Journal of Material Cycles and Waste Management
https://doi.org/10.1007/s10163-023-01717-5

REVIEW

Recovery of precious metals from e-wastes through conventional and phytoremediation treatment methods: a review and prediction

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Received: 24 October 2022 / Accepted: 23 May 2023

Abstract

E-waste, also known as waste from electrical and electronic equipment, is a solid waste that accumulates quickly due to high demand driven by the market for replacing newer electrical and electronic products. The global e-waste generation is estimated to be between 53.6 million tons, and it is increasing by 3–5% per year. Metals make-up approximately 30% of e-waste, which contains precious elements Au, Ag, Cu, Pt, and other high-value elements, valued at USD 57 billion, which is driving the e-waste recycling industry. It is noteworthy that the recycling of precious elements from e-waste has emerged as a profitable enterprise in several parts of developing nations. E-waste contains 50–100 times higher levels of precious metals compared to natural ores, making it suitable for mining. E-waste recycling in developing nations, mostly occurs through the informal sector comprising manual collection, crushing, segregation and selling of precious elements, such as Au, Ag, Cu, Pb, Pt, and other rare elements (Nd, In, and Ga). The organized sector, on the other hand, mostly employs mechano-chemical methods, such as pyrometallurgy, hydrometallurgy, and bio-hydrometallurgy, which have serious environmental consequences. Both the informal and formal sectors of e-waste processing lead to the leaching of toxic elements into groundwater and soils. Owing to the lesser efficiency of greener technologies, such as phytoremediation and bioremediation, their use in precious metal extraction is very limited. However, this review explores several hyper-accumulating and tolerant plants viz. *Brassica juncea* and *Berkheya coddii*, which holds great potential in phytomining of precious metal from e-waste. Thus, the state of the art in precious metal extraction from e-waste as well as the advantages and disadvantages of different metal extraction technologies has been reviewed.

Keywords E-waste · Precious metals · Phytomining · Hyper-accumulation · Gold · Silver

Introduction

In 1995, the governments of 193 nations adopted the 17 Sustainable Development Goals (SDGs) with the collective aspiration to eradicate poverty, protect the planet, and ensure peaceful and prosperous lives by 2030 [1]. Additionally, in pursuit of attaining a carbon–neutral society by 2050, as per the "Paris Agreement" on the issue of climate action, most nations are shifting from conventional energy sources to renewable energy generation, particularly in the transportation sector [2]. The electric mobility has exacerbated the dependency on metals more than the fossil fuel. The consumption of metals, such as aluminum (Al), cobalt (Co), copper (Cu), iron (Fe), lithium (Li), manganese (Mn), and nickel (Ni), in the electric vehicle industry is expected to increase. To attain a low carbon economy, the dependency on 17 metals, silver (Ag), Al, Co, chromium (Cr), Cu, Fe, graphite, indium (In), Li, Mn, molybdenum

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(Mo), neodymium (Nd), Ni, lead (Pb), titanium (Ti), Vanadium (V), and zinc (Zn) is projected to increase in the next 30–40 years [3]. Additionally, in the present global scenario, the advent of cheaper, feature-rich, faster, and compact electronic computing gadgets is replacing the older technologies, much before their "end-of-life" usage. Due to the limited lifespan of electronic and electric products, the world has witnessed an unprecedented rise in waste generation since the late 1980s. On average, the replacement of handheld mobile phones is 1.5 years and personal computing devices (desktop or laptop) is 2 years in developing nations in 2005 and much less in developed nations [4, 5]. On the other hand, the conventional waste management system is not improving at a similar rate to match the pace of e-waste generation. Hence, the scrap materials from electronic products have exacerbated the generation of e-waste and its management has posed a challenge through conventional solid management methodologies. Due to its heterogeneous composition and associated hazards, residents living in the vicinity of e-waste recycling areas are at a high risk of exposure [6].

E-waste is a generic name, considered collectively for discarded electronic devices and/or electronic components [5]. Generally, metals comprise approximately 50% of the total e-waste [7]. The remaining consists of ceramics, refractory oxides, and plastics along with several hazardous substances, such as chlorofluorocarbons (CFCs), polycyclic hydrocarbons, poly-brominated biphenyls, dioxins, epoxy resins, polychlorinated biphenyls, fiberglass, and polyvinyl chlorides [8]. E-wastes are among the fastest growing wastes, with an annual growth rate of 3–5% [9]. Only about 17% of the e-waste is collected and recycled, and the rest ends up in landfills and waste dumps [10]. There is a considerable variation in the estimation of global e-waste generation viz. 53.6 million mega tons (Mt) [10], 40 Mt [11], 52.2 Mt [12], and 44.7 Mt [13]), an average, of 47.62 Mt generated globally. Out of the total of 53.6 Mt of e-waste generated globally in 2019, a major share of 24.9 Mt was generated from Asia, with China (10.129 Mt) and India (3.230 Mt) with estimated formal recycling rates of 34.6% and 5%, respectively [10, 14, 15]. The per capita e-waste generation in 2014 and 2016 was 5.8 and 6.1 kg per person, respectively. With the rise in e-waste generation by 3% per annum, the global e-waste generation is projected to reach 74.7 Mt and 243 Mt by 2030 and 2050, respectively [10, 16, 17]. The estimated net worth of e-wastes was estimated to be USD 61.05 billion and Euros 55 billion [18] in 2016 globally whereas, the value of e-wastes from United States of America (USA) alone amount to be about USD 57 billion [10, 19]. Furthermore, Greenpeace International reported that the contamination levels due to e-waste recycling in China and India were 80% higher than in the rest of the world [20].

Apart from containing hazardous constituents, e-wastes are rich secondary sources of rare earth elements (REEs) and precious metals, such as Ag, Au, Pd, and Pt [21]. Thus, they are termed as "sleeping mines", which are reported to contain about 40–50 times higher element concentration than the natural mines [22]. The worth of e-waste in 2016 was estimated to be USD 61.05 billion from 44.7 Mt [12] containing about USD 21 billion worth of precious metals, including Au (0.5 kilotons), Ag (1.6 kilotons), Pd (0.2 kilotons) [23]. According to the United States Environmental Protection Agency (US EPA), the global annual consumption of Au and Ag are 320t and 7500t, respectively [23] and the electronic industry is a major consumer. It is estimated that e-waste contains 10–1000 g ton^{-1} of Au as compared to 0.5–13.5 g ton^{-1} in natural ores [24], making it a rich source for Au. Similarly, from 1 ton of e-waste, 0.347 kg of Au, 0.15 kg of Pd, 3.63 kg of Ag, 128 kg of Cu, 15 kg of Ni, 6 kg of Pb, 1 kg of Sb, and 10 kg of Sn can be recovered [18]. About 40 tons of Au is contained in 0.5 Mt of scrap printed circuit boards (PCBs) [25], whereas, 200–350 g of Au is present in a ton of mobile phones, in contrast, 5 g of Au is present in a ton of gold ore [18]. Similarly, other precious metal contents (g t^{-1}) range between 0 and 30 for Pt, 0 and 3300 for Ag, and 0 and 294 for Pt [8]. Hence, compared to the natural Au ores, which contain about 0.2–13.5 g t^{-1} of Au [26], e-waste has significantly higher content (0–1000 g t^{-1}), thus making it a lucrative resource for Au extraction [23]. However, the recovery percentages of Au and Ag are 0.1% and 0.2%, respectively from e-waste through conventional techniques [27]. Alternately, there has been a tenfold increase (from 7 in 1900 to 68 billion tons in 2009) of virgin material extraction from ores, which is further likely to increase by 40 times since 1900 [28]. In view of the present rate of metal extraction from ores, the reserves are projected to deplete within next 50 years, including the precious and the REEs [29, 30]. Hence, extraction of precious metals from e-waste holds an immense potential for reducing significant pressure on the global supply of precious and REEs.

Without a proper e-waste management policy/system, this discarded electrical and electronic equipment is expected to overwhelm the existent municipal solid waste management systems, in most of the developing nations. The present e-waste management practices, i.e., dumping of e-waste in landfills and incineration, are not environmentally friendly owing to the high risks of health hazards and lack of space [7] and therefore unsustainable. As a result, e-waste recycling and other non-conventional management methods, integrating several green approaches offer potentiality for an enterprise with long sustainability for future generations. In view of this, there has been a surge in review articles on e-wastes in recent past (for example, between 2020 and present), research and review articles on various topics of e-waste generation and precious metal recovery are presented in Fig. 1. In contrast, reviews on recovery of precious metals involving biological, chemical and physical

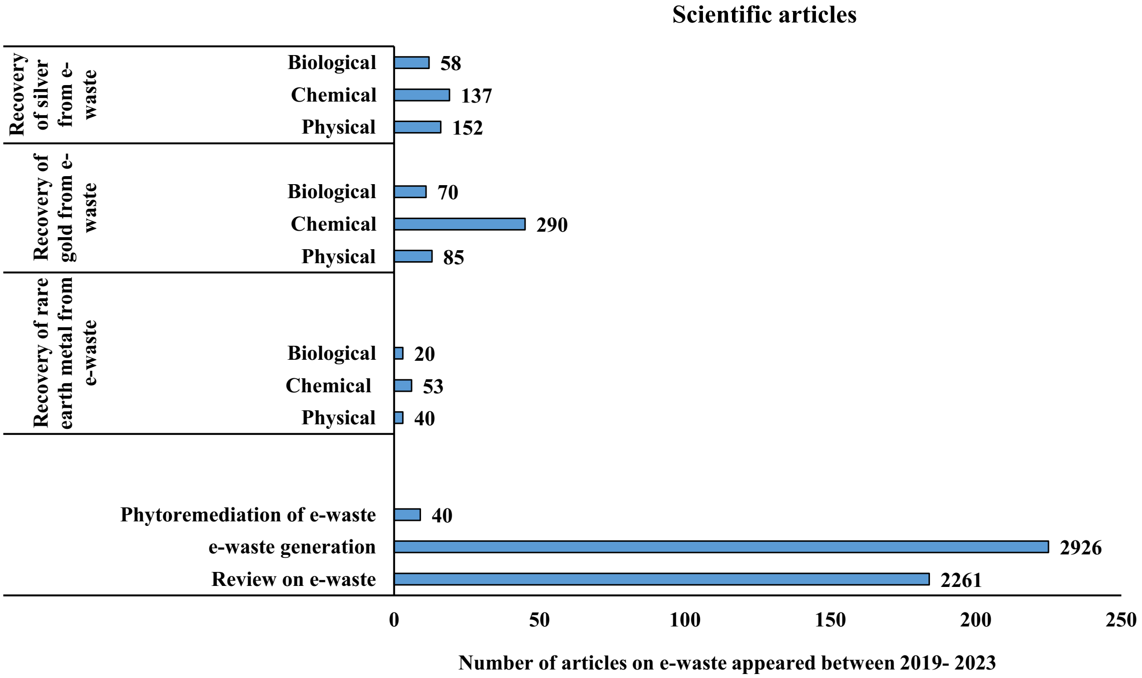


Fig. 1 Number of scientific articles appeared on recovery of precious elements between 2020 and 2023. The values against the bars on the right are the total number of citations of these articles. The number of articles presented in the figure has been considered for the articles exclusively appearing on the topic of recovery of elements from e-waste

processes are relatively few, and furthermore articles on phytoremediation are minuscule [9]. Hence, the present review accounts for the prevalent e-waste management practices for the recovery for precious metals, the extraction efficiencies through conventional physico-chemical and bio-metallurgical procedures, uptake efficiencies of precious metals by different tolerant plants, and the estimated projection of the phytominable Au and Ag from PCB wastes, till 2050. The review also highlights the advantages and disadvantages of each procedure and proposes a conceptual framework for phytomining of precious metals through aquaculture.

