption process. The most important responsibilities in these processes, though, are selectivity, metal-binding ability, renewability of materials, material stability, and cost-efficiency. In light of this, numerous researches have focused on the use of agricultural waste, bacteria, fungi, and yeast as a biosorption material (Bindschedler et al. 2017; Sheel and Pant 2018; Hassan et al. 2018; Vendruscolo et al. 2017). Additionally, the recent research and developments are directed toward improvement in microbes, bioengineering, and mutant enzymes such as expression of metallothioneins, metal-binding peptides, or new metal-binding proteins. A eco-friendly approach is the usage of the metal-binding peptides through a phage surface display. Through this method, specific peptides for metal ions or metallic surfaces were selected by Pollmann et al. (2018).

### *20.6.2 Bioelectrochemical*

Bioelectrochemical methods are the promising modern biotechnology techniques for recovery of critical metals from the e-waste (Nancharaiah et al. 2015).

The electrochemical systems and microbial metabolism are combined in bioelectrochemical systems. On electrodes, microorganisms breathe by capturing electrons from waste streams. This can be used to produce electricity, such as microbial fuel cells (MFCs). Additionally, metals at the cathode can be recovered from the solution using the eliminated electrons. The bioelectrochemical systems developed by Nancharaiah et al. (2016) are a futuristic technique for the removal and recovery of metal ions. The recent research has shown that bioelectrochemical systems are capable of recovering a variety of metals, including Cu, Ni, Cd, and Zn, as well as a few valuable and rare metalloids, including Ag, Au, Co, and Se (Ho et al. 2017). By Peiravi et al. (2017) and Pozo et al. (2017), the most modern bioelectrochemical systems for treating actual mine drainage were created (2017).

### *20.6.3 Bioprecipitation*

According to Hussain et al. (2016), bioprecipitation approaches to remove metals from waste streams have primarily focused on using sulfate-reducing bacteria to generate insoluble metal sulfidic precipitates. The bioreduction of precious metals to metallic nanoparticles has drawn a lot of attention recently. The creation of nanomaterials from waste materials using microorganisms has great promise since (a) the created nanomaterials can be directly utilized in industrial and catalytic processes and (b) microorganisms are regarded as low-cost catalysts. They carry out their synthesis at room temperature and pressure.

Metallic nanoparticles that are produced by biological processes have shown the ability to directly valorize goods from waste streams. By employing *Escherichia coli* and a biomanufacturer of catalytically active Au nanoparticles for the oxidation of glycerol, Deplanche et al. (2007) focused on the bio recovery of gold from waste jewelry. By combining microorganisms with a surfactant, Ilyas et al. (2017) and Akar et al. (2008) shown that unique gold nanostructures and bio-Au nanocomposites had good optical characteristics. While Won et al. (2014) produced membranes containing biogenic Ag (0) precipitates with antifouling capabilities, De Gusseme et al. (2011) demonstrated the useful usage of biogenic Ce and Ag (0) particles for virus disinfection. Consequently, there is a clear necessity for creating experiments focused on the creation of biogenic particles from actual streams of waste, that encompasses electrical and electronic equipment, and technologies scaling up the pilot projects.

## 20.7 Future Perspectives and Developments

E-waste is generating revolution pertaining to unsustainable methods of processing. In developing countries, waste electrical and electronic equipment's generation will increase in the upcoming years. This e-waste is an important secondary source of precious metals. These metals play a critical role in making transition to the green economy. The secure supply of these metals is a challenge; henceforth, we need alternative sources, for example, metal-rich post-consumers' waste materials. Nonetheless, the economic benefits from precious material recovery are not the only driver to generate these technologies. Lack of proper disposal/handling of electronic waste and several toxic metal-bearing secondary sources challenge the sustainable development goals of safe environment and public health.

Biotechnological approaches have a classical niche in processing of low-graded ores. It encompasses to play a central role in the treatment and metal recovery from metal containing waste. Waste bioprocessing for accomplishing of metal recovery allows to meet two main objectives, and those are recovery of resource and mitigation of pollution. Biotechnology accompanied by technological innovations plays a key role in supplementing conventional technologies in valorization of precious metals from the secondary sources making transition to a sustainable management of electronic waste.

When compared to main ores, electronic waste differs from them in terms of chemical makeup, metal richness, and complexity. In diverse mixes, the e-waste typically has higher proportions of ordinary metals and a very low concentration of precious/critical metals. The valuable metals, which are typically present in low concentrations, cannot be effectively targeted by the current e-waste recycling systems (Ilyas et al. 2017). Utilizing autotrophic microorganisms in bioleaching processes allows for the energy-efficient oxidation of sulfidic ores. On the other hand, metals found in e-waste are found in their natural metallic state. It is essential to provide the bacteria with an additional energy source as a result. Innovative approaches are required for this specific difficulty in order to recover precious metals from e-waste.

More fundamental study on e-waste bioprocessing is necessary because many of the main processes for leaching are still being established. Additionally, because e-waste does not contain metals in the form of sulfides, the lessons learned from employing autotrophic bioleaching cannot be immediately applied to bioleaching of metals in other forms, such as carbonates, silicates, or oxides. More research is required to develop into comprehensive applications, as well as to optimize operational conditions and evaluate environmental implications. Additionally, important criteria for biotechnological solutions for precious metal recovery from metals include scale-up studies with environmental sustainability and techno-economic assessment analysis concerns.

## References

Abalansa S et al (2021) Electronic waste, an environmental problem exported to developing countries: the good, the bad and the ugly. Sustainability 13(9):5302

Akar ST, Gorgulu A, Kaynak Z, Anilan B, Akar T (2008) Biosorption of reactive Blue 49 dye under batch and continuous mode using a mixed biosorbent of macro-fungus *Agaricus bisporus* and *Thuja orientalis* cones. Chem Eng J 148:26–34

Arshadi M, Mousavi SM (2014) Simultaneous recovery of Ni and Cu from computer-printed circuit boards using bioleaching: statistical evaluation and optimization. Bioresour Technol 174:233–242

Arshadi M, Mousavi SM (2015) Multi-objective optimization of heavy metals bioleaching from discarded mobile phone PCBs: simultaneous Cu and Ni recovery using *Acidithiobacillus ferrooxidans*. Sep Purif Technol 147:210–219

Arshadi M, Nili S, Yaghmaei S (2016) Ni and Cu recovery by bioleaching from the printed circuit boards of mobile phones in non-conventional medium. J Environ Manag 15(109502):250

Awasthi AK, Li J (2017a) An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. Resour Conserv Recycl 126:228–239

Awasthi AK, Li J (2017b) Management of electrical and electronic waste: a comparative evaluation of China and India. Renew Sust Energ Rev 76:434–447

Awasthi AK, Zeng X, Li J (2016) Environmental pollution of electronic waste recycling in India: a critical review. Environ Pollut 211:259–270

Awasthi AK, Li J, Koh L, Ogunseitan OA (2019a) Circular economy and electronic waste. Nat Electron 2:86–89

Awasthi AK et al (2019b) Environmentally sound system for E-waste: biotechnological perspectives. Curr Res Biotechnol 1:58–64

