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Green Processes for Electronic Waste Recycling: A Review

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Abstract

Electronic waste (E-waste) generation is evaluated at 20–50 million tons, representing 1–3% of the general waste generated yearly worldwide. The large quantities of outdated and life-ended electrical and electronic equipment make it a fast-growing waste production all over the world. Printed circuit boards (PCBs) are the most highly valued precious components of E-waste. Apart from valuable metals, PCBs contain many dangerous and hazardous substances. The very unpredictable mix of such different important and hazardous materials combined in a small volume poses serious challenges for the recovery and recycling of these constituents. To prevent toxicity of these contaminants to humans and environment, it is inevitable to analyze the peculiarities and compositions of various materials in E-waste and determine how to manage their recycling via green ecofriendly processes. This paper will deal with the outline of E-waste problem, its diverse categories, composition, management, and various recycling processes especially the green ecofriendly ones with unique attention toward extraction of valuable metals. Unfortunately, despite the fact that many efforts to develop recycling technologies have been endeavored, these technologies are still rather exclusive and inadequate because of the intricacy of the E-waste system. Hence, the demerits of each process are debated and discussed from the viewpoint of technical advancement and environmental protection.

Keywords E-waste · PCBs recycling · Green processes · Metals recovery · Physical processes · Chemical processes · Bioleaching

Introduction

Environmental management of noxious wastes has attracted a main interest across the world due to the unbridled dumping into the ecosystem in a reckless way leading to possible risks. Currently, nearly 1.3 billion tons of wastes are generated yearly across the world [1], which will be expected to increase to 4.3 billion tons per annum by the year 2025. Electronic waste (E-waste) generation is growing very fast around the world [2], with the rate of generation being threefold higher than any other waste [3]. It is one of the principal contributors to environmental contamination, the reason why it is strongly required to

develop effective recycling techniques for its mitigation [4, 5]. It is predicted that E-waste generation from old computers would rise by 500% and that from the discarded mobile phones would be nearly 18 times higher by the year 2020 compared with the year 2007 [6].

E-waste contains both valuable and hazardous metals which require special handling and recycling methods to diminish environmental contamination and hazardous effects on human health. Knowledge and understanding the compositions of E-waste components help to recycle the components effectively. Several existing recycling processes and techniques are convenient for management of E-waste, but the selection and adoption of an appropriate process need a cautious approach, which depends upon the material composition, and thus it becomes quite important to know about its components. Advanced electronic equipment contains nearly 60 different elements including valuable and hazardous materials. The most complex and valuable materials are found on printed circuit boards [7]. Printed circuit boards (PCBs) are the basic component whereupon electronic items are assembled. They are used to uphold and connect the electronic components together

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using conductive tracks etched from copper sheets laminated onto them [8]. PCBs are viewed as the most economically valuable component of E-waste. Yet, the fact that such a highly complex blend of various valuable and sometimes hazardous materials is constrained in such a small volume poses serious challenges for recycling the constituent substances and materials. The heterogeneous mix of organics, metals, fiber glass, toxic materials including heavy metals, and plastics makes the processing of PCBs a really challenging task. Recycling of waste PCBs (WPCBs) is a very crucial issue for treating waste and recovering valuable metals. In general, WPCBs are incorporated with around 30% metals such as copper, iron, tin, nickel, lead, zinc, aluminum, and precious metals [9, 10]. Beside metals, toxic substances, such as brominated flame retardants (BFR) and polyvinyl chloride (PVC) are also included [11, 12]. Their recycling is a complicated, costly process due to the variety of components, and thus, the associated difficulty in separating them. Marques et al.'s [8] processes based on pyrometallurgy and hydrometallurgy [13–18] are usually used for extracting and recovering metals from WPCBs. In industries, the recycling of E-waste is carried out basically through pre-treatment and pyrometallurgical processes. One of the main international copper manufacturing companies, Aurubis Global, professionally processes electronic waste in addition to other copper materials and precious metals [19, 20]. The main pyrometallurgical procedures used are two reduction processes in a submerged furnace, followed by oxidation process in an anode furnace. The product which is 99% copper is cast into copper anodes, and electrowinning is then applied to purify copper [19, 20]. Other international companies, such as Umicore integrated smelting and refining facility, the Noranda process in Quebec, Rönnskär smelters in Sweden, and Kosaka's plant in Japan, applied several industrial methods for recovering metals from E-waste [21].

Only partial extraction of metals can be attained by thermal processing, leading to a limited recovery of metals. Moreover, further leaching or electrochemical processing is required. Precious metals stay for an extended period during the process and are recovered later at the end of processing. Recent research done on energy recovery from personal computers waste offers an associated example for use of plastics in electronic waste. It indicates that thermal processing of E-waste provides a possible approach for recovery of energy from E-waste if an efficient emission control system is installed [11].

Recently, there have been many researches on hydrometallurgical treatment of E-waste for metal recycling because it entails lower cost, less environmental impact, and is easier to manage compared with pyrometallurgy [3]. Research on the hydrometallurgical method is

directed to precious and common metals' recycling [22]. The targeted metal for recycling in hydrometallurgy is mainly copper because of its high content in waste PCBs [23]. Mostly, the essential steps in hydrometallurgical treatment consist of leaching, purification, and recovery. Leaching treatments of waste printed circuit board can be sorted into four categories: acid, ammonia, ammonium salt, and chloride; other ways of leaching and some of these methods are industrially applied [24, 25]. Commonly, copper is dissolved in leachants, then the solution goes through solvent extraction to improve copper purity, and finally, pure copper is obtained by electrowinning [26–29].