Overview of e-wastes

Definition and composition of e-wastes

E-waste, also known as electrical waste and electronic equipment (WEEE), which is defined by the European Union (2020) as any discarded equipment that operates on electric current or electromagnetic field. Furthermore, e-waste can be divided into six different categories, namely [31–33]:

(a) Temperature exchange equipment (refrigerators, heaters, air conditioner),
(b) Screen and monitors (televisions, laptops, monitors, notebooks, tablets),
(c) Lamps (fluorescent lamps, light-emitting diode (LED) lamps, high-intensity discharge lamps),
(d) Large equipment (large printing machines, washing machines, dryers, electric stoves),
(e) Small equipment (ovens, microwave, toasters, electric shavers, calculator), and
(f) Small information technology (IT) and telecommunication equipment (mobile phones, calculators, global positioning system (GPS), routers, printers).

E-waste, being a complex and heterogeneous waste comprising both recyclable and non-recyclable hazardous components i.e., plastic, glass, wood, rubber, metal, and other items [33, 34], has kindled the interest of scholars, policymakers, and entrepreneurs for its reuse, management, and recovery. It is generally composed of 30% organic (polymers, flame retardants, and glass fibers), 30% ceramic (silica, mica, and alumina), and 40% inorganic components (ferrous and non-ferrous metals) [35]. The higher composition of inorganic components includes various metals, including base metals (Al, Sn, Cu, and Fe), noble metals (Ag, Au, and Pd), heavy metals (HMs) (Ni, Cd, Cr, Zn, Pb, and Hg) and REEs (Ga, Pt, and tantalum group elements) [32, 35]. The heterogeneous component in e-waste increases the complexity of e-waste management, combined with inefficient techniques of its processing, results in a huge burden on the ecosystem and carbon footprint. It is noteworthy that the concentration of precious metals and REEs is significantly higher in e-waste compared to their respective ores. Hence, the extraction of valuable metals form e-waste stream is a lucrative enterprise. For example, the level of Au in PCB waste is about 100 times greater as compared to the natural ores [36]. Thus, integrated recycling and metal recovery techniques have great prospects for extracting precious metals and reusable materials from the e-waste stream.

Existing e-waste management practices

Landfilling and incineration have been among the most common and cost-effective methods of disposing e-wastes in developing nations. Landfilling is the most adopted method for waste dumping with minimal input cost, whereby the waste is directly disposed of with minimal equipment, energy, and material recovery [37]. Alternatively, incineration is also a prevalent waste management technique for significant waste reduction in both volume and matter. Several organic components are altered or converted to fewer hazardous compounds during combustion [37, 38]. However, these methods are environmentally unsafe due to the release of several environmental contaminants with high carbon footprint.

E-waste dumping has led to the contamination of various hazardous chemical substances, i.e., Pb, Cd, and Hg, in the soil through leaching, contamination of groundwater, and loss of soil fertility [39, 40]. For instance, glass in cathode-ray tubes (CRTs) of 2nd- and 3rd-generation computer monitors and televisions contributes to the leaching of Pb and Cd [38]. Heating the polyvinyl chloride (PVC) and PCB emits toxic fumes comprising of polycyclic aromatics (PCAs), polychlorinated dibenzofurans (PCDFs) and poly-chlorinated dibenzo-para-dioxins (PCDDs), that are mostly carcinogens along with other polluting gases like nitrogen oxides (NO_x), carbon dioxide (CO_2), and sulfur dioxide (SO_2) [38, 41, 42].

Despite these risks, landfilling is still employed for e-waste disposal in several countries, including developed nations i.e., USA and several low- and middle-income countries (LMICs) i.e., India, China, and Malaysia [37, 38, 43]. For instance, annually, India produces over 400,000 tons of e-waste domestically, and about 90% of it is not formally recycled and properly disposed [44]. However, some nations, such as Australia, have banned the dumping of e-waste into landfills to encourage the safe management of hazardous components and recovery of valuable materials [41]. Several Asian and African nations employ informal e-waste recycling, adopting primitive recycling techniques, such as manual dismantling, open burning, PCB recycling, plastic fragmentation, and melting. Dismantling is the most time-intensive job, however its efficiency is higher than other methods, by employing a large workforce. This results in contamination of adjoining soil and water streams with hazardous contaminants [45–47]. Moreover, the current gaps in e-waste legislation have enabled many developing nations i.e., Bangladesh, Bhutan, Indonesia, Kenya, Malaysia, Nigeria, Philippines, Sri Lanka and South Africa to import e-waste without any proper policy for its management [35, 46]. About 50–80% of the global e-waste is being exported to developing countries, especially Asian and African nations for recycling [48], in contrast to their individual low e-waste collection rates of 15% and 0%, respectively [49].

Exposure and health effects of e-waste

Residents living in the vicinity of e-waste recycling areas are at high risk of exposure to multiple toxic chemicals, including organic flame retardants, chlorofluorocarbons, polycyclic aromatic hydrocarbons (PAHs), poly-brominated diphenyl ethers (PBDEs), and polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs), as well as inorganic HMs, such as Pb, Cd, Hg, and Ni [50]. PCBs contribute mostly towards the adverse health effect through the release of toxic fumes during incineration or leaching. Endocrine disrupting chemicals (EDCs), such as phenols (-OH), phthalates $[C_6H_4(CO_2C_8H_{17})_2]$, parabens (4-Hydroxybenzoic acid), flame retardants, and HMs, could harm human reproductive health and growth [6]. Poly-brominated diphenyl ethers (PDBEs) lead to thyroid hormone disruption, neuro-developmental deficits and carcinogenic effects [51]. Exposure to endocrine disruptive chemicals (EDC) can affect physiological processes in pregnant women and developing fetuses, potentially jeopardizing early development and exposing the fetus to later health risks [6, 52]. Chronic exposure to e-waste has been positively correlated with deoxyribonucleic acid (DNA) lesions, telomere attrition, inhibited vaccine responsiveness among children, elevated oxidative stress, and altered immune function [6].

Children have the potential to develop lower cognitive scores, slower sensory processing difficulties, disruption of thyroid function, attention-deficit hyperactivity disorder due to blood Pb, lower lung function levels including forced vital capacity (FVC) and forced expiratory volume (FEV1) through exposed to various chemicals from e-waste [6]. Children have higher basal metabolic rates and immature systems that may not be able to excrete the toxic overload through various means of exposure (breastfeeding, placental exposure and repetitive mouth-to-mouth behaviors) [53]. The open-air combustion of e-waste incineration (commonly used for precious metals recovery i.e., Au, Cu, Ag) significantly contributes to fine particulate matter (PM) in ambient air which is potentially harmful to patients with cardiovascular and lung diseases [54]. Residents living in e-waste dismantling environments had increased exposure and body burden of PCBs and specific PBDEs, leading to abnormal alteration in hematological markers [55]. A study in India found that toxic air pollution from burning e-waste correlated with high levels of ambient HMs, which were linked to increased cardiovascular morbidity and hypertension among adult residents in the vicinity [56].

E-waste recycling and metal recovery technologies

E-wastes are reported to contain 69 elements including several precious elements. The use of precious metals, such as Au, in electronic components is prevalent owing to their high conductance and chemical stability [57]. The electronic industry is estimated to use about 300 tons of Au annually [58]. Moreover, the use of Au in computers has quadrupled from 1 g in first-generation computers to 4 g in contemporary computers [59]. Amongst the different components of e-waste, PCBs which constitute about 3–6% of the total e-waste, are the most valuable e-waste in view of their high precious metals' content and can fetch more than 40% of the revenue [60]. However, as of 2016, the worldwide recycling rate of e-waste remains low at 20%, and does not receive the attention it deserves [27]. It is estimated that about 30% of the PCBs are recycled, while the remaining 70% of waste, comprising PCB scraps, cannot be effectively recycled without the pre-removal of toxic substances, i.e., BFRs [61].

Besides, recovering precious metals from e-wastes recycling of the metals also lowers CO_2 footprint, as it consumes less energy than extracting the same form virgin metal ores. It is estimated that 17,000 tons of CO_2 are emitted per ton of Au extracted from natural mines [62], on the other hand, Europe alone is losing USD 10 billion worth of metals and 4 million tons of CO_2 saving potential annually by not recovering metals from e-waste [63]. Processing 1 ton of mobile phone (e-waste) can yield 0.2–0.35 kg of Au, compared to Au ore, which yields about 0.05 kg [64]. The Au content in the gold mines around the world ranges from 0.33 g t^{-1} in Alaska [65] to 0.2 g t^{-1} in the Philippines [26], while the Au, Ag, and Pd content (g t^{-1}) of PCBs are 2.5, 100, and 11, respectively [7]. In addition, recovering metals and other precious elements in e-waste also offers business opportunities, as it creates a new life cycle for electrical and electronic equipment products [42]. For instance, a few computer components can be reused to assemble computers for serving basic computing purposes in rural primary schools and offices, while the remaining materials can be used in various ways for construction, flatware, and jewelry [38, 66].

Conventional e-waste recycling processes

Recycling of e-waste through material recovery, comprises three major steps, (i) collection, (ii) pre-treatment, and (iii) recovery of valuable materials [41]. The collection of e-waste is a vital step that requires both public awareness and strong government policy to facilitate efficient collection systems and create necessary infrastructure. The next step involves the segregation of e-waste components into recyclable and non-recyclable materials, followed by the dismantling of collected e-waste and sorting it into different batches of metals, plastics, and rubber from various sources, i.e., batteries, PCBs, cathode ray tubes (CRTs), and liquid crystal displays (LCDs) [41, 67]. The metals in the e-waste components are then extracted and recovered using established metallurgical processes, such as pyrometallurgy, hydrometallurgy, bio-metallurgy, or a combination of these methods [34, 41, 67]. In recent years, there have been increasing studies on the efficiencies of potential procedures and processes for precious metal recovery from various e-wastes [68–70]. In addition, novel methods such as "waste treating waste" such as utilising PCBs as catalyst in wastewater treatment has also been explored [71].

Physical separation

A physical separation technique is required to segregate each component into a few categories as different waste components adopt varying recycling routes. In this step, all the reusable materials, such as capacitors, resistors, keys, light emitting diodes (LEDs), and transistors, are recovered. E-waste scrap materials are screened according to their size and shape, and the waste is segregated into non-metal and metal classes before undergoing any further recycling process [33, 67]. These procedures can be performed using industrial machineries, such as shredders and granulators [34, 41]. On an industrial scale, the separation between metal and non-metal materials from e-waste can be performed using several techniques, such as magnetic separation, eddy current separation, electric conductivity-based separation, and density-based separation, based on the physical properties of the e-waste components [33, 41, 67, 72]. Additionally, a selective flotation approach is also recognized as good alternative to the conventional separation methods, specifically for separation of plastics constituents in e-waste [73].

