REVIEW ARTICLE

Recycling of Materials from Computer Waste

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Abstract

As new and innovative products with more functions, effectiveness and efficiency are introduced to the market continuously, the lifespan of existing products and equipment are becoming shorter and shorter before they are discarded. Therefore, significant amounts of electronic waste (e-waste) are mainly disposed of in the landfill. This study investigates the recycling of e-waste and recovering precious metals from computer components based on the information available in the literature. The manual dismantling, pre-processing and smelting techniques are discussed and elaborated. Among these techniques smelting/end-processes are employed to collect metals using several methods such as hydrometallurgy, pyrometallurgy and bio metallurgy are analysed critically. It was found that the dismantling techniques depends on the type of appliances, but the pre-processing techniques are almost independent on the appliance or types of metals to be collected. The smelting/end-processes and types of chemicals used depend on the metals to be recovered. The appropriate recycling processes and methods can be used to minimize the negative impacts that e-wastes have brought. In general, bio metallurgy is the most environmentally friendly technique to recover metals though this technique is very selective, less efficient and minor contaminating.

Keywords: recycling, electronic waste, metal recovery, waste management.

1 Introduction

Electronic waste (E-waste) is defined as end-of-life electrical and electronic products/equipment as defined by [1]. E-waste comprises discarded electronic appliances such as computers, mobile devices, televisions, printers, cameras, microwaves and other household electronic appliances. They are usually made of sophisticated and complex blends of plastics, metals, electronics and other materials. As newer and more effective products are introduced into the market each year, thus the existing products and devices are likely to have shorter and shorter lifespan before they go to the waste as they are damaged or simply outdated [1]. By breaking down the electronic wastes, one can understand the elements that are considered to be harmful as well the effect of disposing them in the environment. From this point of view, more research should be placed alongside the search for better recycling methods. With the threat of global

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warming as a major concern, society needs to consider more effective and efficient ways of e-waste recycling. On the other hand, e-waste not only contain significant amounts of harmful materials but also valuable metals such as palladium, copper, gold, silver and rare earth matels like lithium. Thus, recycling of e-waste will decrease the dependence on ores and thus, Earth's valuable resources if they were identified and sorted out properly.

Traditionally, most of the e-waste find themselves in the landfill and keep releasing the pollutants over the years. As most of the e-wastes contain acids or heavy metals, thus such pollutants effect the groundwater and soil adversely which is very harmful for the living beings [7]. As most of the materials in e-waste can be recycled or re-used, thus burying in landfill is not the only way to deal with them. The most recent trend is that, valuable components are usually sent to the recyclers for precious metals recovery and the remaining low-value components such as broken cathode ray tubes, mouse, keyboard are usually sent to landfills [2]. The existence of toxic substances in e-waste has only been discovered within the last two decades. There is no adequate legislation all over the world to effectively manage this type of waste. As a result of the rapidly growth of e-waste and the inadequate legislation, improper management strategies were used in the countries, which lead to serious impacts to the environment. The e-waste management through recycling and landfill disposal has proven to pose a significant risk to the environment.

A research done in 2005 has pointed out that, e-waste had already taken up to 2-5% of the municipal solid waste stream and growing at a rapid rate [3]. In 2009, researchers found that most of the e-waste was generated in developed countries and reached up to 20-25 million tons (Mt) each year [4]. In 2014. the amount of e-waste production has raised to approximately 41 Mt with a 3 – 5% increase per year [5]. A recent trend on the increase of e-waste has shown in Figure 1.

There are only 2.1 million tonnes (approximately 25%) of the 8.7 million tonnes of e-waste produced in the European Union each year was collected and recycled in formal processing plants and the remaining 6.6 million tonnes (75%) e-waste was not tracked and reported [6]. In addition to that, about 50–80% of the e-waste was collected for recycling purposes in industrialized countries ended up exported to