Some of the E-waste recycling processes are related with certain disadvantages that limit their application on the industrial scale because of their slowness, time consuming nature, and adverse impacts on the environment. Some leachants used in hydrometallurgical processes are hazardous and pose serious health risks to the people, and should, therefore, be manufactured or used in accordance with high safety standards. Moreover, there are issues concerning the costs of hydrometallurgical processes compared with pyrometallurgical processes used for the extraction of metals from E-waste [11]. Pyrometallurgical processes have also some disadvantages such as generation of a large amount of slag, loss of precious metals, and difficulty in the recovery of Al and Fe, and other metals [11].

Hence, it is necessary to summarize and discuss in detail the recycling processes of E-waste, especially WPCBs, taking into consideration the concept of “Green process”. Based on environmental protection and resource recycling utilization for the metals, some green integrated recycling processes free from pollution and having high efficiency for E-waste treatment were presented and discussed.

Different Categories of E-Waste

E-waste is an expression referring to all spent electric and electronic devices that have been discarded by its users. Based on the European WEEE Directives 2002/96/EC and 2012/19/EU [30, 31], it is sorted into different types. These types include big and small household appliances, information technology and telecom equipment, consumer equipment, lighting devices, electrical and electronic non-industrial tools, toys, relaxation and sports equipment, medical noninfected devices, monitors and control units, and automatic dispensers as shown in Fig. 1 [32, 33].

E-waste Categories	
Category 1	Monitoring and control equipment
Category 2	Electrical and electronic tools
Category 3	IT and telecommunications equipment
Category 4	Automatic dispensers
Category 5	Toys, leisure and sports equipment
Category 6	House hold appliances(Large & Small)
Category 7	Consumer electronics
Category 8	Medical devices

Fig. 1 Different categories of E-waste (color figure online)

E-Waste Composition and Characteristics

The structural composition of E-waste depends commonly on the type and the model of the electronic device, its manufacturer, date of manufacture, and the age of the scrap. Larger amounts of precious metals are included in scrap from IT and telecommunication systems than those in the scrap from household equipment [23]. For instance, a cellular phone contains more than 40 elements, base metals such as copper (Cu) and tin (Sn) and precious metals such as silver (Ag), gold (Au), and palladium (Pd) [34–36]. Circuit boards in the majority of the electronic equipment may contain toxic elements such as arsenic (As), chromium (Cr), lead (Pb), and mercury (Hg). Ended-life cathode ray tubes (CRTs) in televisions and computer monitors contain barium, copper, lead, zinc, and other rare earth metals. Therefore, most countries have prohibited cathode ray tubes disposal through landfilling. The changing composition of constituents due to the development of technology has led to a severe challenge in evolving policies to manage E-waste [37]. Various factors affect the composition of E-waste, including economic conditions, the reuse market, the recycling industry, waste separation programs, and

control execution. Figure 2 adapted from [32] shows the characteristic material fractions of E-waste components.

E-Waste Management

Commonly, in waste management, waste materials are gathered, transported, disposed or processed, and recycled aiming to diminish their harmful influences on health or the environment. It is also conducted to regain resources from it. Some of the important processes utilized in dealing with E-waste incorporate the following:

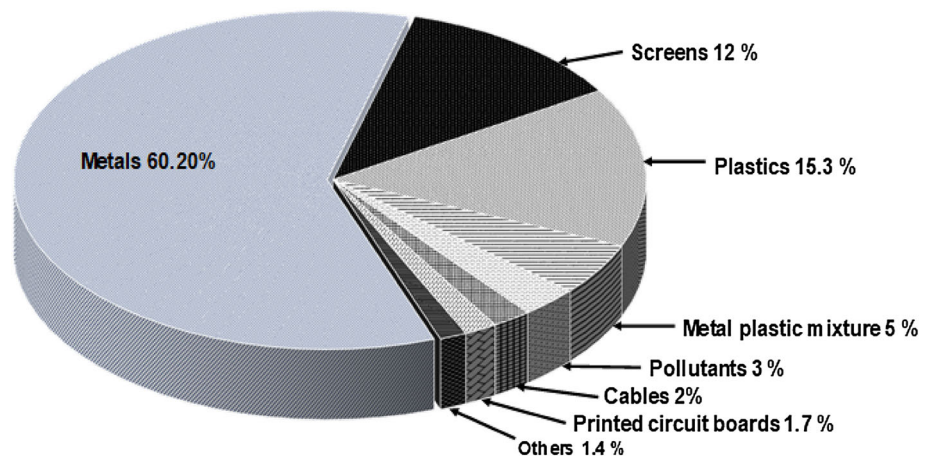
Landfill Disposal

One of the used methods for disposing E-waste is to bury it. Mining voids or burrow depths can be used in land filling. E-wastes ending up as landfills may release pollutants to the environs after some years in natural ways. Leaching some wastes such as batteries may possibly release acids and heavy metals like mercury, nickel, and cadmium. Moreover, E-waste landfills may pollute groundwater [38, 39]. After diffusing into the land soil, polluted water will mix with other water sources such as rivers and streams, and thus cause a potential harm when used by animals and humans [40]. Organic and decayed materials in landfills decompose and penetrate through the ground as landfill leachate containing high amounts of polluting substances depending on the waste type and its decay stage [41].