Pyrometallurgy

Pyrometallurgy is a conventional technique that has been widely used for over 30 years to recover valuable metals [33, 34, 74]. Pyrometallurgy involves thermal treatment of e-waste through conflagration, smelting in furnaces or alkali chemicals, drossing, sintering, plasma melting and other solid–liquid–gas reactions, at high temperatures for the recovery of valuable metals [41]. The process is performed in two steps: pre-combustion (600–800 °C) and post-combustion (900–1200 °C) [57]. The smelting process is an economic and efficient method of pure metal recovery; however, it may not be suitable for alloys and metal mixtures. Since Cu accounts for about 70–80% among all the metal in the e-waste, pure Cu recovery (99%) through smelting (> 1250 °C) followed by a conversion process, remains a popular method [23], although, other precious elements are left over after the process.

Pyrometallurgical methods make metal recovery easier from PCBs by feeding the recovered PCBs into an incinerator or blast furnace to remove the non-metallic fractions. Consequently, the enriched metal is collected in a molten bath or slag and can be further processed using hydrometallurgical or electro-refining methods [31, 34, 41]. This method is often used to recover Cu, Au, Ag, Fe, Al, and Pd [31]. However, the process is highly energy-intensive, requiring high temperatures (300–900 °C), and can also generate toxic gases involving corrosive acids like H_2SO_4, HCl, and HNO_3 [75]. The release of PBDEs from PCBs and e-waste during pyrometallurgy and the formation of dioxins during combustion are also potential hazards [74, 76]. Moreover, Cu present in PCBs catalyzes dioxin formation during the combustion process [77]. In view of the limitations of pyrometallurgy, special attention must be paid to the treatment of harmful gases released during the process for sustainable metal recovery, with the surge of e-waste generation [76].

Hydrometallurgy

The hydrometallurgical method has been considered as an alternative to the pyrometallurgical process owing to its low energy requirements, lesser release of hazardous substances, operability in batches under containment and is economically viable [67, 72]. Hydrometallurgy consists of two stages: (i) leaching, whereaqueous chemicals solubilize the metals at low pH, and (ii) recovery, wherethe leached metals are recovered from the polymetallic leached solution [72]. In this process, the targeted metals are leached into solutions consisting primarily of acids, such as H_2SO_4, HCl, HNO_3, aqua regia solution, and a few alkalis [40, 66]. Various lixiviants, such as cyanide (CN^-), thiosulphate, thiourea (CH_4N_2S), and halide, are also used extensively [41, 72, 78]. Recovery efficiencies of various metals are influenced by varying particle sizes, types and concentrations of solvents, temperature and contact time between solid and liquid (Table 1).

Acid leaching is the most popular leaching method with many advantages, including high washing speed and fast kinetics. However, this method has several disadvantages and problems, as it is completely corrosive. Cyanide leaching, alongthiourea and thiosulfate, is the least dangerous washing method for Au extraction. Nevertheless, the poor stability of thiourea and the slow kinetics of thiosulfate have made it necessary to dependend on these compounds for large amounts of reagents [80].

Moreover, CN leaching is commonly preferred owing to its higher leaching efficiency, operational simplicity and lower operational cost. Cyanide acts as a strong lixiviant for the recovery of precious metals. Above pH 10.5, most of the cyanide exist in ionic form (CN^-), which enhances the efficiency of metal recovery [91]. The extraction of Au from various sources using CN^- has been a predominant practice due to efficient of Au selectivity and stability of dicyanoaurate complex formed, as described in Eq. 1.

$$4\mathrm{Au} + 8\left(\frac{\mathrm{K}}{\mathrm{Na}}\right)\mathrm{CN} + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} \rightarrow 4\left(\frac{\mathrm{K}}{\mathrm{Na}}\right)[\mathrm{Au(CN)}_2] + 4\left(\frac{\mathrm{K}}{\mathrm{Na}}\right)\mathrm{OH} \tag{1}$$

$$\text{Overall: } 4\mathrm{Au} + 8\mathrm{CN}^- + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} \rightarrow 4\mathrm{Au(CN)}_2^- + 4\mathrm{OH}^-$$

During cyanidation of metals, initially CN^- is oxidized to cyanate (OCN^-), thereafter it reacts with metals forming metal complex [62] Eq. 2.

$$4\mathrm{Au} + 8\mathrm{CN}^- + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} \rightarrow 4\mathrm{Au(CN)}_2^- + 4\mathrm{OH}^- \tag{2}$$

The CN^- leaching of Au and Ag from the surface of PCB is effective; however, the simultaneous dissolution of Cu, can reduce the overall efficiency [62]. Moreover, there are several limitations, such as temperature, pH, area of contact for e-waste, and the presence of interfering ions which affect the leaching efficiency. Additionally, CN leaching produces an enormous quantity of toxic waste. Alternatively, in view of the toxicity and hazard involved with CN^-, lesser toxic lixivants, such as thiourea, ferrous sulfate, halide, and thiosulfate, are also preferred [25]. Sodium thiosulfate ($Na_2S_2O_3$) and ammonium thiosulfate [$(NH_4)_2S_2O_3$] are used extensively as lixiviant for Au solubilization. The Au dissolution using $(NH_4)_2S_2O_3$, is an electrochemical reaction catalysed by Cu^{2+} ion, as represented in Eq. 3 and Eq. 4 [57].

$$\begin{aligned}\mathrm{Au} + 5(\mathrm{S}_2\mathrm{O}_3)_3{}^{2-} + \mathrm{Cu(NH}_3)_4{}^{2+} &\rightarrow \mathrm{Au(S}_2\mathrm{O}_3)_2{}^{3-}\\ &+ 4\mathrm{NH}_3 + \mathrm{Cu(S}_2\mathrm{O}_3)_3{}^{5-}\end{aligned} \tag{3}$$

$$\begin{aligned}2\mathrm{Cu(S}_2\mathrm{O}_3)_3{}^{5-} + 8\mathrm{NH}_3 + \frac{1}{2}\mathrm{O}_2 + \mathrm{H}_2\mathrm{O} &\rightarrow 2\mathrm{Cu(NH}_3)_4^{2+}\\ &+ 2\mathrm{OH}^- + 6\mathrm{S}_2\mathrm{O}_3{}^{2-}\end{aligned} \tag{4}$$

Although, the leaching of Cu by thiosulfate process, forming Cu(II)-NH_3 complex and S_2O_3, is stable at 9–10 pH, an alternative method of Cu leaching from PCB waste using H_2SO_4 and H_2O_2, followed by thiourea treatment along with Fe^{3+}, has resulted in greater Au and Ag recovery (85.76% and 71.36%), respectively [92]. The optimization of the Cu and NH_3^+ ions ratio in the S_2O_3 solution is

Table 1 Various leaching methods reported

Leaching methods	Advantages and limitations	Conditions and leaching agents	Metal recovery	References
Inorganic acid leaching	Advantages: • High yield and metal leaching Limitations: • Corrosive • High generation of toxic effluents • Extremely toxic	180 g/L H_2SO_4, H_2O_2, 80 °C, 3 h	95% Cu	[79] [80]
		100 mL HCl, 60 °C, 3–4 h	Cu, Pb	[68]
		500 mL aqua regia—HCl and HNO_3 (3:1), 24 h	95.50% Au 1.26% Cu	[69] [80]
		18 h Citric acid, pH 2.43, 24 h 5 days leaching (contact) time	78% Cu Cu (86%) Zn (88%) Cr (90%) Ni (96%)	[81]
		1.0 mol/L sulfuric acid, hydrogen peroxide 17%, 50 °C, 234 min	Cu (99%)	[82]
Thiourea leaching	Advantages: • Less toxic • Efficient recovery of precious metals Limitations: • High cost • Generation of by-products • High reagent consumption • Strict monitoring of reaction parameters	24 g/L thiourea, 0.6% of Fe^{3+}, room temperature	90% Au 50% Ag	[83]
		20 g/L thiourea, ferric (III) 6 g/L in 10 g/L sulphuric acid at 600 rpm for 3.5 h	82% Au	[25]
		60 g/L thiourea, 2 M H_2SO_4, 0.5 M H_2O_2, 1 h, 60 °C	90% Au 100% Ag	[84] [80]
Thiosulphate leaching	Advantages: • Non-corrosive • Less toxic Limitations: • Slower kinetics • pH sensitivity and low stability	0.12 M thiosulfate, 0.2 M ammonia and 20 mM copper as oxidizing agent	98% Au	[85] [80]
		0.5 M NH_3, 1 M ammonium salt, 50 mM Cu^{2+}, 24 h, 300 rpm agitation	99% Cu	[86]
		10 mM CuSO4, 1 M $Na_2S_2O_3$, 1 M ammonium, 24 h	99% Au	[87]
Halogenated leaching	Advantages: • High leaching rate Limitations: • High cost • Highly corrosive • Specialized equipment required	Solid/liquid ratio is 1:10, contact time 4 h, pH 7; 1.1% iodine Concentration	97.5% Au	[88]
		Aqua regia and HF-HCl-HNO_3-H_3BO_3, 400 rpm agitation	Cu	[89]
		3% Iodine solution, 1% H_2O_2 with solids percentage of 15%, 170 rpm agitation	99.85% Au	[90]

the determining factor for the precious metal recovery. The increase in thiosulfate from 0.1 to 0.14 M, increases Au leaching, but a further increase in concentration decreases the Au recovery [93]. Despite the advantages of S_2O_3 process, i.e., high selectivity, non-toxic and being less corrosive, it has some limitations. There is a loss of about 50% of Cu contained in the ammonical thiosulfate [57], and it requires high energy during extraction [19, 94], limiting its widespread application at the industrial level [95]. Nevertheless, leaching of about 90% Au and 50% Ag has been achieved from PCB of mobile phones using thiourea [83].

Moreover, ammoniacal leaching solutions of multicomponent alloy had higher selectivity towards Cu [86] due to the formation of copper(I) thiosulfate complex and precipitation of copper(I) sulfide. Oishi et al. [96] reported that the use of an ammonium solution for the leaching and recovery of Cu from PCBs. For precious metals, about 95% of Au was selectively recovered from ammonium thiosulfate leaching [87].

Furthermore, halide leaching is a non-cyanide leaching that involves halogens, such as Cl^-, I^-, or Br^-. The prime advantage of halide leaching compared to CN leaching is its powerful oxidizing ability, leading to a rapid metal dissolution. Cui and Anderson [89] reported the recovery of about 95% of the valuable metals viz. Ag, Cu, Au, Ni, and Pb from shredded PCBs by Br leaching. Additionally, the recovery of Au from PCBs using an iodine–hydrogen peroxide (I_2–H_2O_2) solution containing 3% of iodine, under two experimental conditions, i.e., shake flask tests (99.98%) and semi-pilot tests (99.85%) was reported [90]. The process reported 100% Au recovery using 3% I, 1% H_2O_2, and 15% solid concentration. Furthermore, Yaashikaa et al. [61] found NaCl as the most suitable lixiviant. After obtaining Au and Ag in solution, the metals were recovered and collected at the anode. The efficiency of Au and Ag leaching using iodide (I^-) as lixiviant is dependent upon the iodine (I_2) and I^- ratio [97, 98]. Low I_2 concentration generates lesser I^- formation leading to weaker metal complexation and eventually pricipitation of metal-iodide complex. However, higher I_2 concentration has the tendency of forming a greater complex with base metals and leach over the precious metals.

Following the leaching process, a selective separation technique for certain metals or elements is necessary for metal recovery. This recovery process can be performed by a variety of methods, such as solvent extraction [99], ion exchange [100], electrodeposition [101] and adsorption [67]. Each metal element may have different optimization techniques and conditions for refining and fully recovering targeted metals from the leaching solution (Table 2).