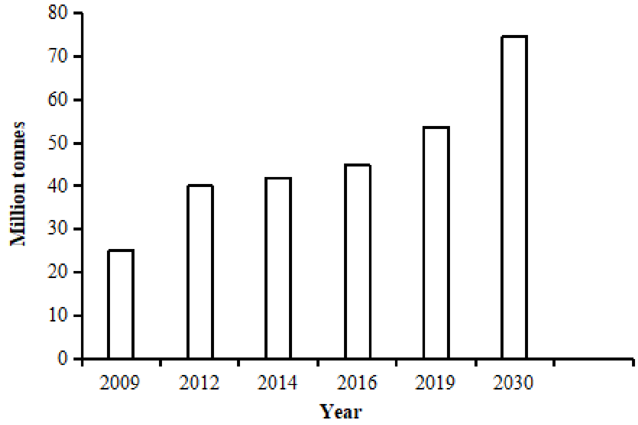

Figure 1. Growth rate of e-waste production per year.

recycling centers in Asian countries included China, Vietnam, Pakistan, India and the Philippines, which take beneficial of low labor fees and less strict environmental laws in those country.

In view of the above-mentioned scenario, this paper aims to study on the appropriate methods that need to be used in the recycling of e-waste. The stated methods seek to serve as an element that displays the best ways to deal with e-wastes and a solution to assist in the minimization of the effects of global warming.

2 Motives for Recycling

E-waste contain significant amount of harmful materials, which are mostly metallic in nature such as barium (Ba), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), lead (Pb), lithium (Li), lanthanum (La), mercury (Hg), manganese (Mn) and molybdenum (Mo) [7]. Cathode ray tube (CRT) displays are one of the largest sources that leads to lead and mercury contamination which is very harmful for living being. A brief list of different components in e-waste is given in Table 1. A research from Robinson et al [4] stated that, the role of an item to the annual e-waste production can be calculated according to Equation 1,

$$E = \frac{MN}{L} \tag{1}$$

where M is the mass of the item in kg, N is the number of units and L is the item's average lifespan in years. Table 1 shows a list of common e-waste items and their lifespan.

Not only land and ground water pollution, air pollution is another impact of inappropriate handling of e-waste. It occurs when e-waste is informally disposed of and involved in dismantling, shredding

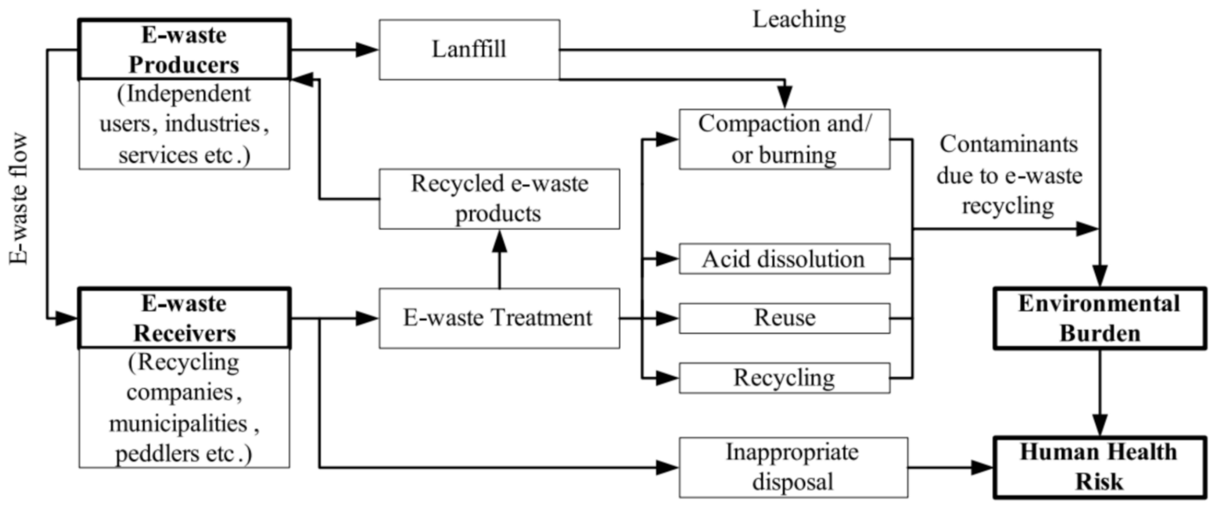

Figure 2. Current e-waste disposal routes and potential environmental impact [57].

Table 1. Typical e-waste components in electronic equipment [16].