Bajestani MI, Mousavi SM, Shojaosadati SA (2014) Bioleaching of heavy metals from spent household batteries using *Acidithiobacillus ferrooxidans*: statistical evaluation and optimization. Sep Purif Technol 132:309–316

Baldé CP, Forti V, Gray V, Kuehr R, Stegmann P (2017) The global E-waste monitor United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA). Bonn, Geneva, Vienna

Barmettler F, Castelberg C, Fabbri C, Brandl H (2016) Microbial mobilization of rare earth elements (REE) from mineral solids—a mini review. AIMS Microbiol 2:190–204

Bas AD, Deveci H, Yazici EY (2013) Bioleaching of copper from low grade scrap TV circuit boards using mesophilic bacteria. Hydrometallurgy 138:65–70

Beolchini F, Fonti V, Dell'Anno A, Rocchetti L, Vegliò F (2012) Assessment of biotechnological strategies for the valorization of metal bearing wastes. Waste Manag 32:949–956

Bindschedler S, Bouquet TQTV, Job D, Joseph E, Junier P (2017) Fungal biorecovery of gold from E-waste. Adv Appl Microbiol 99:53–81

Binnemans K, Jones PT, Blanpain B, Van Gerven T, Yang Y, Walton A, Buchert M (2013) Recycling of rare earths: a critical review. J Clean Prod 51:1–22

Bloodworth A (2014) Track flows to manage technology-metal supply. Nature 505:9–10

Brandl H, Bosshard R, Wegmann M (2001) Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59:319–326

Brandl H, Lehmann S, Faramarzi MA, Martinelli D (2008) Biomobilization of silver, gold, and platinum from solid waste materials by HCN-forming microorganisms. Hydrometallurgy 94:14–17

Brierley CL, Brierley JA (2013) Progress in bioleaching: part B: applications of microbial processes by the minerals industries. Appl Microbiol Biotechnol 97:7543–7552

Brisson VL, Zhuang W-Q, Alvarez-Cohen L (2016) Bioleaching of rare earth elements from monazite sand. Biotechnol Bioeng 113:339–348

Burgstaller W, Schinner F (1993) Leaching of metals with fungi. J Biotechnol 27:91–116

Chen S, Yang Y, Liu C, Dong F, Liu B (2015) Column bioleaching copper and its kinetics of waste printed circuit boards (WPCBs) by *Acidithiobacillus ferrooxidans*. Chemosphere 141:162–168

Das N, Das D (2013) Recovery of rare earth metals through biosorption: an overview. J Rare Earths 31:933–943

Davis C, Heart S (2008) Electronic waste: the local government perspective in Queensland. Aust Resour Conserv Recycl 52(8–9):1031–1039

Deplanche K, Attard GA, Macaskie LE (2007) Biorecovery of gold from jewellery wastes by *Escherichia coli* and biomanufacture of active Au-nanomaterial. Adv Mater Res 20–21:647–650

Duan H, Hu J, Tan Q, Liu L, Wang Y, Li J (2016) Systematic characterization of generation and management of e-waste in China. Environ Sci Pollut Res 23:1929–1943
Faraji F, Golmohammadzadeh R, Rashchi F, Alimardani N (2018) Fungal bioleaching of WPCBs using *Aspergillus niger*: observation, optimization and kinetics. J Environ Manag 217:775–787
Gadd G (2009) Biosorption: critical review of scientific rationale, environmental importance and significance for pollution treatment. J Chem Technol Biotechnol 84:13–28
Gusseme BD et al (2011) Virus disinfection in water by biogenic silver immobilized in polyvinylidene fluoride membranes. Water Res 45(4):1856–1864
Hassan SHA, Koutb M, Nafady NA, Hassan EA (2018) Potentiality of *Neopestalotiopsis clavispora* ASU1 in biosorption of cadmium and zinc. Chemosphere 202:750–756
Ho NAD, Babel S, Sombatmankhong K (2017) Factors influencing silver recovery and power generation in bio-electrochemical reactors. Environ Sci Pollut Res 24:21024–21037
Horeh BN, Mousavi SM, Baniasadi M (2018) Use of adapted metal tolerant *Aspergillus niger* to enhance bioleaching efficiency of valuable metals from spent lithium-ion mobile phone batteries. J Clean Prod 197:1546–1557
Huisman J, Botezatu I, Herreras L, Liddane M, Hintsa J, Luda di Cortemiglia V, Leroy P, Vermeersch E, Mohanty S, Van den Brink S, Ghenciu B (2015) Countering WEEE illegal trade (CWIT) summary report, market assessment, legal analysis, crime analysis and recommendations roadmap. Lyon, France
Hussain A, Hasan A, Javid A, Qazi JI (2016) Exploited application of sulfate-reducing bacteria for concomitant treatment of metallic and non-metallic wastes: a mini review, 3 Biotech 6:119
Hussein H, Ibrahim SF, Kandeel K, Moawad H (2004) Biosorption of heavy metals from waste water using *Pseudomonas* sp. Electron J Biotechnol 7:38–46
Ilyas S, Lee JC (2014) Bioleaching of metals from electronic scrap in a stirred tank reactor. Hydrometallurgy 149:50–62
Ilyas S, Anwar MA, Niazi SB, Afzal Ghauri M (2007) Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria. Hydrometallurgy 88:180–188
Ilyas S, Ruan C, Bhatti HN, Ghauri MA, Anwar MA (2010) Column bioleaching of metals from electronic scrap. Hydrometallurgy 101:135–140
Ilyas S, Kim M, Lee J, Jabeen A, Bhatti HN (2017) Bio-reclamation of strategic and energy critical metals from secondary resources. Metals 7:1–17. https://doi.org/10.3390/met7060207
Işıldar A, van de Vossenberg J, Rene ER, van Hullebusch ED, Lens PNL (2016) Two-step bioleaching of copper and gold from discarded printed circuit boards (PCB). Waste Manag 57:149–215
Kaksonen AH, Mudunuru BM, Hackl R (2014) The role of microorganisms in gold processing and recovery—a review. Hydrometallurgy 142:70–83
Kaya M (2016) Recovery of metals and non-metals from electronic waste by physical and chemical recycling processes. Waste Manag 57:64–90
Kücüker MA, Nadal JB, Kuchta K (2016) Comparison between batch and continuous reactor systems for biosorption of Neodymium (Nd) using microalgae. Int J Plant Anim Environ Sci 6:197–203
Lee J, Pandey B (2012) Bio-processing of solid wastes and secondary resources for metal extraction—a review. Waste Manag 32:3–18
Li J, Liang C, Ma C (2014) Bioleaching of gold from waste printed circuit boards by *Chromobacterium violaceum*. J Mater Cycles Waste Manag 17:529–539
Li J, Liang C, Ma C (2015a) Bioleaching of gold from waste printed circuit boards by *Chromobacterium violaceum*. J Mater Cycles Waste Manag 17:529–539
Li J, Zeng X, Chen M, Ogunseitan OA, Stevels ALN (2015b) "Control-alt-delete": rebooting solutions for the e-waste problem. Environ Sci Technol 49(12):7095–7108
Liang G, Mo Y, Zhou Q (2010) Novel strategies of bioleaching metals from printed circuit boards (PCBs) in mixed cultivation of two acidophiles. Enzym Microb Technol 47:322–326
Mahmoud A, Cézac P, Hoadley FAH, Contamine F, D'Hugues P (2017) A review of sulfide minerals microbially assisted leaching in stirred tank reactors. Int Biodeterior Biodegrad 119:118–149