Solvent extraction is one of the recovery techniques that primarily depends on the relative solubilities of the targeted metals and solution. Due to its simplicity and shorter operating time, many studies have discovered solvent extraction as a method for recovering metals from e-waste as part of the management process. For example, Sadeghi and Alamdari [115] applied solvent extraction with tri-butyl phosphate (TBP) to recover (about 95.16%) of Au(III) from Cl leachates. Raiguel et al. [116] successfully recovered Au from Cu-rich sources using diethyl carbonate (DEC).

Furthermore, with the development of chelating and ion-exchange resins, ion-exchange methods provide a few advantages, including ease of use, no phase disengagement, no reagent losses, environmental safety as well as economic feasibility for low metal ion concentrations [67]. Goc et al. [110] studied the use of three commercial ion-exchange resins (Puromet MTS9200, Puromet MTS9850 and Lewatit K 6362) for the recovery of Pt, Pd, Rh, and Au. Among these resins, Puromet MTS9200 and Lewatit K 6362 were recommended for the use in solutions with a higher concentration of Au, as their sorption yields are relatively low.

Finally, metal adsorption on activated carbon for metal recovery from various streams is also being investigated, especially for Au. Torrinha et al. [99] assessed the potential of tannin resins to recover Au(III) from both aqua regia and HCl solutions. The highest adsorption capacities of Au were obtained at 343 mg g^{-1} and 270 mg g^{-1} for both the solutions, which contained 1.0 mol L^{-1} H^+. However, the adsorption of Au from both types of leaching solutions was significantly hindered by the increased levels of acidity and Cl^- ligands. In comparison to Cu(II), Fe(III), Ni(II), Pd(II), and Zn, the adsorbent exhibited remarkable selectivity towards Au(II). Besides, among the four different recovery methods, adsorption has been advocated as the most suitable method for recovering platinic metal groups, such as Ru, Rh, Pd, Os, Ir, and Pt [117].

Bio-metallurgy

In contrast to the traditional hydrometallurgical process, bioleaching, also known as the bio-hydrometallurgical process, is a simple process that offers multiple advantages, including higher efficiency and safety, lower operating costs and energy consumption, easier management, normal operating conditions at atmospheric pressure and room temperature, eco-friendliness, and fewer industrial steps without the need for skilled workers [118]. The separation of metals from e-waste using a biological process occurs mainly through acidolysis complexation. However, the limitations of bioleaching of metals from e-waste are due to the inherent toxicity of the toxicants to microorganism. Auxoautotrophs i.e., *Sulfobacillus acidianus, Acidiphilium thiobacillus* and *Leptospirillum ferrooxidans* and auxo-heterotrophs are widely used in bioleaching [119] and extract HMs using organic substrates to produce acidic metabolites (HCO_3, HNO_3, H_2SO_4, CH_3COOH, citric acid, oxalic acid, gluconic acid, and formic acid) [49].

Bioleaching employs different fungi and bacteria having the ability to secrete inorganic or organic acids (chemolithoautotropic by acidolysis and redoxylysis) or CN (cyanogenic), which enhances enzymatic oxidation–reduction, proton promoted mechanisms and/or ligand and complex formation [120] (Table 3). Chemolithotrophic bacteria mainly *A. ferrooxidans, A. thiooxidans*, and *L. ferrooxidans* can convert metal sulfides of Co, Ga, Ni, Pb, and Zn, as well as the Pt group metals (Pt, Pd, Rh, Ru, Os, and Ir), into their metal sulfates while generating H_2SO_4 in the system (acidolysis). On the other hand, heterotrophic bacteria and fungi can convert non-sulfides and acid-consuming oxide materials for metal extraction, mostly through production/secretion of organic acids (acidolysis) and complexing compounds to form chelates (complexolysis), and through the change in the oxidation state (redoxolysis) [121].

The most important bioleaching mechanisms include acidolysis, redoxolysis, and complexolysis. The acidolysis involves the protonation of the oxygen atom present on the metal oxide, which leads to its dissolution. Protonation of oxygen atoms occurs through organic acids, such as acetic acid, formic acid, citric acid, gluconic acid, pyruvic acid, etc. [18, 132]. On the other hand, redoxolysis involves oxidation–reduction phenomenon in which insoluble metals are converted to their respective soluble forms and Fe ions act as oxidizing/liquefying agents. Finally, complexolysis involves the chelation of desired metals with ligands, during which mediators, siderophores, cyanides, and organic acids are used, ultimately leads to the dissolution of metals. Some

Table 2 Comparison of four common recovery techniques employed for recovery of precious metals from e-wastes

Recovery techniques	Principles	Leaching solution	Reagent for particular metals	Recovery efficiency (%)	References
Solvent extraction	Separation of constituent target elements in waste by dissolving a liquid solution with an organic solvent	H_2SO_4: 1000 mL, 12 h, 25 °C	Cu: 0.5 mol dm^{-3} benzoic acid, 0.25 mol dm^{-3} aromatic amine p-toluidine, toluene Mo, U, V: di-(2-ethylhexyl)phosphoric acid (D2EHPA) 97%	> 99% Cu 90% Mo 75% U 65% V	[102]
		Aqua regia	Au: N-[*N*,*N*-di(2-ethylhexyl) aminocarbonylmethyl]glycine	96% Au	[103]
		H_2SO_4, NaBr (3 M): 1 h, 70 °C, 500 rpm agitation	Au: 0.1 M tertiary amide extractant	> 95% Au	[104]
		HCl, $HClO_4$ and HNO_3: 1–11 mol/L	0.75 mol/L P_2O_4	99% Sc	[105]
		$AlCl_3$ solutions 20–30 g/L Iron	5–10% carboxylic acid	Sc	[106]
		60% Cyanex 272 40% Cyanex 923	10% $H_2C_2O_4$	98% Sc	[106]
		$H_2SO_4 + H_2O_2$	D2EHPA	60% Al 94% Cu 76% Zn 50% Ni	[107]
Electrodeposition	Recovery of targeted metals occurred through electrochemical reduction of metal ions from an electrolyte	HNO_3 (69%)	–	> 40% Au, Pb, Cu	[108]
		NaCl (100 mM)	–	97% Cu 65% Eu	[109]
Ion exchange	Use of chelating resins to generate metal complexes, allowing for the selective recovery of the desired ion or metal	H_2SO_4	Lewatit TP 207 (1 mL) resin, pH: 0.5–2.0; 25 °C; 180 min; 200 rpm	69% Cu 13% Ni	[110, 111]
		HNO_3 (65%), H_2O_2 (30%)	Puromet MTS9200, Puromet MTS9850, Lewatit K 6362 resins, 10–60 cm^3 volumes; 1 h; 330 rpm	99% Pt 99% Pd 80% Rh 99% Au 99% Cu 81% Zn	[110, 111]
Adsorption	Selectively adsorbed from binary and complex mixtures and recovered at high purity using biosorbents, such as activated carbon, chitosan-derived adsorbents, and silk sericin to purify the targeted metals	–	Aquaminerals PalPower M10	63% Cu	[112]
		HCl (10 wt%)	Chitosan-DB18C6 adsorbent (0.1 g); 2 h; pH 0.5–1.0, 200 rpm	> 90% Pd, Pt, Ru	[113]
		HCl (0.2–3.7 mol L^{-1}); Aqua regia (0.3–4.2 mol L^{-1})	**Tannins** resins with adsorbent dosage of 2.0 g L^{-1}, 72 h, 280 rpm	> 99% Au 11% Ni 10% Pd < 3% Cu, Fe, Zn	[114]

Table 3 Comparison of the microbes used in bioleaching

Microbes	Substrate	Reaction conditions	Leaching efficiency	References
Gold				
1st step: *Acidithiobacillus ferrivorans* and *Acidithiobacillus thiooxidans* 2nd step: *Pseudomonas fluorescens* and *Pseudomonas putida*	Discarded printed circuit board	Temperature: 30 °C pH: 8.0–9.2	44%	[122]
Chromobacterium violaceum and *Pseudomonas fluorescens*	Electronic scrap	Temperature: 30 °C pH: 7.2–9.2	69%	[123]
Bacillus megaterium	Mobile phone printed circuit boards	pH: 10 Pulp density: 8.13 g/L Glycine: 10 g/L	65 g Au/ton	[124]
Chromobacterium violaceum and *Pseudomonas aeruginosa*	Printed circuit board waste	Temperature: 30 °C pH: 7.2 Pulp density: 1% Leaching time: 7 days 150 rpm Optical density: 1.0 at 660 nm 5% inoculum	73%	[125]
Chromobacterium violaceum	Electronic scrap material	Temperature: 30 °C pH: 9.5 Pulp density: 0.5% 170 rpm	22.5%	[24]
Acidithiobacillus ferrooxidans	E-waste	Temperature: 30 °C pH: 2 Pulp density: 1% 150 rpm	39.49%	[126]
Genetically engineered *Chromobacterium violaceum* (pBAD)	Electronic scrap	Temperature: 30 °C Pulp density: 0.5% Pretreated with 6 M nitric acid 170 rpm	30%	[127]
Chromobacterium violaceum	Printed circuit board waste	pH: 11 Pulp density: 1.5% 4.0×10^{-3} mol/L of MgSO4 8 days	11%	[128]
Chromobacterium violaceum	Printed circuit board waste	pH: 8–9 NaCl, $MgSO_4.7H_2O$	70%	[129]
Pseudomonas chlororaphis	Printed circuit board waste	pH: 7	8.2%	[130]
Silver				
Chromobacterium violaceum and *Pseudomonas aeruginosa*	Printed circuit board waste	Temperature: 30 °C pH: 7.2 150 rpm O.D. = 1.0 at 660 nm 5% inoculum Pulp density: 1.5% Leaching time 7 days	8%	[125]
Pseudomonas chlororaphis	Printed circuit board waste	pH: 7	12.1%	[130]
Copper				
Lentinus edodes *Pleurotus florida* *Ganoderma lucidum* *Aspergillus niger* *Trametes versicolor* *Streptomyces* spp. *Pseudomonas* spp.	Printed circuit board waste	Dried biomass: 1.0 g 15.0 mL aqua regia 35% HCl and 70% HNO_3 in 3:1 ratio Temperature: 70 °C	10.5–18.0%	[131]

Table 3 (continued)

Microbes	Substrate	Reaction conditions	Leaching efficiency	References
Iron				
Lentinus edodes *Pleurotus florida* *Ganoderma lucidum* *Aspergillus niger* *Trametes versicolor* *Streptomyces* spp. *Pseudomonas* spp.	Printed circuit board waste	Dried biomass: 1.0 g 15.0 mL aqua regia 35% HCl and 70% HNO_3 in 3:1 ratio Temperature: 70 °C	9.0–13.6%	[131]

metals extracted through complexolysis include Au, Ag, Cu, Fe, Zn, Mg, Pt, and Pd [18, 132, 133]. Complexolysis is often performed after acidolysis to stabilize the extracted metals.