Thermal Treatment

Thermal treatment of e-waste is carried out by either incineration or pyrolysis. Incineration is a method of throwing out waste by burning it [42]. It usually acts as an

Fig. 2 Characteristic material fractions in e-waste [32] (color figure online)



alternative to other disposal methods, especially landfilling. Incineration can lessen the volume of waste and the energy content of its combustible materials. When burning the waste materials, a reduction in its volume occurs, and the materials' energy content can be utilized. Thermal treatment also includes pyrolysis (heating the substance in the absence of oxygen) wherein the substances are converted to fumes, oils, and charcoal.

When burning the plastic or PVC circuit board, the fumes consist of carcinogenic polycyclic aromatics, dioxins and polychlorinated dibenzofurans, and gases such as oxides of carbon, sulfur, and nitrogen are released and minor quantities of heavy metal oxides could be present in the smoke. Although the burning method is a simple, low-cost process, it has been prohibited because of its serious pollution of the environment [43–45]. E-waste incineration plants contribute significantly to the yearly emissions of cadmium and mercury [46, 47].

Re-use Method

Herein, the original hardware is second-hand or used after minor changes. This method has an advantage of reducing generated e-waste volume. However, inducements offered by the retailers to monetize the old appliances by exchanging against new ones are marketing gimmicks for accelerating sales volume. The actual benefits to the consumer in the new-for-old exchange practice are notional once seen commercially [48].

Recycling Method

Recycling is defined as the reworking of the wasted materials for performing the original function or for some other different purposes. Recycling of E-waste comprises disassembly and/or destruction of the wasted equipment to recover their substances. It is an important process in terms of waste treatment and recovering valuable materials. It is also a beneficial alternative relative to disposal. The US Environmental Protection Agency (EPA) has identified distinguished real advantages, such as energy savings and decrease in pollutions, when scrap materials are utilized rather than virgin materials.

Utilizing recycled materials in place of virgin materials results in noteworthy energy savings [49]. The prime targeted aim of recycling E-waste scrap is to diminish the harmful environmental impact caused by hazardous materials and ensure maximum material recovery. To accomplish these goals, detailed information of the E-waste components is required for choosing the right recycling method and facility [50].

Waste Printed Circuit Boards

While dealing with the growing volume of E-wastes, recycling of printed circuit boards (PCBs) is known as one of the most difficult tasks considering their complex structure and the consequent complicated blend of materials [51]. PCBs are fundamental constituent materials in an extensive variety of electrical and electronic hardware (televisions, personal computers, mobile phones, and laptops).

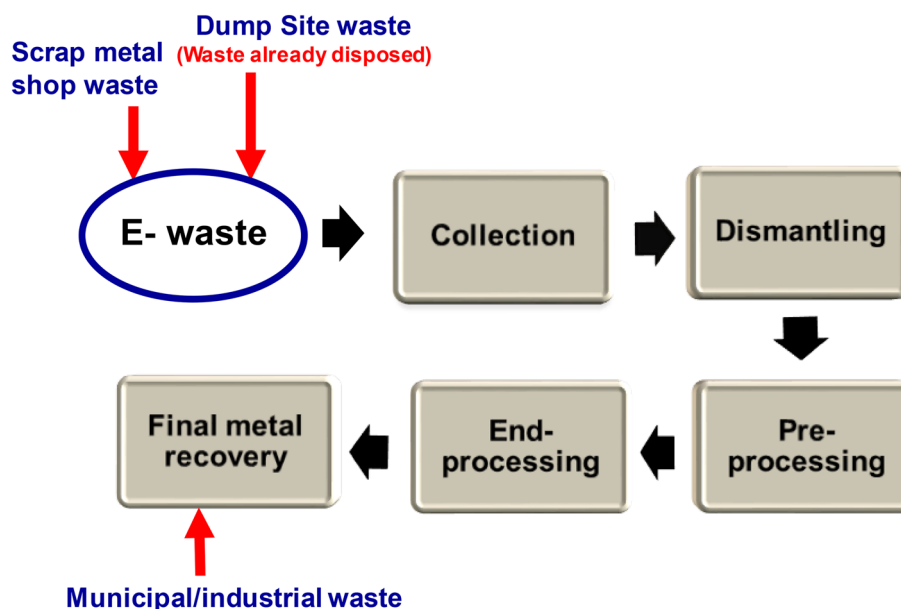
Printed circuit boards (PCBs) are composed of three types of materials: a nonconducting substrate or laminate, printed conducting tracks, and components mounted on the substrate. The substrate is typically composed of glass fiber reinforced with epoxy resin or paper reinforced with phenolic resin, both with brominated flame retardants [50]. Polymers and industrial plastics are other major constituents of PCBs that contain polyethylene, polypropylene, epoxies, and polyesters [21].

WPCBs have been paid careful attention by researchers and industrial personnel, due to their wealthy resource content and associated feasible risks on human health and environment when recycled informally and inappropriately. In this manner, factors that affect metal extraction are financial viability, recovery effectiveness, and environmental impact. WPCBs recycling process for the highest optimal recovery of metals generally includes three stages: pretreatment, size reduction, and metallurgical treatment. Pretreatment means compositional analysis and careful disassembly of the toxic parts by thermally or chemically desoldering [52, 53]. The materials are then shredded, crushed, and screened to reduce their size [3, 5, 11, 49, 54–57]. Metallurgical treatment involves thermal treatment [58, 59], leaching [60], electrolysis [61], and biological [22, 62] processes for recovery and purification of the metals [63–66].