Typical e-waste	Components	Weight (kg)	Lifespan (year)
Refrigerator	Compressor, condenser, PCBs, tubes, wires	35	10
Air conditioner	Heat exchanger, PCBs, compressor, motor	55	12
Washer	PCBs, tub, wires, hose, motor	50	10
TV	PCBs, wires, CRT, LCD, speaker	30	5
Computer	PCBs. CRT, wires, battery, LCD, speaker	25	3
Printer	Roller, toner, PCBs, wires, toner cartridge	60	8
Washing machine	-	65	8
Electric heater	-	5	20
Mobile phone	-	0.1	2
Radio	-	2	10

or melting processes of the materials, especially combustion from burning. As a consequence, dust particles and toxins, such as dioxins, are released into the environment during the process, and hence, cause air pollution and damages to animals and human's respiratory health [8]. In China along, there are 28 million tonnes of e-waste are recycled every year. The carbon dioxide emission can be reduced by more than 90 million tonnes every year, which was about 1.2% total carbon dioxide emission in China in 2009 [9] by such recycling. Figure 2 shows the disposal e-waste in landfills or inappropriate disposal and resultant harm to the environment and human [57].

3 Typical E-waste Components

One of the most widely used electronic equipment are computers. Some of the computer components that can be recycled include plastic or aluminum casings, glass monitors, cables, keyboard, ray tube, CD-ROM drive, circuit board, ray tube, batteries, power cord, and printer cartridges. As shown in Table 3, the outer case of a desktop computer takes 49.8% of the total weight, which is usually made of plastic, iron and glass [10]. The mass and volume of the outer case make the recycling unprofitable, because of the increase of transportation fee. Parts and components such as the power boards and wires contain copper which can be recovered by electrorefining. The rest of the desktop computer components contain printed circuit boards, thus, the valuable metals from printed circuit boards can be extracted by recycling process. Computers are usually expensive to recycle due to their design. In other words, the valuable parts and metals in the computer are in a large number of small parts and might be mixed with plastic in various parts that makes it difficult and expensive to separate and handle in the recycling process. Besides, the large amount of plastics could also reduce the value of recycled materials [11].

3.1 Printed circuit board (PCB)

Printed circuit board (PCB) refers to the traditional name given to the bare board. The printed circuit board supports the electrically connects electronic components using conductive pathways. Printed circuit boards contain some of the primary rare and precious metals containing e-wastes [9]. At the same time, they are also quite hazardous. Printed circuit boards constitute 3-6 wt.% of e-wastes, but they are also important components as they are made from 30% plastics, 40% metals, and 30% ceramics. The contents in PCBs varies depending on the electronic device, with the metal content consisting of 2-19 wt.% aluminum, 8-38 wt.% iron, 1-3wt.% lead, 10-27 wt.% copper, 0.3-2 wt.% nickel, 200-3000 ppm silver, 20-500 ppm gold and 10-200 ppm palladium [12]. Although PCBs have the least percentages in terms of e-waste, their contribution to rare and hazardous metals is very significant. Table 2 shows metal content in different PCBs, whereas, Table 3 shows the metal recovered from 1 tonne of PCBs. Copper is consider to be the most used common metal in the computer waste, whereas gold is the most used valuable metal in electronic due to the high electrical conductivity and non-corrosiveness [14]. According to Kang & Schoenung [3], recovering precious metals from e-waste provides great economic profits for the recycling industry. The printed circuit board contains high value of gold, the gold recovered from printed circuit board can be 40 times greater than the gold contained in ores found in America [3].

Table 2. Metal contents in PCBs of e-waste [10].

Type of PCBs	Weight (g)	Ag (g)	Au (g)	Pd (g)	Cu (g)
HDD drive	84	0.087	0.013	0.014	-
Memory modules	20	0.79	823	0.05	132
PCI cards	62	0.073	0.015	0.01	20.4
Motherboards	459	0.35	0.067	0.089	77.1
Power boards	2000	0.68	-	-	120

To recycle printed circuit board, the plastic on the board need to be removed first. There is no shredding, grinding and burning of printed circuit board. After manual dismantling process, the printed circuit board goes through the end-processing. When extracting metals from printed circuit board, the board is placed into disordering chemical liquid for 5-20 minutes at about 35 – 40 °C [15]. The copper or gold can be selected to be left on the solution based on the selectivity of the desoldering chemical. After that, the desoldered chips from the printed circuit board can be collected. Finally, the printed circuit board goes

Table 3. Metal recovered from one 1 tonne of printed circuit boards [13].