Maneesuwannarat S, Vangnai AS, Yamashita M, Thiravetyan P (2016) Bioleaching of gallium from gallium arsenide by *Cellulosimicrobium funkei* and its application to semiconductor/electronic wastes. Process Saf Environ Prot 99:80–87

Morin D, Lips A, Pinches T, Huisman J, Frias C, Norberg A, Forssberg E (2006) BioMinE—integrated project for the development of biotechnology for metal-bearing materials in Europe. Hydrometallurgy 83:69–76

Nancharaiah YV, Mohan SV, Lens PNL (2015) Metals removal and recovery in bioelectrochemical systems: a review. Bioresour Technol 195:102–114

Nancharaiah YV, Mohan SV, Lens PNL (2016) Biological and bioelectrochemical recovery of critical and scarce metals. Trends Biotechnol 34(2):137–155

Narayanasamy M, Dhanasekaran D, Vinothini G, Thajuddin N, Willner J, Kadukova J, Fornalczyk A, Saternus M (2015) Biohydrometallurgical process for metal recovery from electronic waste. Int J Appl Res 54:255–259

Odeyingb O, Nnorom I, Deubzer O (2017) Person in the port project: assessing import of used electrical and electronic equipment into Nigeria. UNU-ViE SCYCLE and BCCC Africa

Oguchi M, Sakanakura H, Terazono A, Takigami H (2012) Fate of metals contained in waste electrical and electronic equipment in a municipal waste treatment process. Waste Manag 32:96–103

Pant D, Singh P (2013) Chemical modification of waste glass from cathode ray tubes (CRTs) as low cost adsorbent. J Environ Chem Eng 1:226–232

Peiravi M, Mote SR, Mohanty MK, Liu J (2017) Bioelectrochemical treatment of acid mine drainage (AMD) from an abandoned coal mine under aerobic condition. J Hazard Mater 333

Pollmann K, Kutschke S, Matys S, Raff J, Hlawacek G, Lederer FL (2018) Bio-recycling of metals: recycling of technical products using biological applications. Biotechnol Adv 36:1048–1062

Pourhossein F, Mousavi SM (2018) Enhancement of copper, nickel, and gallium recovery from LED waste by adaptation of *Acidithiobacillus ferrooxidans*. Waste Manag 79:98–108

Pozo G, Pongy S, Keller J, Ledezma P, Freguia S (2017) A novel bioelectrochemical system for chemical-free permanent treatment of acid mine drainage. Water Res 126:11–420

Sheel A, Pant D (2018) Recovery of gold from electronic waste using chemical assisted microbial biosorption (hybrid) technique. Bioresour Technol 247:1189–1192

Song Q, Li J (2014) Environmental effects of heavy metals derived from the e-waste recycling activities in China: a systematic review. Waste Manag 34(12):2587–2594

Ueberschaar M, Rotter VS (2015) Enabling the recycling of rare earth elements through product design and trend analyses of hard disk drives. J Mater Cycles Waste Manage 17(2):266–281

Vats MC, Singh SK (2015) Assessment of gold and silver in assorted mobile phone printed circuit boards (PCBs). Waste Manag 45:280–288

Vendruscolo F, da Rocha Ferreira GL, Filho NRA (2017) Biosorption of hexavalent chromium by microorganisms. Int Biodeterior Biodegrad 119:87–95

Wang J, Chen C (2009) Biosorbents for heavy metals removal and their future. Biotechnol Adv 27:195–226

Wang W, Pranolo Y, Cheng CY (2013) Recovery of scandium from synthetic red mud leach solutions by solvent extraction with D2EHPA. Sep Purif Technol 108:96–102

Won SW, Kwak IS, Yun Y-S (2014) The role of biomass in polyethylenimine-coated chitosan/bacterial biomass composite biosorbent fiber for removal of Ru from acetic acid waste solution. Bioresour Technol 160:93–97

Wong MH, Wu SC, Deng WJ, Yu XZ, Luo Q, Leung AOW (2007) Export of toxic chemicals—a review of the case of uncontrolled electronic-waste recycling. Environ Pollut 149(2):131–140

Xu TJ, Ting YP (2004) Optimisation on bioleaching of incinerator fly ash by *Aspergillus niger*–use of central composite design. Enzyme Microb Technol 35(5):444–454

Yang C, Zhu N, Shen W, Zhang T, Wu P (2017) Bioleaching of copper from metal concentrates of waste printed circuit boards by a newly isolated *Acidithiobacillus ferrooxidans* strain Z1. J Mater Cycles Waste Manag 19:247–255

Yoo JM, Jeong J, Yoo K, Lee JC, Kim W (2009) Enrichment of the metallic components from waste printed circuit boards by a mechanical separation process using a stamp mill. Waste Manag 29:1132–1137

# Chapter 21
# A Summary of the Role of Microorganisms in Waste Management

**Rakesh Pant, Amit Gupta, Arsh Singh, Simran Srivastava, and Nirmal Patrick**

**Abstract** Waste issues are as ancient as the human race. The term waste refers to materials that are no longer in use and have been dumped by the owner. Waste management is the management of waste from the moment it is created until it is disposed of or reused at the end of its useful life. In waste management, the main objective is to reduce the influence and consequences of waste on the atmosphere and human well-being. A major challenge to all countries worldwide is the effective management of the waste generated. Microbes are also important in the natural recycling of living elements. Microbes have shown to be beneficial in solving numerous challenges that humanity has faced in sustaining environmental quality. There are several crucial things we have to learn about trash management and disposal in order to keep ourselves and the atmosphere secure. Our choice contributes to a better planet and a healthy ecosystem. As a result, constantly strive for sustainability and make concrete measures to control and treat trash.

**Keywords** Waste management · Composting · Biodegradation · Bioremediation · Biotransformation · Plastics

## 21.1 Introduction

Rising urbanisation, the industrial revolution, and the enormous population demand for natural resources all place significant strain on the global ecosystem. A total of $6 \times 10^6$ chemical compounds have been synthesised, with thousand new compounds produced per year. Approximately, 60,000–95,000 compounds are commercially available. And, over one billion pounds of poisons are discharged worldwide in the air and water, according to third-world network reports (Tiwari and Singh 2014). The

R. Pant · A. Gupta (✉) · A. Singh · S. Srivastava
Department of Microbiology and Biotechnology, Graphic Era (Deemed to be University), Dehradun, Uttarakhand 248001, India
e-mail: dr.amitgupta.bt@geu.ac.in

R. Pant · N. Patrick
Department of Quality, Eureka Forbes Ltd., Lal Tappar, Dehradun, Uttarakhand 248140, India

 
P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*,
https://doi.org/10.1007/978-3-031-25678-3_21

waste management (WM) situation differs greatly between industrialised and developing countries because underdeveloped countries lack effective garbage collection and disposal procedures. As a result of growing concerns about ecological deterioration and sustainability, WM has become crucial and is being prioritised (Mandal and Patil 2019). Since the early twentieth century, tremendous breakthroughs in science, engineering, and technology have produced wonderful instruments and systems that have altered our world and become undoubtedly vital in our everyday lives.