E-waste Recycling and Treatments

Incineration, landfilling, and export to abroad are banned in recent years for E-waste management due to the strict laws that are enforced in developed countries such as the European Union (EU), the United States (US), Australia, and Japan [67]. Thus, environmental worries and the presence of reusable metals or components provoke the need to recover heavy and precious metals from E-waste, before disposing them off into the environment. However, environmental consequences and high-energy demand are the major limitations which hinder their use at large scale. Pyrometallurgical methods may be energy-intensive and high-cost processes [68]. They generate large amounts of slag, and may lead to the formation of mixed halogenated

Fig. 3 Basic E-waste recycling process (color figure online)



dioxins and furans which can be avoided by availing proper off-gas treatment [11, 21]. Hydrometallurgical treatment of E-waste frequently uses cyanide [69, 70], halide [71], thiourea, and thiosulfate [72, 73] as leaching agents to extract most valuable components [8, 74–77]. Bio-hydrometallurgy has also been applied, to leach valuable metals from waste printed circuit board (WPCBs) [60, 78]. Valuable metals can be further recovered from leaching solution through adsorption by means of biomass waste including microbial biomass [79].

Chelating agents have been used by many researchers for the effective and efficient removal of metals such as Zn, Cu, and Pb from E-waste [80–82]. Chelating agents could be used to extract metals, due to their ability to form soluble and stable metal complexes [83]. EDTA and Nitrilotriacetic acid (NTA) have been found capable of extracting up to 86% of Cu, Pb, and Zn. Di-Palma and Mecozzi [84] found that Cu and Pb can be more effectively extracted with EDTA than with citric acid, whereas Kolencić et al. [85] used *Aspergillus niger* fungi, along with citric acid and oxalic acid, and found it to be effective as a pretreatment or a final phase of E-waste metal recycling [86].

Unfortunately, even though several conventional methods are available, they sometimes just transfer the pollutants from one place to another. Researchers are therefore trying to develop more environmentally friendly processes that can efficiently solve this problem. Most of the used recycling practices aim to recover valuable metals from E-waste using physical and chemical methods.

It is usual in waste management that wasted materials are collected, transported, disposed off, or processed and recycled to diminish their harmful effects on health or the environment. Several recycling processes are used and the

proper process depends on type of the material, its metal content, and volume. However, to extract valuables from E-waste, it must endure a basic process including collection, breaking, and detaching, pretreatment, and final metal recovery as revealed in Fig. 3.

Several issues have to be considered in evolving a new treatment for recycling WPCBs driven by novelties, societal effects, and influence on the environment, a unified waste management plan, and the procedure economics. The WPCBs are various and complex in terms of type, size, configuration, components, and composition. Over time, the composition of PCBs is continuously changing, making it more challenging to acquire a constant material composition. In general, the recycling techniques of WPCBs can be abridged as physical recycling methods and chemical recycling methods.

Separation of metals and nonmetals from WPCBs as a rule completed by physical techniques relies upon various parameters, for example, separation by shape, density, electric conductivity, and electrostatic properties [11]. Then again, chemical recycling forms incorporate gasification, burning, and pyrolysis. Metallic fraction can be treated by pyrometallurgical, hydrometallurgical, or biotechnological process, and the recovery process becomes more complicated when the elements are available in minor concentrations. The recovery of metal values, which is nearly 30% of the full weight of WPCBs, is the primary motive for recycling, while the nonmetallic materials (approximately 70%) have rather less economic values. The main targeted aim of most recycling processes is to recover the most valuable metals from WPCBs using processes which occasionally are not very ecofriendly.

Physical Treatment Processes

Physical processes are commonly applied during the upgradation stage when various metals and nonmetals contained in E-waste are liberated and come apart by some means of shredding and crushing processes. The effort to recover the valuable metals in particular Au, Ag, Pd, and Cu has received enormous attention in recent years using extraction processes such as physical, chemical, and combined pyro/hydro leaching separation routes. Physical processes include dry crushing and pulverizing and then high-voltage electrostatic separation to get a variety of metal powders (Cu, Pb, Zn, Al, Sn, Au, Ag, etc.) which are conductive and nonmetallic resin powder materials which are nonconductive. The consequence of a recycling process can be measured from two aspects: the material recuperation proficiency and the effect on the environment. Physical separation processes gain low running expenses and experience from a high valuable metal loss (10–35%) due to insufficient metal liberation. To evade pollution with dust, a three-stage dust removal equipment (i.e., cyclone, bag, and air cleaner) are commonly practiced. This type of physical WPCBs recycling systems has a separation efficiency reaches 99%.

Mechanical method has been considered as the preferable recovery technology for E-waste since no secondary pollution was taken out during the process [87–90]. Magnetic separation has been generally used in mineral processing or solid waste industry to recover magnetic materials from other materials [91]. Conversely, to recover the nonferrous metals such as Cu, Al, Pb, and Zn from the solid E-wastes, eddy current separation has been used [92, 93]. Table 1 summarizes physical methods for recycling E-waste.

Physical recycling methods have many advantages. They are simple, appropriate and environmentally friendly processes. Their equipment and energy used are low cost and potential application of the products is distinguished. Significant dust generation and metal loss during shredding and grinding are some important weaknesses of the performance. Nowadays, some developed countries generally use physical processing of E-waste for the recovery of raw materials. Their process flowcharts include manual selective disassembly, shredding, magnetic and electrostatic Eddy current separations [100].