Metals	Weight	Cost ($US)
Copper	190.512kg	$1470 ($3.5 per 453.59g)
Aluminum	145.152kg	$448 ($1.28 per 453.59g)
Lead and Tin	30.844kg	$144.16 ($2.12 per 453.59g)
Silver	450g	$213.15 ($14.7 per 31g)
Gold	279.93g	$6115 ($685 per 31g)
Other precious metals	93.31g	$3852 ($1284 per 31g)

through the gold leaching process, which is usually hydrometallurgy process, for about 10 minutes at less than 30 °C [15]. When the chemical solution is saturated with gold, the gold can be extracted by electroplating tool. After gold is formed onto a carbon cathode, the gold is then taken from the carbon cathode and finally melted down to make a gold bar.

3.2 Typical monitor

There is different form of monitors in electronic appliances such as cathode ray tube (CRT), LED, LCD, etc. [17]. The CRT technology monitor for computers and TVs has been obsolete over the years as it had been replaced by the new LCD, LED and OLED technology. Firstly, the front of the monitor is removed so that the cathode ray tubes can be removed. The shell is then recycled along with regular plastic e-waste. Cathode ray tubes are more complicated to recycle as they contain lead and mercury, the hazardous metal for human health [18] and generally recovered by smelting. The glass portion of CRT is recycled to produce new products or as a fluxing agent in the metal's separation process. The silica eventually mixes with slag to form an iron-silicate waste product [19] during metal refining process. Waste cathode ray tube glass contains high content of lead in the funnel glass (15-25% PbO), which can be recovered by hydrometallurgical and pyrometallurgy processes.

On the prospects of metal recovery, recycling of hazardous heavy metals is quite slow. To give an example, only 5% of lead is recycled as most heavy metals have little value, in contrast, precious metals, which are more valuable, have much higher recycling rate. For example, there is a 99% recycling rate for gold and a 98% recycling rate for silver from the printed circuit boards [20]. Pyrometallurgy processing has also been a traditional technology for recovery of precious metals from waste electronic equipment other than lead [21].

3.3 Glass

The glass recycling process involves washing, crushing, and melting used glass in the stated order before it could be molded back into bottles and jars. The stated process can be repeated in a cycle without any loss in quality to the final product. In United Kingdom, glass manufacturers recycle almost 70% of the packaging sold, with a significant portion of the figure applying to glass bottle recycling [22]. Once the glass has been separately collected, it is subjected to a pre-treatment process that eliminates any paper or plastic using blown air. However, before processing continues, the glass has to pass through a sorting station, with the first two being dedicated to organizing contaminants such as aluminum cans, ceramics, light bulbs, pyrex, mirrors, window frames, and cardboard. The rest of the stations are needed to categorize non-brown glass, which is later processed in a batch [22].

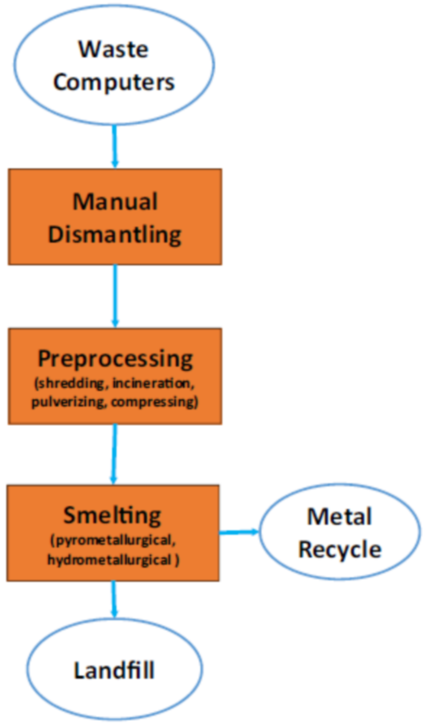

Figure 3. Recycling flow diagram [7].