Higher disposable incomes and increased urbanisation in many industrialised nations have accelerated technical advancement and the use of electric devices. Although contemporary technology has indisputably raised living norms and brought about lifestyle comforts, it has also had two negative effects on the ecosystem: contamination and natural resource exhaustion. The Global E-waste Monitor 2020 estimated a record 53.6 million metric tonnes of e-waste created in 2019, by tiny electric devices accounting for the majority of e-waste, followed by big machinery and consumer products. This number is low when compared to the 2.01 billion tonnes of MSW created globally in 2016 that contained 242 million tonnes of plastic garbage. E-waste is predicted to grow by 3–5% each year, making it one of the fastest-growing waste streams. Worldwide e-waste is projected to range 74 million tonnes by 2030, driven by rising infiltration of power and electronic equipment in emerging nations, an anticipated substitute market in affluent nations, and rising product obsolescence rates (Han et al. 2022).

Waste issues are as ancient as the human race. Humans quickly learned that trash is a dangerous cause of illness. The earliest well-managed waste treatment record was dated 500 BC in Athens, Greece, where rules required garbage to be placed at least a mile out from the city border and covered by dirt. Municipal solid waste is any non-fluid waste produced by human activities like houses, small commercial institutions such as schools, colleges, and hospitals, hotels, and so on. These waste materials are referred to as "trash" or "junk", and they include common goods. Things that are broken ruined food, kitchen debris, papers, iron rods, plastics, rubber bands, and so on. The product which is an unavoidable product of all human activities is municipal waste. Monetary social advances and rising living standards of human beings in society lead to increases in waste generation. In recent years, the huge quantity of electronic waste created which is named e-waste has increased drastically as peoples become more dependent on electronic goods such as computers, and cell phones. A major challenge to all countries worldwide is the effective management of the waste generated (Singh et al. 2020).

Municipal waste is a by-product of all human activity that cannot be avoided. Increases in trash output are caused by monetary societal advancements and growing human living standards in society. In recent times, the massive amount of electronic garbage known as e-waste has expanded dramatically as people have become more reliant on electronic products such as computers, mobile phones, and so on. The appropriate management of trash created is a critical concern for all nations globally (Singh et al. 2020). The term waste refers to materials that have been dumped by the owner because they are not anymore in usage. Every day, a large amount of rubbish is produced, which is now in need of disposal. This has led in a plethora of challenges, together with the subject of huge amounts of harmful garbage and extra garbage created by electric equipment, dubbed "electronic waste".

Because of the prevalence of lethal chemicals and poisonous compounds in electronic devices, e-waste disposal is becoming an ecological and health nightmare (Patel and Kasture 2014). The bacteria *Chromobacterium violaceum* is renowned for generating violacein, an antibiotic agent. But *C. violaceum* is useful for more than just medicine. The bacteria may be capable of extracting valuable metals from huge amounts of electrical and electronic trash (e-waste) created worldwide (Kwok 2019). Microbes are extensively spread throughout the biosphere due to their outstanding metabolic power and ability to proliferate in a broad variety of ecological circumstances. Microbial nutritional adaptability can also be used for pollution biodegradation. This is referred to as bioremediation. Energy and biomass are created through the conversion, alteration, and consumption of harmful contaminants by bacteria (Abatenh et al. 2017). Nigeria, which has a population of 182 million, garbage generation and disposal are issues that must be discussed. Municipal garbage in Nigeria is derived from home, farming, and industrial bases and can be classified as liquid, solid, gaseous, or toxic. Yet, liquid and solid wastes are the most troublesome (Fig. 21.1). Solid WM is a difficult important topic that necessitates technology, human resources, and financing. To attain intended objectives, major coordinated endeavour must be placed into waste control at all phases of manufacture, assemblage, conveyance, treatment, and dumping (Adebayo and Obiekezie 2018).

Ancient waste disposal methods, as well as sanitary sewers and landfills, have been discovered in the remains of prehistoric Crete and ancient Assyrian towns. The Romans built storm water drains that are still in use today. Although their primary purpose was drainage, the Roman practice of depositing garbage in the streets resulted in a substantial amount of organic matter being transported with rainwater runoff. Below-ground privy vaults and, subsequently, cesspools were created during the end of the Middle Ages. When the containers were filled, sanitation employees withdrew the deposit at the expense of the owner. The wastes were either utilised as fertiliser on surrounding farms or thrown into waterways or on uninhabited land

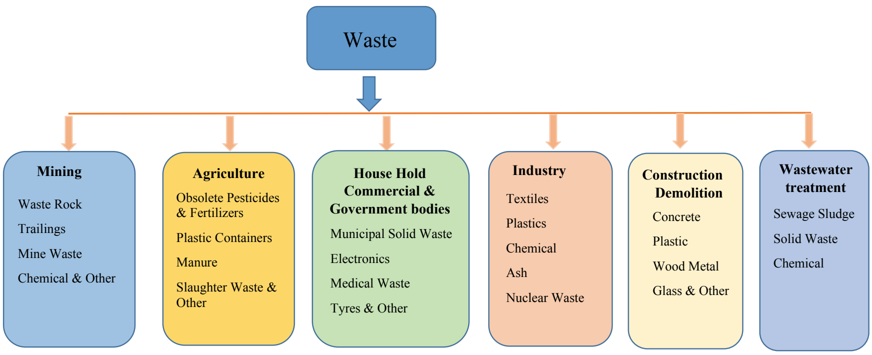



**Fig. 21.1** Origin of waste from different areas

(Jinjiri et al. 2018). Microbes can transform organic wastes that are plentiful in the organic component into sustainable biogas and compost underregulated circumstances. The dig estate from the AD system may be used as fertiliser to improve the soil. During agricultural waste composting, lignocellulose, starch, and protein make up a large portion of the biomass. Before composting or AD, the substantial lignocellulose content frequently necessitates pre-treatment techniques such as chemical and industrial enzyme addition, heat treatment, or biological treatment with microbes. Bacteria and fungi are more advantageous among bacteria due to their efficacy in decomposing organic materials (Leow et al. 2018).

Plastic contamination has emerged as an ecological hazard and challenge in recent years as a result of its increased presence in the water. Plastic may be biodegraded by a variety of microbial and fungus species. The variables controlling plastisphere composition are diverse, largely geographical and seasonal, although polymer type, surface properties, and shape all play a role. Plastics may be degraded by microorganisms like microbes and fungi. *Streptomyces*, *Rhodococcus*, *Corynebacterium*, *Pseudomonas*, *Micrococcus*, *and Arthrobacter* remained the most prevalent bacteriological species in the study lab that could use MPs as a power and carbon source. Microbial breakdown of MNPs involves a number of metabolic processes. Biosynthesis, biodeterioration, bio-fragmentation, and mineralisation are all phases in the breakdown of microbial MPs.