Chemical Treatment Processes

Various researchers studied the extraction methods of copper, lead, and zinc and precious metals from E-waste using chemical methods [88, 101–103]. These methods are based on the classic hydrometallurgical technology of

metal extractions from their ores. Acids or alkalis are used as leachants for dissolution of precious metals from E-waste, and then they are separated and purified for the metal content enrichment and removing impurities. The wanted metal is separated through solvent extraction, adsorption, or ion exchange processes. Lastly, metals are recovered from solution via electrorefining or chemical reduction processes [26, 27, 29, 104, 105]. The processes utilized for recovering metals from E-waste were surveyed and described by Cui and Zhang [11]. Hydrometallurgical chemical processes were found to have extra benefits when contrasted with pyrometallurgical processes since they are more particular, expectable, and easily controllable [106]. A concise clarification of the green hydrometallurgical processes is given in Table 2.

Although chemical processes have been successfully used to recover metals from E-waste, they are accompanied with some disadvantages limiting their industrial-scale application [112, 113]. Chemical process operations are tedious, time consuming, and impact recycling economy. However, mechanically handling the E-waste to reduce the size required for efficient dissolution consumes long time. Approximately 20% of metals is mechanically lost during the liberation process that leads to a substantial reduction in the overall metal recovery. Moreover, halide leaching is difficult to enforce due to strong corrosive acids and oxidizing conditions; besides, special equipment made of stainless steel or rubbers is required for the leaching process. Also, there are risks of metal losses during subsequent steps affecting the overall recovery of metals.

Bioleaching Treatment Processes

Bioleaching process is a well-thought-out one of the most auspicious technologies in metallurgical processing. It is considered a green technology [114, 115] having a lower operative cost and energy demands when comparing with chemical methods [116]. It is an excellent process for extracting metals from low-grade ores [117–121]. Bioleaching is technically practicable using bacteria-assisted reaction to extract base metals such as Cu, Ni, Zn, Cr, and precious metals such as Au, Ag, from E-waste. Recently, some studies for extracting metals from E-waste scrap have been done by many researchers [122–124]. Heavy metals were excellently leached when Acidophilic bacteria were used [125–127]. For example, Wang et al. [128] succeeded in mobilizing metals from WPCBs using *Acidobacillus* bacteria. The bacteria, *Acidithiobacillus ferrooxidans* (*A. ferrooxidans*) and *Acidithiobacillus thiooxidans* (*A. thiooxidans*), were grown and accustomed in WPCBs and then used as bioleaching bacteria to solubilize metals. Very few studies reported the use of fungus for recovery of metals from E-waste [81, 85, 122, 129].

Table 1 Physical processes for the E-waste recycling

Method	Conditions	Materials separated/metals recovered	Process description	Advantages	Disadvantages	References
Supergravity separation	Optimal conditions include a gravity coefficient of 1000, centrifugal time of 5 min, and temperature of 410 °C	Pb–Sn alloy	<p>The centrifugal device had two centrifugal containers. The first is used for heating and centrifuging samples, whereas the second is used for balancing the equipment to keep the centrifugal process stable</p> <p>PCB particles were added into a set of graphite crucibles having some small holes. The crucible was heated to the preset temperature, holding time for 30 min, then the centrifugal device was rotated at a definite angular velocity. Finally, the centrifugal apparatus was closed off and the crucible quenched in water</p>	The process has a sure positive effect on the environment in the resource-saving society	Formation of some solid solutions of Sn leads to low recovery of Sn	Meng et al. [94]
A three- step separation process of sieving, magnetic separation, and dense medium separation	Electric/electronic components (EECs) were disassembled under several treatment conditions with variations in the speed of grinder (2500, 5500 rpm), the height of grinder (0.5, 1.5 mm), and the rotational speed of the PCB on the apparatus (1, 3, 5 cm/s).	Disassembly of EECs from WPCBs	<p>An effectual device for removing EECs from PCBs consists of three units. The principal unit is a feeding unit with three rotating arms, one of which has nine pressing cylinders to fix and move PCB. The second one removes the EECs from the PCB with four grinders that wear out the solder junctions on the backside of PCBs. The third one receives the separated EECs and the scratch powders containing firm metals, using a vacuum and back-filter system</p>	<p>Enhances the recycling percent of metals in WPCBs</p> <p>Minimizes emissions after recycling</p> <p>The disassembled EECs can be reused as restoring components in PCB manufacturing</p>	Maximum separation efficiency was less than 60%. Therefore, other methods should be suggested for improving separation efficiencies and reusing these EECs	Lee et al. [95]
Rotation disassembling cylinder (RDC) and vibration segregating screen	System operates under normal pressure and incubation period are 265 ± 5 °C, 10 rpm, and 8 min.	Separation of ECs from WPCBs	<p>Using rotation disassembling cylinder (RDC) and vibration segregating screen (VSS) to replace the conveyor and pulse jet.</p> <p>(2) Increasing the diameter of air pipe and adding EHPs around the RDC to guarantee the evenness of the temperature field inside the ECs-ADM, thus melting solder efficiently.</p>	<p>No harmful impact on the worker health and environment</p> <p>No gas leaked</p> <p>Applicable for most WPCBs kinds</p>	Some toxic substances are released during this process due to its low operating temperature	Wang et al. [70]

Table 1 (continued)