3.4 Plastics

Computer wastes contain significant amounts of plastic which can be recycled. Mechanical recycling is considered to be the most widely considered method of plastic recycling. The stated technologies are classified into three primary stages: sorting and cleaning, size reduction, and melt processing. Computer waste and its components are initially shredded and then sorted using a range of mechanisms such as magnetic separators, manual sorting, optical sorters, and eddy-current separators depending on the required end-product [23]. The next process involves the melt processing techniques such as extrusion, especially for creating pellets or injection molding varying on the end product. However, the manual sorting of e-wastes helps in the adeptness of the e-waste recycling process.

4 Recycling process

Every form of the recycling process has to begin with the collection of discarded electronics from waste collection points. Some electronic collection centers have unique operating capacity depending on the policies incorporated during the process. Some recyclers have to pay the electronic owners, while others are having to charge the owners for disposal. Some electronic manufacturers' recyclers are known to accept trade-ins to minimize the environmental footprint, recovering some elements for reproduction and promoting the sale of new electronics. Once collected, the next step is sorting the collections based on item type before proceeding to other stages involving processing and reuse. If a given item is still functional or in a good working condition, and the parts do not require that much upgrading, they often refurbished or upgraded and sold as cheaper price. Once the items are checked for potential reuse, the ones that are not satisfactory are taken to recycle. As shown in Figure 3, the e-waste recycling processes can be break up into three main steps: (1) Manual dismantling process, (2) Pre-processing and (3) End-processing (recovery and refining process).

4.1 Manual dismantling

Dismantling aims to separate and classify the valuable or toxic materials and components into different categories, for example, small and large metal parts, printed circuit boards, plastic glass or cables [15]. Dismantling of electronic waste can improve the efficiency of the recycling process. In this procedure, the subassembly, parts and components are manually removed and separated from the electronic equipment with simple tools such as conveyors, screwdrivers and hammers. Manual choices are considered quite effective compared to mechanized procedures in accessing the best secondary raw resources. The workers then classified the disassembled components into different categories for the next procedure. In some instances, when manufacturers dismantle items, the recyclers will opt to break them further down and categorize them into circuit boards, plastics, cathode ray tube, ferrous and non-ferrous materials. Other hazardous parts such as rechargeable batteries are sent to recyclers who have the proper battery recycling and production knowledge [58].

4.2 Pre-processing

After Manual dismantling sorting, the disassembled components are subjected to preprocessing procedure. Pre-processing is a physical process that separates the metallic and non-metallic materials from e-waste. Although it is a physical process, pyrolysis and incineration can also be considered [10]. It involves shredding components into small pieces using grinders and crushers and then the metals and nonmetals materials can be separated by using separation processes including magnetic separation and eddy current separation. As reported in different studies, if the complex and highly valuable components were not manually dismantled before shredding or grinding, the precious metals could be mixed with materials such as glass, plastic or iron that will produce dangerous dusts and toxic compounds and can lose up to 40% of precious metals [15].

4.2.1 Shredding and separation process

The shredding and separation process involve reducing the particle size of the material for the following processes. Metal shredders, grinder and mills are currently being used for shredding which is a fully mechanized recycling process [24]. The shredded pieces can be further identified as either metals or plastics and separated for later use. After shredding and separation, the magnetic, eddy current separation or chemical processes can be used depending on the types of shredded materials.

4.2.2 Magnetic separation

The magnetic separation has the ability to separate the ferrous metals with the help of an electric or permanent magnet. Due to the magnetic force and the characteristic of magnetism [25], the ferrous metals can be separated from the shredded components. The magnetic separator always contains magnets, conveyors, collection bins and power system [26]. The overhead belt magnetic separator is one of the common magnetic separation systems [3]. The magnetic forces create a magnitude that has a separator that progresses the separation of elements. In addition, the separator's beginning houses a permanent magnet for capturing the ferromagnetic components [27]. At the same time, the grains on the moving belt are influenced by the magnetic field of a diversified strength. As the process proceeds, grains from the highest to lowest magnetic proneness are eliminated from the belt to the four housings. The order in which the magnets identified includes ferro magnetics, strong, weak paramagnetic, and diamagnetic [27] as shown schematically in Figure 4.