Chitinases are enzymes formed by microorganisms such as *Micrococcus*, *Flavobacterium*, *Pseudomonas*, *Achromobacter*, *and Vibrio* sp., while *Pseudomonas* sp. has been proven to destroy MPs particles, the particular method is uncertain (Singh et al. 2022). Food and vegetable waste, sludge, paper, and garden trash are all examples of organic solid waste. Unreasonable organic waste disposal has resulted in serious issues such as organoleptic susceptibility, land occupation, and environmental recontamination. The last produce obtained from organic waste is broadly employed in farming and further trades like urban green zones and landfill cover (Behera and Samal 2022). Biogas and biofertiliser can be produced by anaerobically digesting organic wastes from farms, households, and industrial facilities, such as cabbage leftovers, rice-straw, maize stover, sugarcane, oilseed-cakes, jatropha-fruit coats. The biodegradability and chemical composition of biowastes are the most important factors in their selection for biogas production.

In reality, the best process constraints for various feedstock substrates should be determined by the local climate and types of feedstock waste. A biogas can be generated by co-digesting food waste with WAS and/or another cellulosic substrate (25–50% $CO_2$ and 50–70% $CH_4$). Additional advantages of AcD of food waste with WERE include increased buffering capacity, nutritional balance modification, and thinning of hazardous compounds. Municipal solid waste is made up of degradable, partially degradable, and non-degradable items from households and businesses. Among them, degradable wastes, which account for the majority of MSW load in developing countries and are often characterised by high water content, necessitate higher functioning costs and fewer possibilities of material recovery. The Ministry of Environment in India published SWM rules in 2000 for the efficient assemblage and discarding of municipal solid rubbish, while the current SWM system has shown to be successful over the last decade, it may still need to be changed to the changing characteristics of urban rubbish. Material recycling, trash reduction, and solid waste stabilisation prior to landfill disposal are all encouraged in modern SWM techniques, as is energy recovery (Pan et al. 2021).

Yet, these procedures need official accreditation and may vary across developing and developed countries, rural and metropolitan locations, and inhabited and manufacturing settings. Municipal Solid waste (MSW) situation in India the recent decade has seen an exponential surge in garbage output due to the rapid expansion in the human population and the hastened economy. In metropolitan India, around 188,500 tonnes of municipal solid trash are created every day. However, only 24% of this massive trash is processed, handled, and disposed of properly. In India, garbage is mostly disposed of by open disposal, landfilling, composting, and incineration; open disposal is low-priced and commonly used option. Waste landfilling is mostly used for garbage handling and removal; however, the need for greater regions restricts MSW disposal, particularly in larger cities. It is estimated that by the year 2047; 1400 $km^2$ of land space would be requisite for the landfilling of MSW generated in India, which is nearly joint size of the three most populated Indian metropolises (Rastogi et al. 2020).

## 21.2 Classification of Waste

We produce a significant amount of garbage in our daily lives as a result of urbanisation. Waste is defined as undesired materials and things that are abandoned after usage, or when the goods can no longer be used, such as food packets, broken plastic utensils, paper bags, and so on. The numerous sources of garbage may be easily identified by distinguishing the categories of wastes. All of these things lead to trash creation in our culture. Trash is produced by households, hospitals, farming garbage, industrial effluents, mining operations, public places, and other sources. Our wastes are harmful in nature and are the source of many ailments.

Depending on where they come from and what they are, waste can be categorised. Waste can be created from four sources: industrial, municipal, biomedical, and electronic. Waste can be categorised according to many characteristics, including substance, degrading feature, environmental effect, and source (Jinjiri et al. 2018).

## 21.3 Waste Management System

WMS is a method an organisation uses to eliminate, minimise, recycle, and prevent waste. There are several ways for disposing of garbage, including recycling, composting, incineration, landfills, bioremediation, waste to energy, and waste reduction. The term “waste management” describes the techniques used to control waste throughout its entire life cycle, from generation through disposal or recovery. The


**Fig. 21.2** Waste management types

storage, assembly, disposal, and management of waste materials are all included in WM. The main objective of WM is to minimise the effects and results of waste on both human health and the environment. With increased urbanisation, the industrial revolution, and massive population demand on the NR, it remains a major problem that places significant strain on the worldwide environment. WM is divided into four categories: industrial, electronic, municipal, and biological waste, and each of these wastes is governed by specific rules (Fig. 21.2). Reducing, reusing, and recycling are the 4R concept principles of WM.

Several WM systems and technologies are available. These tactics can be joint/changed to develop a WM strategy that is appropriate for an organisation. Recent WM solutions are oriented at long-term sustainability. Other waste management options include reducing, reusing, and recycling garbage. In India, waste management strategy is based on trash creation, storage, collection, transportation, recycling, treatment, and disposal. Landfills, incineration, composting, and gasification are among of the most often employed WM processes (Saha et al. 2021).

## 21.4 Microorganisms in Waste Management

In WM, microbial biotechnology refers to the use of modern scientific tools and procedures to alter a variety of microorganisms in a supervised setting without upsetting the ecology. The most common and effective techniques utilised at different levels of WM are decomposition, biodegradation, bioremediation, and biotransformation. *Bacillus* sp., *Corynebacterium* sp., *Staphylococcus* sp., *Streptococcus* sp., *Scenedesmus platydiscus*, *S. quadricauda*, *S. capricornutum*, *Chlorella vulgaris*, and others have been used successfully for WM (Dimassi et al. 2022).

Microbes are also important in the usual reprocessing of living elements. All naturally occurring compounds are biodegradable. Microbes have shown to be beneficial in solving numerous challenges that humanity has faced in sustaining environmental quality. To mention a few, they have been used to treat municipal and industrial waste, protect the environment, and promote human, animal health. Bacterial technologies have effectively addressed a widespread ecological difficulty, including WM issues. Man's actions in his surroundings include a significant amount of chemical synthesis in the procedure of turning natural materials in the surroundings into more suitable forms for consumption.

Man produces environmental concerns throughout the manufacturing process. Thus, the utmost suitable solution to waste created in the environment is one that allows them to be easily integrated back into the ecosystem (Patel and Kasture 2014). This approach makes use of microbes. These bacteria or their products are mixed with substrates to create desired industrial goods such as bioleaching, biodetergent, pulp biotreatment, biofiltrations, aquaculture treatments, waste and textile biotreatment, biocatalysts, biomass fuel generation, biomonitoring, and so on. Microbes are also vital to people and the environment because they engage in the carbon and nitrogen cycles, as well as recycling the dead remnants and residual items of other creatures through decomposing. As symbionts, bacteria play an essential role in higher-order multicellular creatures (Kwok 2019).

### *21.4.1 Composting*

Composting is a quick and natural biodegradation method that turns organic wastes like flora remains, yard debris, and kitchen scraps into nutrient-rich plant food. A variety of bacteria help composting, which is a form of aerobic decomposition. The process of composting, which is frequently used in organic farming, involves leaving organic wastes in one place for months while microbes break them down. Since dangerous organic waste may be turned into safe compost, composting is usually regarded as one of the best methods of garbage disposal. Composting produces humus and plant nutrients as its primary by-products, with carbon dioxide, water, and heat as by-products. This process involves a numerous microorganism, like microbes, actinomycetes, yeasts, and fungus. Composting takes place in three stages: mesophilic, thermophilic, and cooling and maturation. Microorganisms, temperature, pH, moisture content, carbon and nitrogen ratio, and particle nature and size are all factors in composting (Mahitha et al. 2016).