Method	Conditions	Materials separated/metals recovered	Process description	Advantages	Disadvantages	References
Electrostatic Separation	In the first stage, the parameters of electrostatic separator were set as $U = 30$ kV and $n = 50$ rpm In the second stage, the parameters of the electrostatic separator were set as $U = 5$ kV and $n = 80$ rpm	Separation of conductors and semiconductors In the first stage, woven glass was separated from the mixed particles In the second stage, copper was separated from silicon on conductors.	Two-stage separation processes were done to separate a multiplex mixture containing copper (20 g), silicon (5 g), and woven glass reinforced resin (75 g) with size $- 0.45 + 0.3$ mm	Simplicity, low energy consumption, and no wastewater discharge	Higher voltage level Higher roll speed	Xue et al. [153]
Vibration separator	PCB particles (less than 1.5 mm in size) can be separated under dry conditions by the application of a vertical vibration separator	Separation of metallic from nonmetallic fractions of PCBs (95% separation)	Dry separation approach in which vertical vibration is applied for separating the metallic and nonmetallic components of PCBs. When PCBs were ground to less than 1 mm in size, metallic grades as high as 95% could be attained in the recovered products	Dry treatment in absence of water limiting dewatering and sludge disposal cost Offered the potential for easier process integration	Successive stage cutting and milling are required for higher metal liberation	Habib et al. [96]
Centrifugal separation and vacuum pyrolysis	Pyrolysis condition vacuum condition at 600 °C for 30 min Separation condition at 400 °C under vacuum condition, and the rotating drum was rotated at 1200 rpm for 10 min	Organic materials and solder from WPCBs	WPCBs were thermally treated under vacuum at 600 °C for 30 min in a laboratory reactor. The attained pyrolysis residue was heated under vacuum then the molten solder was separated from the pyrolysis residue by the centrifugal force	Clean and cost-effectively recovering solder with high separation and recovery efficiency	Needs further treatment for recovering various metals contained in the pyrolysis residue	Zhou and Qiu [97]
Inverse flotation process	The pulp was carried out by mixing water with the 250 µm material with a solid content of 1.25 wt.% for 15 min at room temperature. The optimal operating condition of the flotation column is achieved with a superficial air velocity of 0.4 cm/s	Separating the metallic fraction from the nonmetallic fraction	Using a lab-scale flotation column with 250 cm length and diameter 9.5 cm with a manage loop to adjust the froth depth, using a pressure transducer, which was connected to the controller and an electronic signal was sent to the peristaltic feed pump	The process does not use any chemical reagents but only water and air for the flotation process hence, avoiding environmental pollution	prevents the creation of more e-waste and hence reduces pollution associated with this waste	Estrada-Ruiz et al. [98]

Table 1 (continued)

Method	Conditions	Materials separated/metals recovered	Process description	Advantages	Disadvantages	References
Mechano-chemical activation	Co-milling with mixtures of $K_2S_2O_8$ and NaCl.	Soluble metallic compounds were separated (Cu, Pd, and Ag)	<p>E-waste particles were milled in a 250 mL-capacity corundum pot with 120 g zirconia balls (9 mm in diameter) then, activated by co-milling reagents of NaCl, NH_4Cl, EDTA-2Na and mixture of $K_2S_2O_8$ and each of the three reagents</p> <p>After milling, the ground sample mixed in 0.5 mol/L diluted hydrochloric acid, stirred for 15 min. at room temperature. Then, the mixture was filtrated and the residue was collected and dried at 105 °C</p>	<p>Highly efficient and quick leaching speed</p> <p>Avoiding the use of corrosive mineral acids, consequently avoiding the release of gaseous pollutants, such as NO_2 or NO</p>	Care must be taken in management of diluted acidic wastewaters and a small amount of ammonia containing wastewater	Zhang et al. [99]

Because of constant supply of nutrients for fungal growth, handling of fungi in turnover and long processing time restricts the use of fungus [130]. Besides these limitations, fungal bioleaching has several advantages over bacterial bioleaching: they can grow at high pH, which makes them efficient for alkaline materials bioleaching. They can leach metals rapidly and conceal organic acids that chelate metal ions, thereby, being useful in metal-leaching process [122, 131]. Even with such advantages, still, there is an information shortage about using fungi to leach metals from E-waste [131–134]. The E-waste has no source of energy that is required for growing the bacteria, and therefore, an external supply of nutrients is a must for leaching metals from E-waste. Table 3 shows the mostly used bacteria, and microorganisms for E-waste leaching are given in the table. Although bioleaching process has many advantages, commercial performance of the process is still in the nascent stage. This is imputable to the completely slow nature of this process. Many of the bioleaching processes require long time ranging from 48 to 245 h to recover metals without recovering all the metals present in E-waste [135]. Therefore, there is a necessity to develop a fast and economic bioleaching process that can be applied industrially.

Vacuum Recycling Processes

Metals can be recovered from E-waste utilizing vacuum processes which have no wastewater pollution. Here, the nonmetallic components from E-waste can be removed by vacuum pyrolysis so the metals can be easily recovered [14, 143]. Metals separated out and recovered from WPCBs depend on their vapor pressures at the same temperature. Zhou research group [97, 144] recovered metals from WPCBs by a two-step vacuum pyrolysis process. The chief process separated and recovered the solder alloy at temperature ranges from 400 to 600 °C. In the ensuing process, WPCBs were pyrolyzed and the residue heated under vacuum to recover the solder by centrifugal separation. Glass fiber and other inorganic metals and materials in the resulting residues still need additional treatment. Cadmium (Cd) and zinc (Zn) metals from WPCBs were recycled using vacuum process for their separation [145–148]. The research group used their self-made vacuum furnace, and they succeeded to favorably evaporate Cd and separate Zn because of their vapor pressure differences. The separation of lead found in the solders of WPCBs was more difficult because the Pb–Bi alloy was formed with a low vapor pressure.