During acidolysis, protons of organic acids produced by heterotrophic bacteria (malic, oxalic, gluconic, acetic, citric, succinic, pyruvic and formic acids) and also bacterial inorganic acids (H_2SO_4) possess the ability to protonate the oxygen atoms that cover the metallic compound surface. The complexolysis mechanism exhibited by several fungi can produce $CN^-$by decarboxylation of glycine in the late stationary phase of growth [134]. Few CN-producing bacteria can detoxify the cyanide to β-cyanoalanine (Cyanoalanine: $NCCH_2CH(NH_2)CO_2H$) by β-cyanoalanine synthase, making bio-cyanidation process an attractive process for metal recovery, as it generates less hazardous CN in the wastewater streams [135]. *C. violaceum* is a commonly used cyanogenic microorganism for bioleaching of PCB, owing to its six HCN synthase enzymes producing more CN [136], thus qualifying as the most promising microorganism for Au recovery [137].

Several studies have reported using consortia of chemolithoautotrophic bacteria (*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*) for the bioleaching of e-wastes including PCBs [12, 138–140], Li-ion batteries [141, 142], Zn-Mg batteries [143, 144] and CRT [145] exhibiting better metal recovery due to the synergic effect of bacteria (Table 3). Yang et al. [146] reported the extraction rate of 68.5% and 85% of Au using *C. violaceum* and *L. acidophilus* respectively, also *Klebsiella pneumoniae* reported to extract 99% of Ag and Pd [49]. Earlier, Brandl et al. [123] and Brandl and Faramarzi [147] also reported the extraction of Au, Ag, and Pt from e-waste, jewelry waste, and catalytic converters, respectively using cyanogenic bacteria *C. violaceum, P. fluorescens* and *P. plecoglossicida*. *C. violaceum* was most effective in mobilizing Au from e-waste with the higher amount of dicyanoaurate (68.5% in 7 days) at a low-pulp density of 5 g L^{-1} as compared to *P. fluorescens*. Bioleaching by *Aspergillus niger* has been reported to recover Au from e-wastes with 87% efficiency [148] and 97.11 mg g^{-1} of Ag [149]. Pd has been extracted with 95% efficiency from e-waste using *Desulfovibrio desulfuricans* through three phases [150], involving hydrometallurgy followed by the electrochemical method for recovery of base metals from the solution, thereafter in the second phase the residue containing Au and Pd upon dissolving by aqua-regia, *D. desulfuricans* is allowed to react with Au^{3+} in the solution for Au precipitation, in presence of H_2 and $NaAu(III)Cl_4$. After obtaining the Au through filtration, in the third phase, H_2 and $Na_2Pd(II)Cl_4$ are added to the filtrate and *D. desulfuricans* are allowed to react with Pd^{2+} forming Pd precipitate, thereafter Pd extracted through filtration.

However, there are a few limitations of the bioleaching process which include (i) toxicity to the microbes (ii) precipitation due to the jarosite formation and complexation and (iii) presence of toxic HMs and organic compounds, epoxy plastics and BFRs, which can hinder microbial growth. Jarosite is a basic hydrous sulfate of potassium and ferric iron (Fe-III), represented by $M_n(Fe^{3+})_6(SO_4)_4(OH)_{12}$ where M could be K, NH_4, Na, Ag, or Pb and "$_n$" equals 1 and 2 for monovalent and divalent cations, respectively. The metal of interest (Ag and Pb) can be trapped in the crystal lattice of the jarosite, decreasing the efficiency of bioleaching [137].

Apart from bioleaching of precious metals from e-waste, few report exhibit scope for extraction of precious metals. Two strains of *Cladosporium* spp. (*Cladosporium* sp. A and *Cladosporium* sp. B) along with *Penicillium chrysogenum* strain that have been reported to extract Ag with bioleaching efficiency of 67%, 40% and 53%, respectively from mine tailings [151]. Similarly, using two strains of *Aspergillus niger* viz. MXPE6-MX7, both individually as well as in combination, Au was extracted from mobile phone and computer PCBs with bioleaching capacity ranging between 42 and 87%, within pH ranging between 4 and 6 at 25 °C [148].

Combined processes

Molding with electrolysis

Recycling e-waste can be accomplished in various ways, including extracting precious metals. Some methods are suitable for small-scale operations, while others require specialized equipment for larger volumes. Engraving is a method that is particularly effective at separating Au from e-waste such as computer PCBs, mobile PCBs, along with other electronic components.

The process starts by melting e-waste containing precious metals in presence of Cu in a kiln, resulting in a Cu tablet or ingot. The next step involves filtering the Cu ingot or tablet in an electrolysis device, which causes the Cu powder to settle on the electrolyte floor. This separates all precious metals and forms an anodic sludge that may still contain some precious metals. The sludge can be recycled through acid treatment, and the remaining metals can be further separated [152].

Molding with Cu and electrolysis

This is a chemical method in which the e-waste is crushed and ground. After crushing and grinding the e-waste, it is dissolved in HNO_3 to separate the precious metals from the rest. The recycling process of e-waste by the hydrometallurgical method can be conducted once the electronic components are separated from the other wastes [153, 154]. The desired e-waste must be ground and filtered using magnetic separation. The ground wastes are then dissolved with acid to separate Ag and Pd. Finally, the remaining material from the previous step is dissolved in another acid to recover the Au and Pt. Although this method can be used for large volumes of e-waste from the industries, it is mostly used for smaller scale [154, 155].

Alternately, the desired e-waste is converted to ash through pyrolysis. The obtained ashes are ground, and Fe is separated from the desired waste using magnetic separation. Next, the Cu is molded and the obtained Cu tablet is electrolyzed. The anodic sludge obtained by electrolysis is collected and then acidified with HNO_3 to recover Ag and Pd. In the final step, the acidic anodic sludge is electrolyzed to separate Au and Pt [156].

Lead molding and coupling method

The Pb molding and coupling method is commonly used for recycling e-waste from computers. The process involved melting the desired e-waste, and lead oxide (PbO) in a kiln to produce a Pb ingot or tablet. The precious metals, including Au, Pt, and Ag, are then separated from the Pb using the coupling method. The remaining metals are separated by acidification. Before commencing this process, the electronic components and waste are separated, followed by pyrolysis, thereafter the waste is mixed with PbO to create the Pb ingot or tablet.

Non-conventional metal recovery method

Innovative, greener and cost-effective techniques for metal recovery have become an emerging interest in the field of e-waste management. With a focus on environmental sustainability, several biotechnologies and combined approaches have been recognized as remarkable methods for recycling and recovering precious metals [119]. Currently, hyper-accumulator-mediated phytomining has been identified as a non-conventional method for metal recovery due to its cost-effectiveness, low-technology methods, lower environmental risk, and high selectivity towards metals [46, 119, 157, 158]. In addition, the combination of process such as the hydrometallurgy and electrolysis has been reported to improve the metal recovery process from e-waste [33, 74, 75, 119].

Phytoextraction

Phytoextraction of precious metals, such as Au, Ag, Pd, and Pt, by plants holds potential both economically and environmentally from e-wastes. Phytoextraction has been employed for two major sectors: phytoremediation and phytomining [157]. Phytoremediation is a soil remediation technique known for extracting HMs from contaminated soil by accumulating them in its shoots [45, 147]. On the other hand, phytomining is the technique used to reclaim valuable metals from mineralized soils, mill tailings and low-grade ores [157, 158].

Hyper-accumulator plant can accumulate metals up to 10,000 mg kg^{-1} in roots and stems tissues [159, 160]. These plants can be ranged from perennial shrubs to various trees and grasses, such as *Sedum alfredii*, *Thlaspi caerulescens*, *Trifolium alexandrinum*, and *Panicum maximus* [159, 160]. Based on the normal Au concentration in plants (0.01 mg kg^{-1}), Sheoran et al. [161] considered plants accumulating > 1 mg kg^{-1} of Au as hyper-accumulators. For instance, the levels of Pt, Au, Pd and Ag to make matrices profitable are considered to be 4, 6, 5–15 and 1000 mg kg^{-1}, respectively and their concentrations in biomass that make it economically viable, ranges between 0.04–0.4, 0.06–0.6, 0.05–1.5, and 10–100, respectively [162–164]. *Brassica juncea* (L) Czern. can hyperaccumulate Au in levels > 57 mg kg^{-1} DW with suitable treatment of the substrate [165]. Similarly, other noble metals, such as Pt and Pd, also have low solubility in the natural environment, hence chemical amendments are often applied to soil to enhance the leachability of these elements for phyto-accumulation.

Phytoextraction of precious metals can be achieved through the use of metal-tolerant hyperaccumulating plants or plants with high biomass and enhanced phytoextraction rate using chelants. Common biodegradable chelants include citric acid and nitrilotriacetic acid (NTA) and ethylene-di-amino-di-succinate (EDDS) are biodegradable whereas, ethylene-diamine-tetra-acetic acid (EDTA) is non-biodegradable [166–168]. Despite limited studies of phytoextraction of precious metals from e-waste, Dinh et al. [157] has extensively reviewed phytoextraction efficiencies of Au, Ag, Pt and Pd by *B. juncea*, carrot, red beet, onion and two cultivars of radish, *Berkheya coddii, Cichorium intybus, Zea mays, Helianthus annuus*, *Lindernia crustacean, Paspalum conjugatum* (carabao grass)*, Cyperus kyllingia* (nut grass)*, Nicotiana tabacum* (Tobacco)*, Brassica napus, Euphorbia macroclada* (spurge), *Verbascum cheiranthifolium boiss* (Mullein flowering plant)*, Astragalus gummifer* (leguminous), two mushroom species *Amanita strobiliformis,* and *A. solitaria, Lupinus* sp.*, Medicago sativa, Pinus flexilis* (limber pine), *Cannabis sativa* (hemp)*, Salix purpurea* (willow)*, Miscanthus* (silver grass)*, Daucus carota* (wild carrot)*, Sinapis alba* (white mustard)*, Phragmites australis* (common reed), from a range of substrates including oxidized ore pile, disseminated Au in sand, artificial Au-bearing soil, cyanidation tailings, mine tailings, base-metal mine tailings, aqueous substrate, Pd and Pt contaminated soil, gossan rock as well as soil from vicinity of the heavy traffic (Table 4). The accumulation of metals in these plants ranges from 20 to 760 mg kg^{-1} for Au, 54.3 to 730 mg kg^{-1} for Ag and 0.22 to 183 mg kg^{-1} for Pt. To enhance phytoextraction, several leaching/lixiviating agents, such as ammonium thiocyanate (NH_4SCN), sodium cyanide (NaCN), potassium cyanide (KCN), potassium iodide (KI), potassium bromide (KBr), and ammonium thiosulfate [$NH_4)_2S_2O_3$], have been used in these studies [169–171].

The level of Au (mg kg^{-1}) in the leaves of *Brassica juncea* (Indian mustard) have exhibited the highest level (mg kg^{-1}) among all the studied plants, ranging between 57 and 760, compared to a background concentration ranging between 0.6 and 48 mg kg^{-1} of Au [165, 169, 170, 172]. *Helianthus annus* accumulated 14.9, 21.5, and 19.2 mg kg^{-1} in roots, stem and leaves, respectively, compared to a background of 2.35 mg kg^{-1} of Au in mine tailing [158]. The roots of carrot and salad radish and oriental radish accumulated 48.3, 113.0 and 102.0 mg kg^{-1}, respectively compared to a background of 3.8 mg kg^{-1} [173]. The accumulation of Au in the Australian native plant *Trifolium repens* cv. Prestige stems were 26.8 mg kg^{-1} against a background concentration of 1.75 mg kg^{-1} [174]. The level of Au in the plant *Berkheya coddii* was reported to be 1.580 mg kg^{-1} against a background of 0.0614 mg kg^{-1} [183]. The lowest accumulation of Au was in *Cannabis sativa*, with a mean of 4.5 mg kg^{-1} and a highest level of 7.635 mg kg^{-1}, compared to a background of 0.02 mg kg^{-1} [175]. There are relatively fewer reports for Ag, but similar to the accumulation of Au, *Brassica juncea* also exhibited high Ag accumulation. In a hydroponic experiment where Ag was provided in a concentration ranging from 500 to 10,000 mg L^{-1}, the highest accumulation was 124 g kg^{-1} after 48 h [176]. In the same study, *Medicago sativa* accumulated the highest level of 136 g kg^{-1} of Ag. On the other hand, tobacco accumulates 54.3 mg kg^{-1} against 18.2 mg kg^{-1} [178].