### 21.4.2 Biodegradation

Biodegradation is the biological breakdown of chemical substances. Living microbial organisms are employed in this technique to breakdown organic molecules into smaller ones. Three steps make up the biodegradation process: biodeterioration, which weakens an object's structure mechanically; bio-fragmentation, which involves bacteria breaking down materials; and integration, which involves the insertion of the degraded material into fresh cells.

Various microorganisms have been discovered to be capable of decomposing hydrocarbons. These bacteria can biodegrade HC both aerobically and anaerobically, with anaerobic biodegradation being more important. A large range of microorganisms with HC-degrading abilities were isolated from the water ecosystems (Steensels et al. 2019).

Microorganisms linked with flora, like rhizospheric microbes and endophytic microbes, are excellent biodegraders of hazardous compounds in polluted soil. Plant growth-promoting rhizobacteria are naturally occurring microbes in the rhizosphere of flora roots and stimulate plant development. In most circumstances, the interaction between plant and bacterium is favourable to plants since the bacteria aid in N fixation and fill the earth with nutrients.

Aerobic microfungi are eukaryotic bacteria that range from single-celled yeasts to mycelial mold. Fungi, like microbes, have degrading abilities, and OM in a dissolved condition is effectively digested by them. Fungus may proliferate and thrive in low humidity and pH environments that are ideal for OM breakdown. Fungi having extracellular multienzyme complexes are thought to be the most effective biodegraders of natural polymeric substances. Mycorrhiza is a fungus–fungus relationship that occurs between the roots of vascular plants. Fungi can be intra/extracellular and have an important part in soil life. Although algae may biodegrade several types of HC, their role in HC biodegradation is currently underreported.

Plastics are chemically manufactured artificial polymeric materials that are ready for human use and, in many aspects, are extremely similar to natural resins. Because of its adaptability, it has established a presence in many parts of daily life. Besides being durable and stable, they also have acceptable mechanical and thermal properties, which make them widely used in our daily lives (Fig. 21.3). Monomeric HC is used to make plastics. Plastics are mostly created by the chemical reaction of raw ingredients that might be organic/inorganic. Plastics are classified into three kinds depending on their physical properties: thermosetting, elastomers, and thermoplastics and thermosoftening plastics (Table 21.1). They can also be classified based on their molecular structure (Hossain et al. 2022).

Plastics are largely non-biodegradable and are widely discarded after usage. As a result, widespread usage of plastic can pose a serious ecological peril to several habitats. The build-up of plastic waste has substantially affected land and aquatic environments. Plastic disposal is a big issue due to its widespread use and massive manufacturing. Chlorinated plastics also have a negative impact on the groundwater ecology (Atanasova et al. 2021).

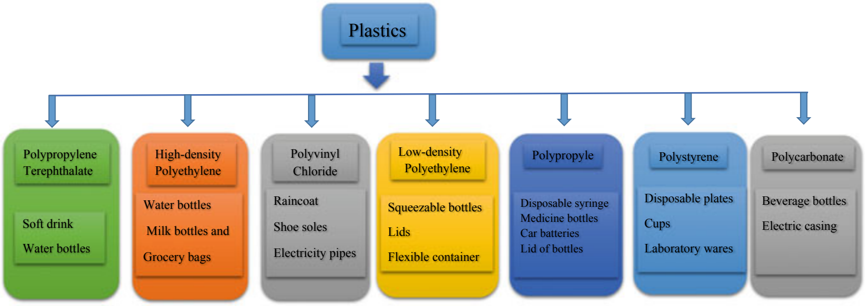



**Fig. 21.3** Synthetic plastics and its use

## *21.4.3 Bioremediation*

Bioremediation is a natural process that employs microorganisms to eliminate trash and pollutants from water and soil (Fig. 21.4). This technology is environmentally benign and sustainable since it uses eco-friendly bacteria to handle solid waste (Boni et al. 2022).

Bioremediation is a biotechnological process which lessens/eradicates contamination. Its WM approach which uses microbes to eliminate/devour contaminants from polluted areas. There are various methods for purifying polluted water or solids, including chemical treatment, burning, and burial in a landfill. Bioremediation is distinct in that it does not employ hazardous chemicals.

There are three types of bioremediations.

### 21.4.3.1 Bio-stimulation

Bio-stimulation means to start the procedure, the microorganisms are activated. The polluted soil is first blended with particular fertilisers and other important components, which are either liquid or gas. It promotes microbial development, leading in effective and rapid elimination of pollutants by bacteria and other microorganisms.

### 21.4.3.2 Bioaugmentation

Bioaugmentation means at times, microbes are necessary to remove pollutants from specific places. Consider municipal wastewater. Bioaugmentation is employed in these exceptional instances.

**Table 21.1** Microbes used in plastic degradation

| # | Source | Microorganisms | Plastic | References |
|---|---|---|---|---|
| 1 | Fungi | *Aspergillus flavus* | Polycaprolactone (PCL) | Muhamad et al. (2015) |
| 2 | | *Penicillium funiculosum* | Polyhydroxybutyrate (PHB) | |
| 3 | | *Aspergillus niger* | PCL | |
| 4 | | Streptomyces | PHB, PCL | |
| 5 | Actinomycetes | *Sporichthya* sp., *Actinoplanes* sp. | Polyethylene | |
| 6 | Bacteria | *Cyanobacteria* (*Calothrix*, *Pleurocapsa*, *Phormidium*), *Erythrobacter* | Polyethyleneb (72.2%) + PP (18.0%) and PS (2.8%) | Atanasova et al. (2021) |
| 6 | | *Arthrinium arundinis*, *Leptosphaeria* sp. | Polyethylene (PE) and/or polyurethane (PU) | Brunner et al. (2018) |
| 8 | | *Rhodococcus ruber* C208 | Low-density polyethylene (LDPE) | Mandal and Patil (2019) |
| 9 | | *Bacillus* sp., *Micrococcus* sp. | High-density polyethylene (HDPE) | |
| 10 | | *Pseudomonas* sp. | Poly(ethylene terephthalate) (PET) | Wilkes and Aristilde (2017) |
| 11 | | *P. fluorescens* | Polyester | |
| 12 | | *P. chlororaphis* | Polyester | |
| 13 | | *Arthrinium arundinis*, *Leptosphaeria* sp. | Polyethylene (PE) and/or polyurethane (PU) | Brunner et al. (2018) |

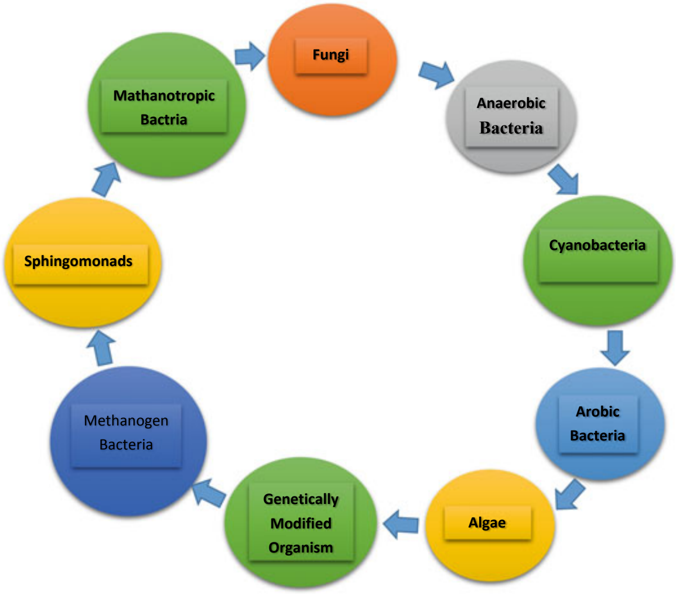



**Fig. 21.4** Biodegradation mediated by different types of microbes

#### 21.4.3.3 Intrinsic Bioremediation

Intrinsic Bioremediation means because soil and water are always contaminated with poisons and pollutants, the procedure of intrinsic bioremediation is greatest successful in these two biomes. Only microbes can therefore eliminate poisons and clean the tanks.