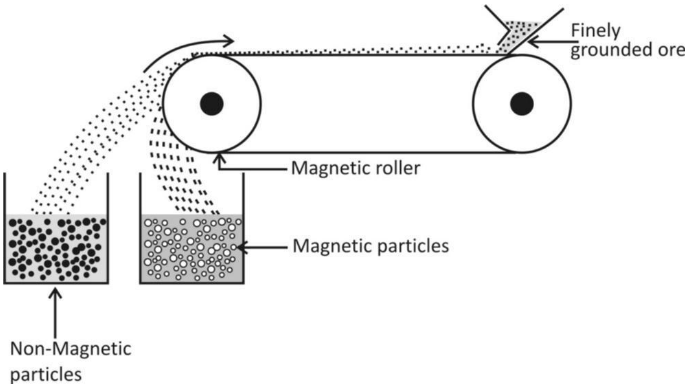

Figure 4. Schematic diagram of magnetic separator.

4.2.3 Eddy current separation

Eddy current separators are used to remove non-ferrous metals such as copper and aluminum from non-metallic material [3]. In eddy current separator, a high rotation speed magnetic drum is placed under the conveyor which creates a change of magnetic field. When the non-ferrous metals such as copper and aluminum pass over the magnetic drum, eddy current appears in the non-ferrous metals due to the change of magnetic field. Thus, a magnetic field is created around the non-ferrous metal. The magnetic field around the nonferrous metal has the same polarity as the rotating magnetic drum, and thus repulsive force generate. As shown in Figure 5, the non-ferrous metal repels away from the magnetic drum, causing the non-ferrous metal to have a further dropping distance than those non-metallic materials. The previous studies stated that aluminum, zinc, silver, copper, brass and lead could be separated [28] by this process. The most vital elements determining the material's deflection behavior are the particle's size, shape, and deflection coefficient. Incidentally, the deflection coefficient is considered the electrical conductivity/specific density ratio of a conductive material. The higher a metal's deflection coefficient, the higher its repulsive force affected the particle, causing better separation [30]. Plastic, stainless steel or glass could not be separated by eddy current separator [29] including copper wire with insulation covering.

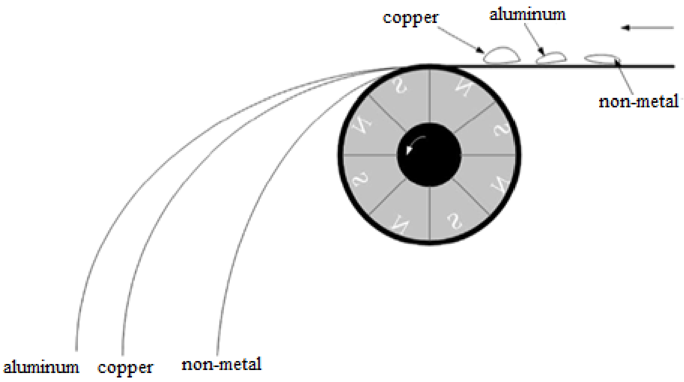

Figure 5. Schematic diagram of eddy current separator [26].

4.3 End-processing

End-processing is the third procedure of the e-waste recycling process and most commonly employed techniques are hydrometallurgy, pyrometallurgy and bio-metallurgy [24]. These processes are mostly used for the high valuable metal recovery after pre-processing and purifying metals such as gold, silver, copper and palladium. As gold, silver and palladium can be dissolve in copper [15], therefore, end-processing focuses on smelting e-waste to recover impure copper, thus, to recover the pure copper and other metals by electrorefining the impure copper.