Rapeseed (*Brassica napus*) has been reported to accumulate about 50,000; 30,000; 15,000 mg kg^{-1} in its roots, stems, and leaves, respectively against Ag level of 22.1 mg kg^{-1} in mine tailings [171]. A mushroom species, *Amanita strobiliformis*, has been found to have high accumulation of Ag, with 1253 mg kg^{-1} against 1.01 mg kg^{-1} in soil [177]. Palladium accumulating plants can be considered as hyperaccumulators, which exhibits accumulation > 1 mg kg^{-1} in their biomass. *Berkheya coddii* was reported to accumulate 7.7 mg kg^{-1} of Pd against a background of 0.32 mg kg^{-1} from mine tailing [175]. Similarly, *Cannabis sativa* accumulated high levels of Pd, with the highest being 62.42 mg kg^{-1} and a mean of 30.33 mg kg^{-1} [175]. *Salix purpurea* accumulated 820 mg kg^{-1} in its leaves against a background of 50 mg kg^{-1} in a synthetic ore medium [179]. The same study showed *Miscanthus* sp. leaves accumulated 505 mg kg^{-1} when Pd content in ore was increased to 100 mg kg^{-1}. The aerial part of *Sinapis alba* accumulated 500 mg kg^{-1} of Pd when grown on a synthetic tailing medium containing 50 mg kg^{-1} [179]. Although an abundance of Pt is very low in the earth's crust (0.005 mg kg^{-1}), to make phytoextraction economically viable, plants have to accumulate 800 times more than their background (Mungall and Naldrett, 2008). *Berkheya coddii* has been reported to have a bioaccumulation factor (BF) and translocation factor (TF) > 1 ($BF = 5.5$, $TF = 1.2$), showing its high efficiency for Pt accumulation [157]. The plant has been reported to accumulate 0.183 mg kg^{-1} against a 0.315 mg kg^{-1} background [175]. Additionally, *Sinapis alba* has been reported to accumulate 95.8 mg kg^{-1} in aboveground parts against a background of 1.0 mg kg^{-1} [180].

The underlying premise of using hyperaccumulators for metal extraction is a great biological approach for metal recovery. Despite the various benefits and advantages of phytoextraction, it is time-intensive, low in efficiency, and non-applicable for large scale. The process of metal extraction depends on the plant's physiological properties and several abiotic and biotic factors. The recovery of precious metals from phytomining biomass remains a challenge due to the unstandardized extraction process on an industrial scale. Two methods reported by Lamb et al. [184] and Krisnayanti et al. [178], mainly involve the ash of phytomined biomass (550 °C), followed by

Table 4 Studies on level of accumulation of precious metals in plants

Plant's Botanical name	Substrate (mg kg^{-1})	Lixiviant	Metal content in plant biomass (mg kg^{-1})	BCF (level in biomass/ level in substrate)	References
Gold					
Brassica juncea (Indian Mustard)	Disseminated Au in sand (5)	0.64 g kg^{-1} of NH_4SCN	Up to 57 of Au in areal part	11.4	[165]
Brassica juncea	Soil spiked artificially with Au (5)	KCN, NaSCN, KI, KBr, $(NH_4)_2S_2O_3$	88, 46, 326 in root, stem and leaf, respectively	1.6, 9.2 and 65.2, respectively	[169]
Berkheya codii			36, 94, 97 in root, stem and leaf, respectively	0.6, 18.8 and 19.4, respectively	
Cichorium intybus	Oxidized ore dump pile at Fazenda Brasileiro mine, Brazil (0.6)	NH_4SCN/peroxide (4.3 g/L of SCN^-), NaCN (1.40 g/L CN^-), KCN (1.03 g/L CN^-)	164 in whole plant	32.8	[170]
Brassica juncea			39	65	
Zea mays			20	33.3	
Brassica juncea	Artificially spiked soil (48)	KCN	760	15.8	[172]
Helianthus annus	Mine tailing (2.35)	NaCN	14.9, 21.5, 19.2, in root, stem and leaves, respectively	6.34, 9.14 and 8.1, respectively	[158]
Carrot, Salad radish, Oriental radish	Artificially spiked soil (3.8)	NH_4SCN (1.0 g kg^{-1}), $(NH_4)_2S_2O_3$ (2.0 g kg^{-1})	Carrot (48.3), Salad radish (113), Oriental radish (102)	12.7, 29.7 and 26.8, respectively	[173]
Trifolium ripens	Oxidized ore tailing (1.75)	NaCN (0.1 and 1 mg kg^{-1})	Stems (26.87)	15.35	[174]
Bothriochloa macra			Leaves (23.78)	13.5	
Berkheya codii	Mine tailings (0.0614)	KCN (10 g L^{-1})	Plant (1.58)	25.73	[175]
Cannabis sativa	Rock (gossan) (0.020)	KCN (8 g L^{-1})	7.63	381	
Silver					
Brassica juncea	$AgNO_3$ provided in aqueous medium (500–10,000 mg L^{-1})	–	124 g kg^{-1}	–	[176]
Medicago sativa			136 g kg^{-1}		
Brassica napus	Mine tailing (0.5164)	NH_4SCN (1 g kg^{-1}); $(NH_4)_2S_2O_3$ (2 g kg^{-1}) + *Aspergillus niger*	50,000, 30,000 and 15,000, respectively in roots, stems and leaves	–	[171]
Amanita strobiliformis	Soil (0.07–1.01)	–	Range (200–700); Highest: 1253	693	[177]
Nicotiana tabacum	Cyanidation tailings (18.2)	NaCN (0.05 g kg^{-1} of substrate)	54.3	2.96	[178]
Palladium					
Berkheya coddi	Mine tailing (0.315)	KCN (10 g l^{-1})	7.6	24.12	[175]
Cannabis sativa	Rock (0.205)	KCN (8 g l^{-1})	mean:30.33; highest: 62.4	25.17	
Salix purpurea	Synthetic ore (50)	KCN	Leaf: 820	16.4	[179]
Miscanthus sp.	Synthetic ore (100)	KCN	Leaf: 505	5.05	
Sinapis alba	Synthetic tailing (50)	KCN (100 mg kg^{-1})	Aerial part: 500	10	[180]
Quercus chrysolepsis	0.14	–	Biomass ash (0.4)	2.8	[181]
Platinum					
Berkheya coddi	Soil (0.04)	–	Leaf:0.22; root: 0.14	2.8	[182]
Berkheya coddi	Mine tailing (0.0614)	KCN (10 g l^{-1})	Plant biomass (0.183)	2.98	[183]
Sinapis alba	Nutrient solution (1.0)	–	Ariel parts (95.8)	95.8	[180]

acid dissolution (2 M HCl) of Au and Ag through solvent extraction (using methyl isobutyl ketone). The metals are then precipitated from the solvent using a suitable reducing agent (such as $NaBH_4$ or ascorbic acid), and the resulting metal-containing precipitate is filtered and heated at a high temperature to obtain the pure metal. Therefore, optimizing the process of phytomining of precious metals through phytoremediation remains a challenge, and a great deal of research is necessary in this area [119, 157].

Hydroponics for phytomining

Hydroponic culture is a subset of aquaculture that grows plants using a water-based nutrient media instead of soil. Hydroponic farms have complete control over the growing environment, including climate, temperature, humidity, light, air composition, significantly less water requirement, and year-round plant growth regardless of the season. Commercially viable vegetables with a shorter growing period are usually grown hydroponically using cheaper nutrient media viz. fish excrement, duck manure and artificial nutrient solutions.

There are two commonly used hydroponic techniques: (i) static solution technique, where plants are grown in containers of nutrient solutions usually on a small scale, and (ii) continuous flow solution culture, which employs a continuous flow of nutrients across the roots. A variation in the continuous flow culture is the nutrient film technique, where a very shallow stream of water containing all the dissolved plant nutrients is recirculated in a thin layer across the bare root mat of plants, ensuring an abundant oxygen supply to the plant's roots [185].

A conceptual schematic diagram has been proposed (Fig. 2) for recovery of precious metals form the PCB slurry. The aqueous slurry solution containing a cocktail of metals, including precious metals from e-wastes, can be used in the continuous flow solution culture or deep water static hydroponic culture for phytomining using tolerant and efficient grasses species, i.e., *Vetiver zizanioides*, lemon grass and *Miscanthus* sp. [46, 186, 187].

Several studies are using *V. zizanioides* in hydroponics for remediation of brewery wastewater [188], and paperboard mill wastewater [189]. Thus, phytomining of precious metals from e-waste slurry through hydroponics, not only has a commercial advantage, but is also environmentally safe. The biomass thus obtained is rich in precious metals, which is greater than the content in virgin ores and thus can be extracted through incineration of the biomass and electrodeposition.

Prediction of precious metals' phytomining from e-waste (PCBs)

A lot has been said about the advantage of phytomining of precious elements from e-wastes, both in this review as well as in the published literature. Here we predict the global

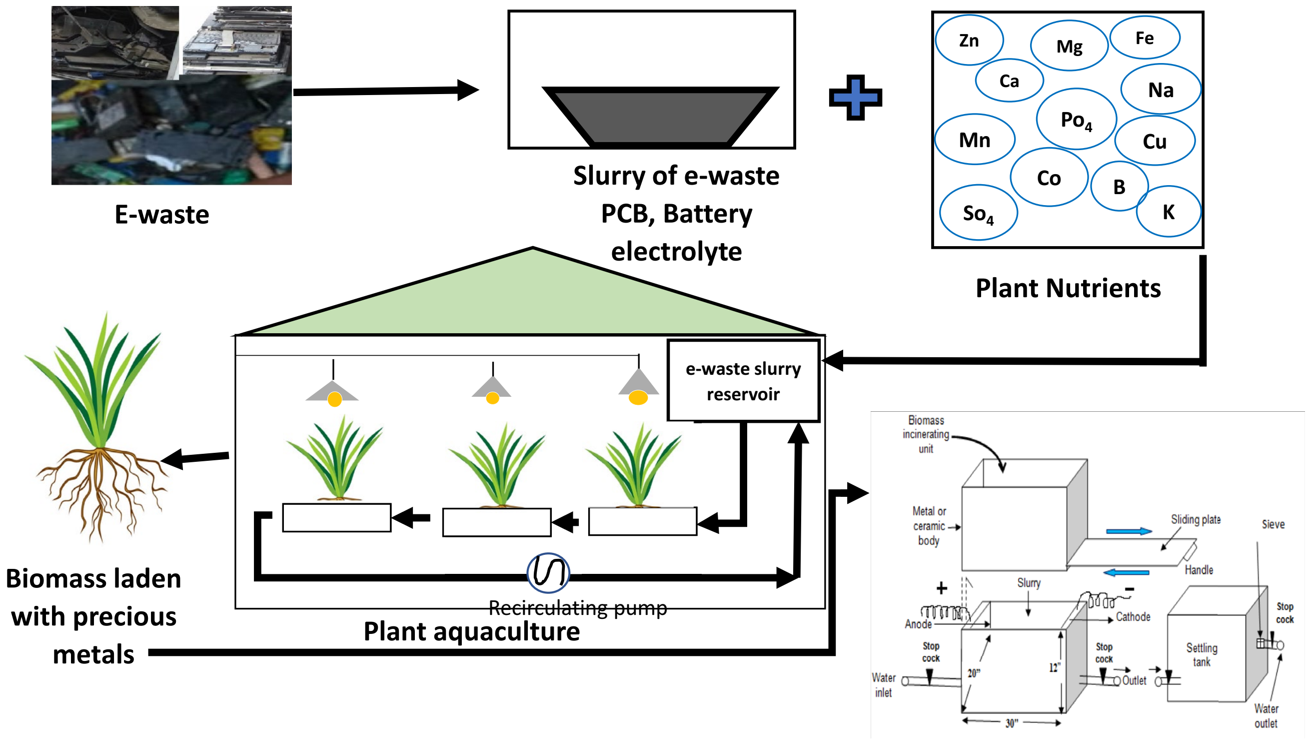


Fig. 2 Conceptual schematic flow diagram for phytomining of precious metals from waste PCBs through aquaculture. Recovery of precious elements from waste PCBs, by converting into a slurry rich in plant nutrient can help suitable plant to accumulate precious elements, which can be extracted by incineration and electroplating