### *21.4.4 Biotransformation*

Biotransformation is the process by which harmful substances are converted into a less persistent and less toxic form. The principal groups of microbes are bacteria and fungus, and their enzymes are involved in this method. Microbe's cells are important for biotransformation for a variety of reasons, including surface-volume ratio, rate of microbial cell development, rate of metabolism, and sterility (Rai et al. 2023).

**Table 21.2** Microbes that perform best at bioremediating wastewater

| Type of microorganisms | Name |
|---|---|
| Bacteria | • *Bacillus cereus*<br>• *Bacillus subtilis*<br>• *Pseudomonas veronii*<br>• *Pseudomonas putida*<br>• *Stenotrophomonas*<br>• *Kocuria flava* |
| Fungi | • *Aspergillus fumigator*<br>• *Aspergillus versicolor*<br>• *Aspergillus niger*<br>• *Rhizopus*<br>• *Penicillium caneseens*<br>• *Ganoderma lucidum* |
| Algae | • *Chlorella*<br>• *Scenedesmus*<br>• *Phormidium*<br>• *Botryococcus*<br>• *Chlamydomonas*<br>• *Spirulina*<br>• *Oscillatoria*<br>• *Desmodesmus* |
| Yeast | • *Candida tropicalis*<br>• *Candida glabrata*<br>• *Saccharomyces cerevisiae*<br>• *Streptomyces longwoodensis* |
| Engineered microbes | • *Pseudomonas aeruginosa-NRRL B-5472*<br>• *P. putida* |

## *21.4.5 Performance of Microbes in WMS*

Microbes, fungus, algae, protozoa, rotifers, and other higher fauna are among the microorganisms that live in aerobic biological treatment systems (Table 21.2). The growth of any or all species of microorganisms in specific industrial trash disposal will be influenced by the chemical properties of the industrial waste, the ecological constraints of the specific waste system, and the biochemical properties of the bacterium (Gold et al. 2018).

### 21.4.5.1 Bacteria

In aerobic WTS, microbes are basic biological units. Microbial have the most important role in WW therapy. Microbes' complex metabolic nature allows them to digest the majority, if not all, organic chemicals present in industrial waste. The competitive ability of a species to get a portion of the obtainable organic material in the system determines its growth. Both autotrophic and heterotrophic bacteria are present in WW treatment systems, although heterotrophic bacteria predominate.

Microbial predomination typically divides into two broad groups: microbes that use organic compounds in waste and microbes that use the lysed harvests of the 1st cluster of microorganisms. The most important category of microorganisms and those that will decide the characteristics of the treatment system are those that utilise the organic substances in the waste.

Several major microbes discovered in WW treatment systems are *Achromobacter* sp., *Alcaligenes* sp., *Arthrobacter* sp., *Citramonas* sp., *Flavobacterium* sp., *Pseudomonas* sp., *Zoogloe* sp., *and Acinetobacter* sp. Bacterial are the most vital microorganisms capable of stabilising inflowing garbage in WW treatment systems. The fascinating thing is that the most of microorganisms are acknowledged to create unusual body masses that are clumps of microorganisms that breakdown waste and also function as waste absorption sites.

#### 21.4.5.2 Alga

Algae are the third type of biological plant that contributes to the overall stabilisation of organic wastes. Because algae get their energy for synthesis from daylight, they do not need to digest organic substances as microbes and fungus do. Algae are a powerful organism for biologically purifying WW because it can gather heavy metals, pesticides, and organic and inorganic contaminants.

#### 21.4.5.3 Fungi

Septic system treatment is dependent on fungi, which are multicellular organisms. Fungi have a vital function in organic waste stabilisation. Fungi, like bacteria, can digest nearly every form of organic chemical found in industrial waste. If fungus is cultivated with microbes under certain ecological conditions, they may compete with bacteria and also metabolise organic substances found in nature. Some fungi have also been shown to successfully break down OM present in the sewage system. In a low pH environment, fungus' main function is to break down OM, which prevents bacterial growth. It has been found that a number of filamentous fungi secrete enzymes that aid in the breakdown of substrates during WW treatment.

Fungi have the capacity to dominate microbes, but they do not do so except in exceptional ecological situations. Most fungi found in industrial waste are undesirable due to their filamentous character, unlike tight compact flocs, they settle easily. For this reason, much effort is devoted to improve ecological circumstances that favour bacteria predomination over filamentous fungal predomination (Brunner et al. 2018).

## 21.5 Advantages of Waste Management

Waste treatment and management have multiple benefits.

***Better Environment***
A cleaner and fresher ecosystem is the most obvious benefit of waste management. Systems for garbage disposal promote overall welfare and aid in maintaining people's health. The finest part is that whatever occurs as the extra is safely and hygienically disposed of. Multiple trash disposal facilities need to be constructed in tier 1 and tier 2 cities to prepare the garbage disposal process. It will also assist in the long-term implementation of fantastic safety precautions.

***Reduces Pollution***
When trash is handled effectively, it not only prevents the creation of further waste but also lessens the severity and impact of harmful GHGs like $CO_2$, CO, and $CH_4$, which are regularly released from accumulated landfill waste. WM decreases our dependence on landfills despite the fact it also greatly plummeting the various elements that have a bad influence on our ecosystem.

***Conserves Energy***
The crucial aspects of WM are reprocessing, which over time aids in energy conservation. The practise of recycling paper is one of the most notable examples of this advantage. There is far less need to cut down trees when used paper is recycled to generate new paper. This reduces your carbon impact while also saving power.

***Brings About Jobs***
The recycling industry alone generates hundreds of jobs. Businesses that produce and market recycled goods become increasingly well known as more people follow this ecologically beneficial strategy. This boosts their business and creates hundreds of jobs at the same time.

***Aids in Changing Things***
By limiting rubbish, we can also influence society and the world at large. We can all practise eco-friendly waste reduction and reuse even if none of us can completely eliminate trash. By doing this, we may serve as positive role models for individuals in our community who are now motivated to choose a more responsible approach (Wilkes and Aristilde 2017).

## 21.6 Conclusion

In order to keep ourselves and the surroundings safer, there are a number of important things we need to understand regarding waste management and disposal. Although it might not be immediately apparent, our decision benefits the environment and the ecosystem. As a result, constantly strive for sustainability and make concrete measures to control and treat trash.

The protection and sustainability of the ecosystem are regarded as top objectives that need for urgent attention on a global scale since they are important for future development.