He et al. effectively recovered metallic indium from a distinct sort of E-waste which is waste liquid crystal display (LCD) panels, using coke powder as a reducing agent [149]. Indium oxide (In_2O_3) was reduced to metallic

Table 2 Summary of green hydrometallurgical processes for the recovery of metals from E-waste

Method	Metals separated/recovered	Process description	Conditions	Advantages	Disadvantages	References
Supercritical methanol process	Ultrafine copper from PCBs	Waste PCBs were pretreated twice in nitric acid. Sn and Pb were recovered by the first nitric acid pretreatment. The leach liquor with a high concentration of copper ions after the second nitric acid leaching was subjected to SCM process	First step is immersing waste PCBs pieces with different sizes in 8.1 wt% dilute nitric acid solution for 20 min at 90 °C with agitation in a closed chamber Second, the samples were ground to particle size < 4 mm. Dilute nitric acid solution was used as leachant, and the time was managed at 3 h under room temperature Ultrafine copper material particles prepared from the second leachant liquor of waste PCBs by SCM at 360 °C, 28 MPa and a reaction time of 10 min	Simple, efficient process No need to use any reducing agents or surfactants	Involves a longer time and consumes a higher energy	Xiu et al. [152]
Ionic liquid acids	Copper from PCBs	Six ionic liquids (IL) were used to leach copper from WPCBs compared with inorganic acids.	Leaching experiments were carried out in a batch of 250-mL glass conical flasks placed in a constant temperature water bath oscillator, operated at a constant oscillating frequency of 250 rpm at 40–70 °C. WPCBs particle size, IL acid concentration (V/V, in liquid solution), IL acid adding amount, H ₂ O ₂ adding amount, temperature and time were examined.	No disassembling of the electronic components from the PCBs is needed	Effective only for copper	Chen et al. [74]
A green process for cuprous chloride synthesis	Copper from PCBs	PCBs were first cut into pieces then, pretreated by thermal shock. A centrifugal air separator was used to obtain the metallic components after being crushed. The metallic components were treated with solution of cupric sulfate and sodium chloride	The optimal condition (V NaCl/ <i>m</i> CuSO ₄ ratio = 6, [Cu]/[Cu ²⁺] mole ratio = 1.05, treatment time = 30 min, operation temperature = 60 °C), yield of cuprous chloride was 74.0% and about 98.5% of the copper could be recovered	No corrosive acids or strong oxidants were used. High-quality cuprous chloride with a purity of 98.7% was obtained	Effective only for copper And needs pretreatment.	Zhang et al. [110]
Chelation technology	Copper	Two-step process consisting on using a first nonselective Cu leaching step with HNO ₃ followed by a purification step using a chelating bispicolylamine resin with high Cu	The PCBs samples (< 0.250 mm) were roasted in air at 850 °C for 3 h in a muffle furnace, followed by leaching using 2 mol/L HNO ₃ at 50 °C, 210 min, and then using a bispicolylamine resin (0.17 mL/min/g) to recover Cu obtained after eluting, with 4 mol/L H ₂ SO ₄	Simple to operate. Is a low-cost process (use of inexpensive reagents and a resin of low commercial price) Fast (the global process involving a short duration of time)	Mechanical pretreatment required	Neto et al. [107]

Table 2 (continued)

Method	Metals separated/recovered	Process description	Conditions	Advantages	Disadvantages	References
Pyro-hydro hybrid process	Base metals (Cu, Fe, and Ni)	Thermal pretreatment process of pyrolysis on waste PCBs to recover metals using hydrometallurgical route of leaching and solvent extraction	First, pyrolysis followed by physical beneficiation and hydrometallurgical process to recover valuable metals from low metal concentrate (small fraction) of polycracked (pyrolyzed) PCBs left over after vacuum pyrolysis The low metal concentrate obtained after beneficiation was leached in acid under pressure. The leach liquor generated was further subjected to solvent extraction process	The process is cleaner and environmental-friendly with zero waste concepts and enables the subsequent physical beneficiation and hydrometallurgical treatment easier	The process has potential to be commercialized after some validation on pilot-scale studies	Kumari et al. [108]
Chemical desoldering and leaching (patented green chemistry and engineering methodologies)	> 99% copper recovery and Sn and Au	Chemical desoldering (10–20 min at 35 °C) and precious metal-leaching (5–10 min at 30 °C) recovery at near-room temperature using cost-effective, sustainable and scalable methods	Leaching for 20 min in an acidic solution at a temperature between 30 and 40 °C Pb, Sn and Ag salts (typically oxides) are recovered in high purity (> 95% recovery) and are sold. From solder free bare PCBs, Au, Ag, Pd, etc. can be leached with 99.9% efficiency and > 99.9% purity via chemical reduction or electrowinning	No shredding or grinding cost-effective No need for using cyanide or aqua regia Low volumes of chemicals required Near room temperature operation	Needs a site for location near sources of e-waste	Jiang et al. [109]
Chelation technology	Copper (83.8% recovery)	PCB sample was added to the chelating agent solution at alkaline pH and a certain L/S ratio. Slurry was transferred to the reactor used for chelation experiments. After completion of reaction, slurry is vacuum filtered and the filtrate was sent for the dechelation experiments. The insoluble leach residue was washed with distilled water and then dried at 100 °C for 4 h	Particle size of 150 µm. EDTA concentration: 0.5 M, liquid to solid ratio: 15:1 (v/w), temperature: 100 °C, reaction time :3 h, stirring speed: 700 rpm and pH – 7	Zero discharge to the environment	Entails high cost for grinding	Jadhao et al. [80]