recovery of precious elements from e-waste (PCB) through phytomining, using data from the published literature that includes (i) annual e-waste generation, (ii) annual rate of increase in e-waste generation, (iii) the content of PCBs in the e-waste, (iv) amount (mg kg^{-1}) of Au and Ag present in PCBs, (v) the biomass (ha^{-1}) of model plant for phytoremediation (i.e., *Brassica*), and vi) the level of uptake of Au and Ag in *Brassica*. Thus, for our prediction we have considered the global e-waste generation during 2018 as the base year for the recovery of Au and Ag through phytoremediation and has been forecasted till 2050. Correspondingly, the amount of land required for the phytoextraction has also been calculated.

The annual global total e-waste generated during 2018 was 47.62 million metric tons [13], which is predicted to increase by 4% annually. Further, PCBs constitute 4% of the annually generated e-waste globally [60]. Based on the above reported values of annual e-waste generation (4%) and its PCBs constitution (4%), year-wise values for total e-waste generation and the share of PCB, have been accordingly calculated till 2050 and presented in Fig. 3A and the values in Supplementary Table 1. To determine the Au and Ag level present in the substrate for photomining, the concentration of Au present in PCBs was calculated. About 40 tons of Au is present in 0.5 Mt of PCBs [25], which amounts to 80 mg kg^{-1} of Au in total of 47.62 Mt of waste PCBs (Fig. 4). Since plants cannot grow solely on PCBs, a 70:30 mixture of soil to PCBs were considered for phytoremediation [190]. Furthermore, the bio-leachability of Au from soil substrate being reported at 44% [157], an effective Au concentration of the substrate 10.56 mg kg^{-1} was derived.

Next, the Au accumulation by *Brassica* biomass using straight-line correlation was derived (Eq. 5) using literature reported values of Au accumulation by *Brassica juncea* (mg kg^{-1}) as 57, 760, and 39 from the substrate concentration of Au (mg kg^{-1}) as 5, 48 and 0.6, respectively [157],

$$16.121x - 14.659 = y \tag{5}$$

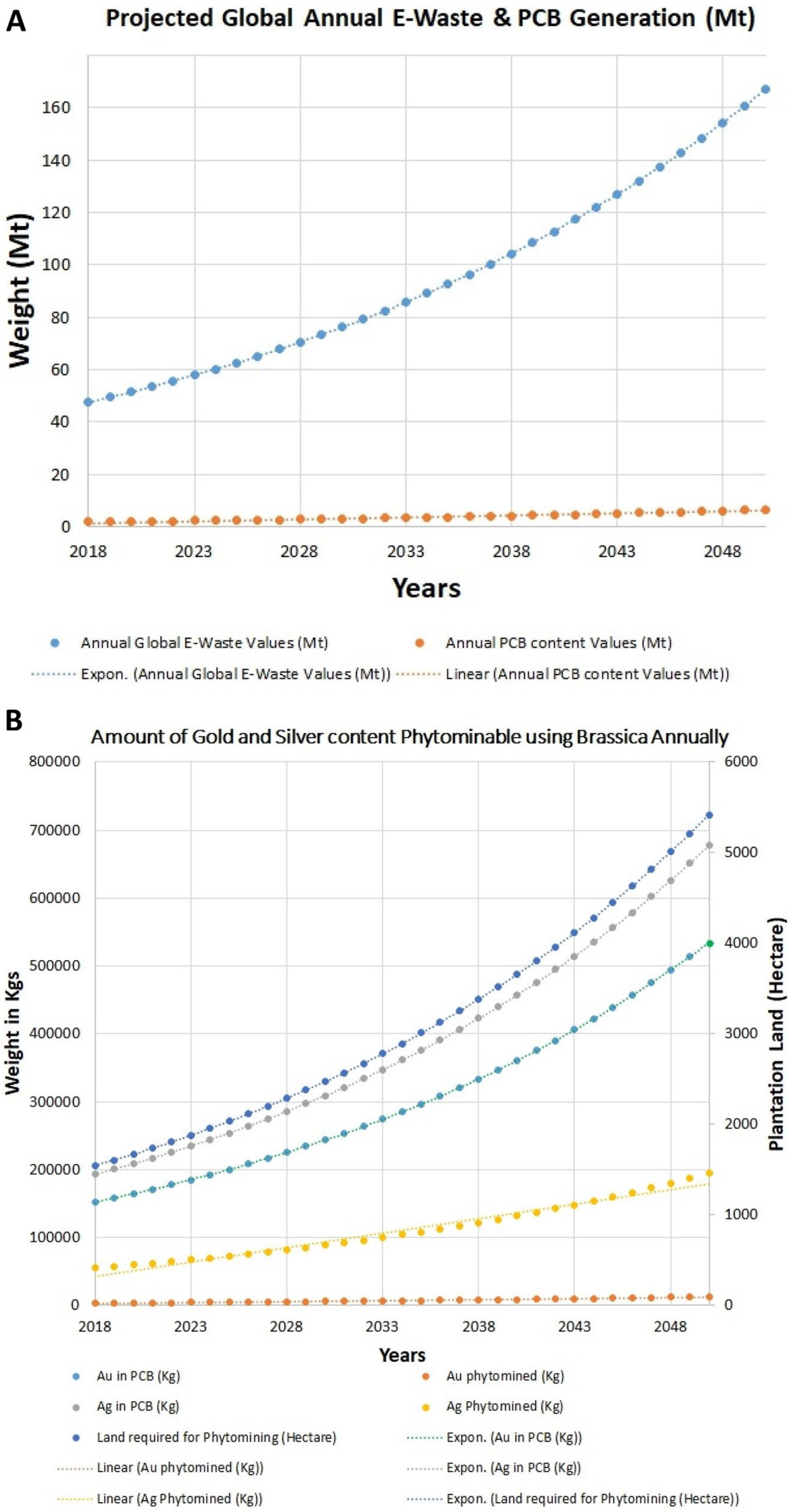
Hence, using the value of "y" as 10.56 mg kg^{-1} as the effective substrate Au concentration derived earlier, the Au accumulation by *Brassica juncea* was obtained as 155.57 mg kg^{-1} [157], using Eq. 5. Further, in order to use the substrate at farm level the area required was calculated, considering the top soil volume (20 cm depth) of the substrate [e-waste (PCB)] to be phytomined. The rooting depth of *Brassica* is 0.2 m. thus 2000 meters^3 volume of substrate (100 m × 100 m × 0.2 m) was considered for calculation of the volume of soil/substrate within one hectare (ha). Hence, the volume of PCBs suitable for 1 ha plantation area, constituting 30% of the total substrate volume amounts to 600 m^3 of PCBs. Also, the density of PCBs was used to derive the weight of 600 m^3 of PCB indirectly from FR-4, the base material of PCBs. FR-4 is a composite material composed of woven fiberglass cloth with an epoxy resin binder, having a density of 1.85 g cm^{-3} [191]. Hence, 1,232,100 kg of PCBs could be used ha^{-1} for phytomining. Since, the average biomass of *Brassica* ha^{-1} has been reported to range between 1400 and 1800 g m^{-2} [192], we have considered the average 1600 g m^{-2} for our calculation, amounting to 16,000 kg ha^{-1} (1600 g m^{-2} × 10,000 m^{-2}) of *Brassica* biomass could be harvested ha^{-1}. Hence, the amount of Au accumulated by *Brassica juncea* ha^{-1} would be 16,000 kg × 155.57 mg kg^{-1}, yielding a value of 2.5 kg ha^{-1} of Au phytomined (Fig. 3B). Therefore, the amount of Au which can be extracted by *Brassica juncea* from PCBs generated annually, has been thus calculated and plotted in Fig. 3A till 2050. The predicted amount of Au which could be phytomined during 2023 from 2.32 Mt of PCBs (Supp. Table 1) is 4702.30 kg, requiring an area of 1880.92 hectares. This when extrapolated to the values of 2050, has a potential to phytomine ~ 13,558.46 kg of Au requiring an area of 5423.38 ha.

Similarly, for calculation of the phytominable Ag, considering 1000 mg kg^{-1} of Ag is present in PCBs [25]. Same ratio (30:70) of PCBs to soil was considered as substrate for the phytorextraction. Hence, the concentration of Ag present in substrate was determined to be 300 mg kg^{-1}, which was further reduced to effective concentration of 101.4 mg kg^{-1}, considering 33.8% bio-leachability of Ag in soil [22]. Thus, using effective Ag concentration of 101.4 mg kg^{-1}, a linear correlation was obtained (Eq. 6) using the Ag uptake values (mg kg^{-1}) of *Brassica juncea* i.e., 730 mg kg^{-1} against 31 mg kg^{-1} of Ag supplied in sand substrate, 22,500 mg kg^{-1} (avg of leaves and stem) by *Brassica napas* from 22.1 mg kg^{-1} in mine tailing [157].

$$32.157x - 974.77 = y \tag{6}$$

From the above equation, 2285 mg kg^{-1} of Ag could be possibly accumulated by *Brassica* from effective concentration of 101.4 mg kg^{-1} from soil substrate. Hence, the amount of Ag accumulated by *Brassica* ha^{-1} would amount to 16,000 kg × 2885 mg kg^{-1}, yielding 36 kg ha^{-1} of Ag uptake by *Brassica* biomass. Figure 3A reports the annual amount of Ag phytoextracted by *Brassica* from total PCB waste generated annually till 2050. Hence, the amount of Ag predicted to be phytomined during 2023 is 67,713.09 kg from an area of 1880.91 hectares (Fig. 3B), and by 2050 the potential for phytomining of Ag using *Brassica juncea* L. form total waste PCBs generation (6.68 Mt), is predicted to be 195,241.79 kg from an area of 5423.38 hectares.