The main areas that must be prioritised in order to ensure sustainability are waste management, conservation of natural resources and biodiversity, and treatment of toxins and pollutants. Numerous environmental issues can be resolved with the help of microbes. The use of microbes and bacteriological methods has also unlocked up new avenues for supportable growth, chiefly in ecosystem and other major environmental problems. Effective WM is directly impacted by community involvement and raising knowledge of sustainability. The notion of recycling and reuse has to be scaled up throughout the community.

## References

Abatenh E, Gizaw B, Tsegaye Z, Wassie M (2017) The role of microorganisms in bioremediation—a review. Open J Environ Biol 2(1):038–046

Adebayo FO, Obiekezie SO (2018) Microorganisms in waste management. Res J Sci Technol 10(1):28–39. https://doi.org/10.5958/2349-2988.2018.00005.0

Atanasova N, Stoitsova S, Krasteva TP, Kambourova M (2021) Plastic degradation by extremophilic bacteria. Int J Mol Sci 22(5610):1–19. https://doi.org/10.3390/ijms22115610

Behera S, Samal K (2022) Sustainable approach to manage solid waste through biochar assisted composting. Energy Nexus 7(100121). https://doi.org/10.1016/j.nexus.2022.100121

Boni AD, Melucci FM, Acciani C, Roma R (2022) Community composting: a multidisciplinary evaluation of an inclusive, participative, and eco-friendly approach to biowaste management. Clean Environ Syst 6:1–10. https://doi.org/10.1016/j.cesys.2022.100092

Brunner I, Fischer M, Ruethi J, Stierli B, Frey B (2018) Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. PLOS 1–14. https://doi.org/10.1371/journal.pone.0202047

Dimassi SH, Hahladakis JN, Yahia MND, Ahmad M, Sayadi S, Al-Ghouti MA (2022) Degradation-fragmentation of marine plastic waste and their environmental implications: a critical review. Arab J Chem 15:1–31. 104262. https://doi.org/10.1016/j.arabjc.2022.104262

Gold M, Tomberlin JK, Diener S, Zurbrügg C, Mathys A (2018) Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: a review Waste Manage 82:302–318. https://doi.org/10.1016/j.wasman.2018.10.022

Han P, Toe WZ, Yew WS (2022) Biologically engineered microbes for bioremediation of electronic waste: Wayposts, challenges and future directions. Eng Biol 6:23–34. https://doi.org/10.1049/enb2.12020

Hossain R, Islam MDT, Ghose A, Sahajwalla V (2022) Full circle: challenges and prospects for plastic waste management in Australia to achieve circular economy. J Clean Prod 368:1–25. https://doi.org/10.1016/j.jclepro.2022.133127

Jinjiri BA, Garandawa M, Sabo R, Mustapha AU (2018) An overview of microorganism in waste management and control. Int J Sci Res Publ 8(12):814–818. https://doi.org/10.29322/IJSRP.8.12.2018.p84100

Kwok R (2019) How bacteria could help recycle electronic waste. PNAS 116(3):711–713. https://doi.org/10.1073/pnas.1820329116

Leow CW, Fan YN, Chua LS, Muhamad II, Klemeš JJ, Lee CT (2018) A review on application of microorganisms for organic waste management. Chem Eng Trans 63:85–90. https://doi.org/10.3303/CET1863015

Mahitha U, Devi GD, Sabeena MA, Shankar C, Fast KV (2016) Biodegradation of waste cotton fibres from Yarn industry using microbes. Proc Environ Sci 35:925–929

Mandal S, Patil D (2019) Effective role of microorganism in waste management and environmental sustainability. Sustain Agric For Environ Manage 487–508. https://doi.org/10.1007/978-981-13-6830-1_14

Muhamad WNAW, Othman R, Shaharuddin RI, Hasni MSI (2015) Microorganism as plastic biodegradation agent towards sustainable environment. Adv Environ Biol 9(13):8–13

Pan SY, Tsai CY, Liu CW, Wang SW, Kim H, Fan C (2021) Anaerobic co-digestion of agricultural wastes toward circular bioeconomy. iScience 24(102704):1–23. https://doi.org/10.1016/j.isci.2021.102704

Patel S, Kasture AE (2014) (Electronic) waste management using biological systems-overview. Int J Curr Microbiol Appl Sci 3(7):495–504

Rai PK, Sonne C, Song H, Kim KH (2023) Plastic wastes in the time of COVID-19: their environmental hazards and implications for sustainable energy resilience and circular bio-economies. Sci Total Environ 858:1–15. https://doi.org/10.1016/j.scitotenv.2022.159880

Rastogi M, Nandal M, Khosla B (2020) Microbes as vital additives for solid waste composting. Heliyon 6:1–4. https://doi.org/10.1016/j.heliyon.2020.e03343

Saha AL, Kumar V, Tiwari J, Sweta, Shalu Rawat S, Singh J, Bauddh K (2021) Electronic waste and their leachates impact on human health and environment: Glob Ecol Threat Manag Environ Technol Innov 24:1–28. https://doi.org/10.1016/j.eti.2021.102049

Singh S, Parihar SS, Singh R, Saxena A (2020) The role of soil microorganism in municipal solid waste management. IJRAR 7(3):340–348

Singh SP, Sharma P, Bano A, Nadda AK, Varjani S (2022) Microbial communities in plastisphere and free-living microbes for microplastic degradation: a comprehensive review. Green Anal Chem 3(100030):1–11. https://doi.org/10.1016/j.greeac.2022.100030

Steensels J, Gallone B, Voordeckers K, Verstrepen KJ (2019) Domestication of industrial microbes. Curr Biol 29:R381–R393. https://doi.org/10.1016/j.cub.2019.04.025

Tiwari G, Singh SP (2014) Application of bioremediation on solid waste management: a review. Bioremed Degrad 5(6):1–8. https://doi.org/10.4172/21556199.1000248

Wilkes RA, Aristilde L (2017) Degradation and metabolism of synthetic plastics and associated products by *Pseudomonas* sp.: capabilities and challenges. J Appl Microbiol 1–13. https://doi.org/10.1111/jam.13472

# Correction to: Current Scenario on Conventional and Modern Approaches Towards Eco-friendly Electronic Waste Management

**Ponnusamy Karthika, G. K. Dinesh, Velusamy Sathya, Sangilidurai Karthika, Murugaiyan Sinduja, Sangilidurai Kiruthiga, Sudha Kannojiya, P. Sakthi Priya, Shiv Prasad, and Ravindra Soni**

## Correction to: Chapter "Current Scenario on Conventional and Modern Approaches Towards Eco-friendly Electronic Waste Management" in: P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*, https://doi.org/10.1007/978-3-031-25678-3_1

The original version of the chapter was inadvertently published with incorrect affiliation for co-authors "Sudha Kannojiya and Shiv Prasad". Both authors affiliation has been updated as "Division of Environment Science, ICAR-Indian Agricultural Research Institute (IARI), New Delhi, 110012, India".

The correction chapter and the book have been updated with the change.

The updated original version of this chapter can be found at https://doi.org/10.1007/978-3-031-25678-3_1



P. Debbarma et al. (eds.), *Microbial Technology for Sustainable E-waste Management*, https://doi.org/10.1007/978-3-031-25678-3_22