4.3.1 Hydrometallurgy

Hydrometallurgy is a low temperature process that involves the use of aqueous solutions for recovering metals [15]. This process is more arcuate, predictable and controllable than pyrometallurgical process, leading to this process has become more popular [31]. The metal recovery from e-waste by this process has begun in the late 1960s [7]. The process is often incorporated to extract less electro positive or less reactive metals such as silver and gold. The process is divided into three general regions, metal recovery, solution concentration and purification, and leaching [33]. Metals are dissolved into leaching chemical solutions which usually consist of acids extracting the soluble components. The leaching agents common used in chemical leaching are cyanide, sulfuric acid, thiosulfate, alkali, hydrochloric acid and nitric acid [34]. In e-wastes, the parameters are defined by the solvent's concentration, particle size, contact time of liquid and solid, and temperature. The parameters could affect the efficiency of the leaching. The acids have the most efficiency as being leaching agents, since acids have the great ability of leaching both precious metals and base metals. [35]. The solution is then separated and purified for the metal content, thus, the impurities in the solution can be removed. Acid leaching is commonly used for extracting copper, gold and other precious metals from the printed circuit board. Copper is able to be oxidized directly for the production of copper nitrate by dilute nitric acid Therefore, additional oxidizer is not needed for leaching copper by nitric acid. Acidic gas is produced during this leaching process, the process should be done in the air circuited safe place. The copper needs to turn into pure copper sulfate solution before electrorefining, since the copper nitrate do not form high purity of copper by electrorefining [26]. The chemical solution containing the selected metal and impurity is then refined for the purpose of concentrating the metals by using ion exchange process which is incorporated to recover a range of metals from aqueous solution. After that, the metal is further refined through electrochemical or electrorefining reduction reaction to reacquire the solid metals from the e-waste [36, 37]. A general flow chart of hydrometallurgy leaching is shown in Figure 6. Cyanide-based solvents present a problem concerning toxicity problems [38], industrial operations used in the gold recovery from the e-waste have presented promising concentrations by mixing alkaline solutions to dissolve the gold at gas-filled environments [39]. The stated Cyanide-incorporated compounds are involved in electroplating processes. Chlorine has been used for extracting gold by forming Au^{+} and Au^{3+} complexes [40]. Chlorination is a practical method to recover gold from waste printed circuit boards with the advantages of less pollution higher leaching rate and selective leaching of different metals by controlling the redox potential. Thiourea is considered to be a complex element, a sulfur-centered agent which creates a catatonic soluble compound with the selected metal, contrasting a range of anionic compounds. The thiourea leaching could speeds be up to 99% for the stated compound, when the thiourea mass concentration increases, there is a linear increase in leaching rates [41].

A summary of different leaching agent together with their respective advantages and associated recovered materials are given in Table 4.

4.3.2 Pyrometallurgy

Pyrometallurgy is identified as the branch of science and technology that is involved with the use of high temperatures to purify and extract metals. Currently, instead of mechanical processing, about 70% of e-waste is treated in smelters via pyrometallurgy [43]. In pyrometallurgical process, it involves