Fig. 3 Projections of the **A** annual global e-waste and PCB generation till 2050 **B** phytominable Au and Ag by *Brassica juncea* from the PCB waste. The projections have been made using the reported estimates of global e-waste generation, rate of annual increase in e-waste, PCB content in the e-waste, probable contamination level in farm soil, bio-leachability of Au and Ag, phytoaccumulation of Au and Ag in *Brassica juncea* biomass, requirement of land for phytofarming etc.



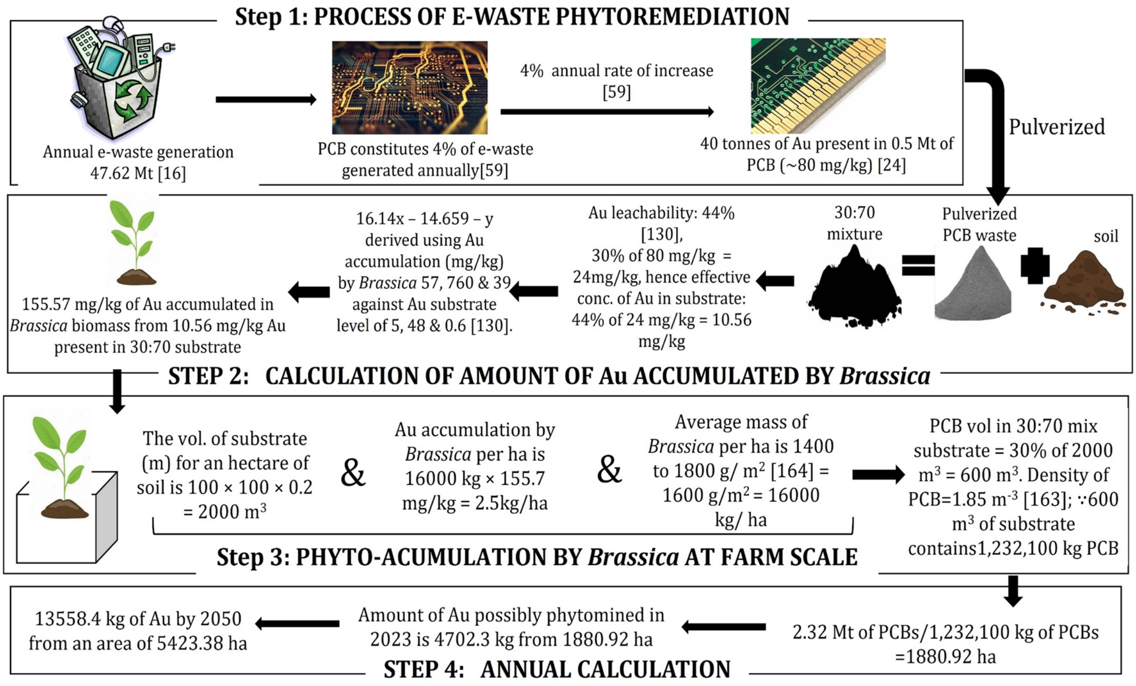


Fig. 4 Flow diagram of the methodology adopted for calculation of the phytominable Au and the area of land required till 2050

Advantages and limitations of metal recovery technologies

Selecting an efficient e-waste management system is a challenge due to varying factors, including different regional policies, limited resources, untrained personnel, and a lack of technology understanding [19, 193]. Each management system has varying feasibility depending on the type of e-waste and the available infrastructure. Table 5 presents advantages and limitations of available e-waste management technologies.

Pyrometallurgy is the most traditional method for metal extraction from e-waste, but has poor flow control, leading to metal loss and risk of dioxin formation. Hydrometallurgy offers better control, accuracy, and is a greener option, but mostly focuses on Cu and precious metal recovery. Leaching of metals with mineral acids is most common, however lacks selectivity. Ammonia-based leaching has high selectivity to Cu, whereas bio-metallurgy using bacteria usually acidophilic groups is favored for metal extraction from PCBs, However, bioleaching suffers from low reaction rates, metal deposition, long reaction times, and bacterial toxicity [80, 203].

Chemical leaching methods have the advantage of short processing time but high maintenance and energy costs. On the other hand, bio-leaching methods are environmentally friendly, simple, and have low energy consumption but long duration of operation and dependence on environmental conditions. Direct dumping and incineration of e-waste are prevalent in developing nations but contaminates the environment. Energy recovery through incineration may reduce e-waste quantity and recover thermal energy but requires high initial investments.

Direct dumping and incineration of e-waste are considered the last resort for e-waste management, unfortunately, these methods are prevalent in developing nations. These approaches can potentially contaminate the environment through the emission of fumes and HM leaching into the soil [193, 204]. However, with the use of sophisticated technology, incineration may be capable of recovering heat energy [37, 193]. Energy recovery through incineration may help to reduce the abundant quantity of e-waste at a fast-processing time and recover thermal energy to substitute for the use of fossil fuels [37]. E-waste is composed of several components such as plastic waste, which have a high calorific value and may help to contribute to excellent energy sources through an appropriate energy recovery technique. For example, burning electronic chips, which contain a large portion of volatile composites (83.44%) can provide a prominent source of energy [205]. Besides, catalytic de-polymerization process technology (CDPT) can potentially generate 40 MJ/kg energy from plastic in e-waste [193]. As a result, energy recovery is a good technique for managing e-waste; however, it involves high initial capital investments [193, 204].

From the circular economy and environmental viewpoints, recycling e-waste through various means, such as metal and energy recovery, will be a crucial sector shortly, owing to its waste utilization properties and its commercial

Table 5 Advantages and limitations of current e-waste management and metal recovery approaches

Technologies		Advantages	Disadvantages	Environmental impacts	References
Informal e-waste management practices	Landfilling	• Cost-effective method • Does not involve any intensive procedures • Does not require pretreatment for e-waste collected	• Slow degradation process • Requires leachate treatment • Not suitable for non-biodegradable materials • No material and energy recovery	• Soil toxicity • Carbon emission • Global warming	[38, 173, 193]
	Incineration	• An organized and controlled technique • Huge waste reduction rate • Very fast processing time • Can use for energy recovery	• Requires good incinerator design • Energy intensive procedures • Requires downstream processing for ash generated	• Production of toxic gases • Climate change	[37]
Conventional e-waste recycling method	Physical separation	• Separates various waste materials, metals, plastic and glass • Removal of hazardous materials	• Hard to dismantle newer complex electronic and electric products • Time-consuming • Increased risk of public health and safety	• Greenhouse gases emissions • Generates dust from the shredding process	[31, 33]
	Pyrometallurgical	• Fast and physical shape of the e-waste is not important against chemical processes • Recovery rates of valuable metals > 95%, where ceramics and plastics may be separated • Melting point is low with good liquidity of materials	• Not economical due to high energy (temperature) consumption • Hydrocarbon chains break down into molten alkaline compounds • Very low basicity in this process which may stop the separation of valuable metals	• Production of toxic gases (dioxin and furans)	[77, 194–197]
	Hydrometallurgical	• High recovery rate with low energy demands • Chemical reactions are performed in organic and aqueous solution to extract metals	• Requires high concentration of acids and expensive solvents	• Environmental hazards due to toxic reagents • Large amount of byproducts • Cl_2 emission to the atmosphere • Leachate is toxic and causes health risk	[67, 72, 196–198]
	Bio metallurgical	• Cheap and low energy consumption • Operating conditions at ambient pressure and temperature • Can be used for highly contaminated metals	• Longer operating period than chemical sales • Dependence on environmental conditions	• Environmentally friendly (green technology)	[199]

Table 5 (continued)

Technologies		Advantages	Disadvantages	Environmental impacts	References
Non-conventional recovery method	Phytoextraction (Phytomining)	• Low-technology methods • Cost-effective • Utilizes hyperaccumulator plants that have high selectivity towards metals	• Focuses on the metal's recovery in a medium, such as rocks, soils, water, etc • Plant influences by some abiotic and biotic factor throughout the process • Time-consuming • Downstream or recovery processing has yet to explore • Limited to the purification of dilute solutions	• Environmentally friendly (green technology)	[46, 200]
	Combined process	• Efficient enrichment • Less time-consuming • Can achieve metal specific extraction	• High installation cost due to hybrid techniques • High energy consumption	• Minimize pollution	[201, 202]

prospects [72, 206]. Several advantages of the hydrometallurgical method are the possibility of recovering the precious metals in the first stage which are suitable for a small volume of e-waste, cost-effective and lower energy consumption as compared to other recycling methods. However, the disadvantages include the high volumes of effluents and wastes, the requirement of chemical and acidic substances, low efficiency and the production of hazardous effluents which requires precautionary measures [155]. The recovery of precious metals through hydrometallurgy is often associated with environmental concerns due to the use of strong chemical lixiviants, producing highly toxic wastewater [19, 34, 67]. Thus, integrated wastewater treatment is imperative to treat the high volumes of wastewater, indirectly increasing the overall operational cost [34, 67]. The application of biotechnology in e-waste management through the bio-metallurgy process has initiated a myriad of studies to explore the feasibility to overcome the limitations of the present recovery methods [19, 72]. The utilization of microorganisms in recovering metals from e-waste is relatively economical and beneficial to the environment.

An integrated process such as a combination of methods using pyrometallurgy or hydrometallurgy with bioleaching was studied to improve the recovery efficiency of the metal in e-waste [201, 207]. However, this hybrid process is still at the infant stage where various studies are required especially on the downstream processing of the metal recovery in bioleaching [207]. Although, the phytoextraction (phytomining) of precious metals is a promising approach; however, the phytomining in both pilot and industrial scales is not operational. Furthermore, a robust economic review is necessary to determine the potential profits for commercial-scale phytoextraction operations [157, 158].

Conclusions and way forward

Recycling of e-waste for extraction of precious metals viz. Au, Ag, Pt and Pd is occurring in various proportions across the globe, mostly through the informal sectors. The extraction of precious metals from the e-waste in developing nations occurs through manual scavenging, pyrometallurgy, and hydrometallurgy, which are not only hazardous to the people but are also to the entire environment. In the future (2022–2050), the e-waste is estimated to increase from present 47.62–167.05 Mt, with an average annual rate of increase in e-waste generation of 4%. The source of e-waste, particularly the PCB are the rich source of precious metals, with estimated level of Au and Ag in 80 and 1000 mg kg^{-1}, respectively, almost 40–70 times higher than the natural ores. In contrast to the conventional recycling of e-waste for precious metals, which are mostly physical and chemical, integration of bio-leaching (*Acidithiobacillus ferrooxidans, Chromobacterium violaceum* and *Pseudomonas putida*) and some tolerant plants for phytomining viz. *Brassica juncea, Helianthus annus, Cannabis sativa* and *Berkheya coddii* for Au as well as *Brassica juncea* and *Brassica napus* for Ag can be used for precious metal phytomining from e-waste. It is estimated that 2.5 kg ha^{-1} and 36 kg ha^{-1} of Au and Ag, respectively can be extracterd from PCB e-waste using oil crop, *Brassica juncea*. Phytomining of Au and Ag from PCB can be a profitable enterprise using e-waste slurry in hydroponics and extraction of the precious metals through electro-chemical process thereafter.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-023-01717-5.

Acknowledgements The authors (K, SM) are thankful to the Director NBRI for providing necessary financial support (OLP0102) and infrastructure. The authors (NHZ, CCN) are thankful to Xiamen University Malaysia for providing the necessary support. The MS was subjected to Ethical checking through the "Ethical clearance committee", upon scrutiny the MS has been allotted a "CSIR-NBRI_MS/2022/01/10" as identification number.

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