Table 2 (continued)

Method	Metals separated/recovered	Process description	Conditions	Advantages	Disadvantages	References
Selective recovery of palladium	Palladium	Palladium was first enriched during copper recovery process and dissolved in cupric sulfate and sodium chloride solution in the form of PdCl_4^{2-} and then recovered by S201(dioisomyl sulfide) extraction In the extraction process, the influence of base metals was negligible due to the relatively weak nucleophilic substitution of S201 with the base metal ions and stronger steric hindrance of S201 molecular, which could be regenerated and used several times for Pd(II) extraction. The recovery of palladium reached 96.9% during the dissolution–extraction–stripping process	Copper in metallic particles was recovered as CuCl and palladium was concentrated in the residue under the condition of $[\text{Cu}]/[\text{Cu}^{2+}] = 1.4$ Dissolution of palladium was achieved with over dosage of Cu ($[\text{Cu}]/[\text{Cu}^{2+}] = 0.9$) in the leaching solution. The optimal conditions of Pd(II) extraction using S201 from the leach liquor were: 10% S201 in <i>n</i> -dodecane, two stage extraction at A/O ratio of 5 and the extraction time was 2 min The concentration of Pd(II) in raffinate was 0.12 mg/L corresponding to 99.4% Pd(II) extraction efficiency	Nonacidic process	Requires enrichment of palladium from base metals, especially copper	Zhang and Zhang [110, 111]

Table 3 The most used microorganisms for bioleaching E-waste

Microorganisms	Leached metal	Recovery (%)	References
<i>A. ferrooxidans</i> + <i>A. thiooxidans</i>	Cu, Ni, Al, Zn	> 90	Brandl et al. [120]
<i>A. ferrooxidans</i>	Cu	99	Yang et al. [134]
<i>A. ferrooxidans</i>	Cu	99	Wang et al. [126],
<i>A. thiooxidans</i>	Cu	74.9	Mražíková et al. [135]
<i>A. ferrooxidans</i> + <i>A. thiooxidans</i>	Cu	99.9	
<i>Sulfobacillus thermosulfidooxidans</i>	Ni, Cu, Al, Zn	81, 89, 79, 83	Ilyas et al. [114]
<i>Chromobacterium violaceum</i>	Au	68.5	Brandle et al. [136]
<i>A. ferrooxidans</i> , <i>A. thiooxidans</i> and mixture	Cu, Pb, Zn	99, 74.9, 88.9	Wang et al. [126]
<i>Aspergillus niger</i> , <i>Penicillium simplicissimum</i>	Cu, Sn, Al, Ni, Pb, Zn	65, > 95	Brandl et al. [120]
<i>Aspergillus niger</i> , <i>Acidithiobacillus thiooxidans</i>	Cu	83	Saidan et al. [127]
<i>Thermosulfidooxidans sulfobacillus</i> + <i>Thermoplasma acidophilum</i>	Cu, Zn, Al, Ni	86, 80, 64, 74	Ilyas et al. [137]
<i>A. ferrooxidans</i>	Ni, Cd	54	Velgosová et al. [138, 139]
<i>Lactobacillus acidophilus</i>	Au	85	Sheel and Pant [140]

indium under high-temperature condition by reducing atmosphere. The processing conditions were 1223 K and 1 Pa with 30 wt% carbon additions for 30 min. and the recovery rate of indium reached 90 wt%. Indium was also recovered from wasted LCD panels by chlorinated vacuum-separation method [150]. In this method, a chlorinating agent, ammonium chloride (NH_4Cl), was used at temperature of 400 °C. The weight ratio of the used NH_4Cl -to-glass powder was 1:2, and the optimal particle size was less than 0.13 mm. Purity of the recovered indium chloride reached 99.50%, and its recovery rate attained 98.02%.

The environmental and financial benefits of vacuum processes for the E-waste recycling have been validated. Gas flow can be efficiently controlled, and furthermore, no wastewater will be released or dust emission will occur. This process is a promising and environment-friendly method for metal recycling from E-waste, still, it needs to be improved for further advancement. On the one hand, vacuum processes have many benefits for separating metals having low boiling point and high saturation vapor

pressure, such as Zn, Pb, and Cd. In contrast, separation of the valuable and rare metals having low saturated vapor pressure through vacuum condensation method is not so great. Still, pretty much hypothetical issues are waiting for additional clearance before its modern industrial application [151].

Conclusion

E-waste is not a common rubbish or an ordinary waste. Instead, it is a valuable scrap that contains considerable quantities of metal resources and should not be dumped wrongfully anywhere. Traditional processes may not meet the future industry requirements because of environmental contamination, high cost, and low efficiency. It would be greatly important to develop green processes for the recycling of WPCBs for both the economy and environment. The authors wish that this review will bring issues to light regarding E-waste management using cleaner economical recycling process. Even though various activities about development of recycling processes have been attempted, even now there is still a huge area left to achieve the environment-friendly recycling for metals. Furthermore, using a single technology still has some limitations and cannot solve all problems because of the complexity of the E-waste system. A combination of more than one process or technology should be applied to recover metals later on. We can also prefigure that future recycling technologies of metals from E-waste will turn out to be more effective, of low cost, and meeting the necessities of environmental safety.

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Compliance with Ethical Standards

Conflict of interest No competing financial interest is declared.

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