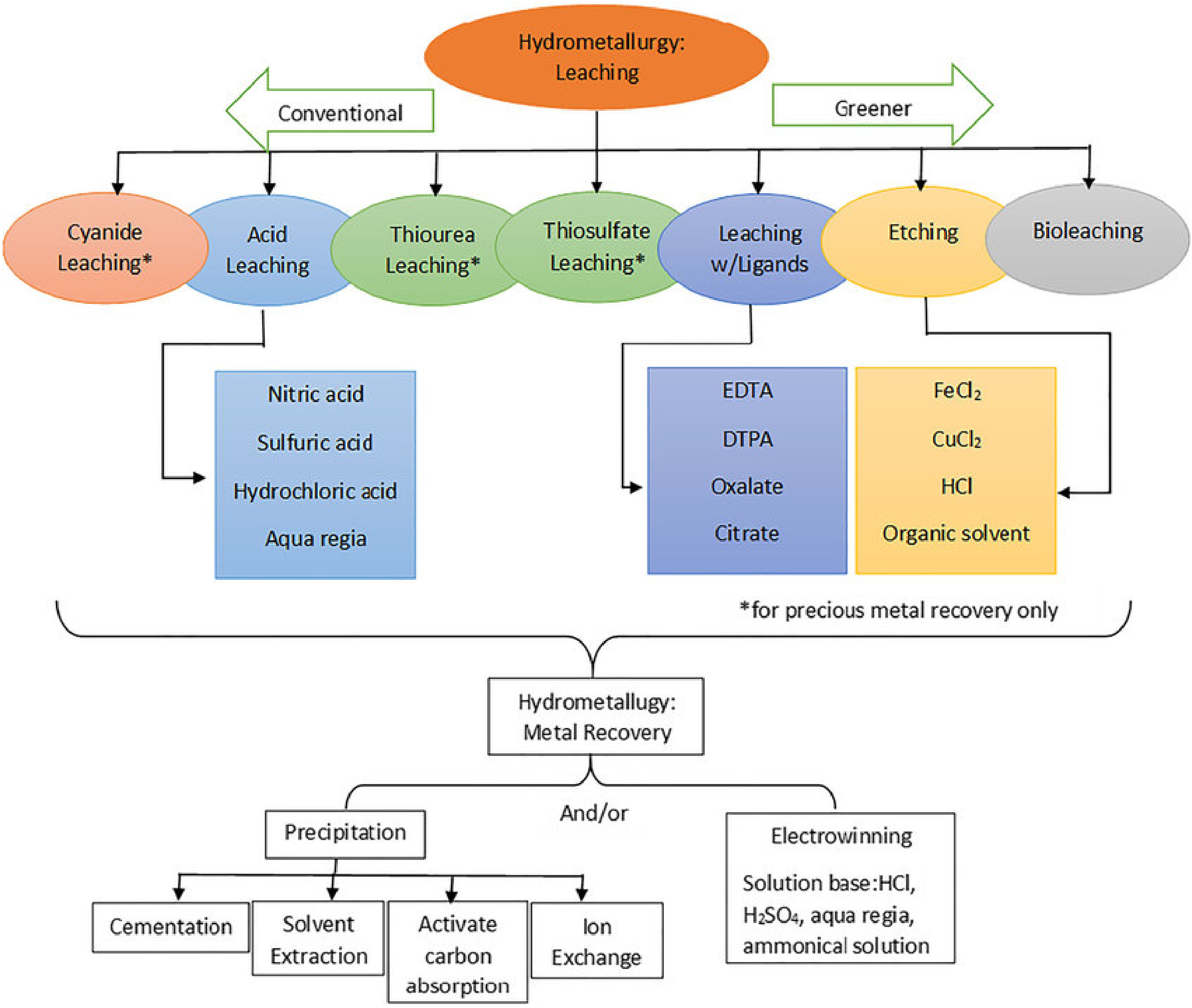

Figure 6. A flow chart of hydrometallurgical recycling process [32].

Table 4. Summary of leaching agents in hydrometallurgical.

Leaching agent	Advantages	Materials recovered
Nitric acid	Very short reaction time and high efficiency	Cu, Zn, Ni and Au
Ammonia	More selective, less corrosive and lowering reagent consumption	Cu, Ni and Co
Chlorination	High leaching rate and less pollution	Au
Thiosulfate	High recovery rate and low energy consumption	Au and Ag
Thiourea leachant	High recovery rate, low toxicity and low energy consumption	Au
Cyanide leaching	Low energy consumption and high recovery rate	Au

melting the shredded components to obtain an impure copper which contains other metals, then purify the non-ferrous and precious metals by electrorefining. To deal with industrial scale e-waste in pyrometallurgy, manual dismantling and sorting and mechanical pre-treatment processes are needed before the main smelting process, the energy efficiency for the valuable metal production can be maximised [42]. Also, this process is often used for non-ferrous and precious metals recovery such as recovery of gold, silver, copper and palladium. Aluminum and iron are not recovered in this pyrometallurgical process, as aluminum and iron are usually oxidized slag [24]. Analyzing the techno-economic examination of pyrometallurgical process has shown that the recycling procedures of e-waste in copper smelting has the proposed worth and is considered economically viable with a least plant capacity of 30,000 tonnes of waste annually [44]. Currently, the e-waste is mainly sent to four integrated smelters worldwide for processing the waste and recovery of valuable materials. Three of integrated smelters are located in Germany, Belgium and Sweden, the other one is located in Canada. Two of the medium sized e-waste smelters are located in South Korea and Japan [15]. Although the United State has been the largest e-waste generation country, the United State does not have the treatment capacity for e-waste. The e-waste or other used electronics are usually exported to other developed countries for further processing.

The most vital operations in pyrometallurgical process include refining, roasting, and smelting [45]. Once separation and sorting has been done, pyrometallurgical processes and the metal liberation is attained by smelting furnaces by using high temperature [31]. Consequently, the process involves sorting metals by taking advantage of their metallurgical and chemical elements. The most common smelting process used to extract copper is either "flash" or "bath" smelting [53]. In application, bath smelting is a molten liquid bath where the smelting and conversion happens with the concentrate being in contact with the matte and liquid slag. The air is injected into the bath or on top of the bath converters identified as the matte. In flash smelting, conversion happens in the air stream [46]. The physical methods used in the process create the finally pre-processed e-waste with the main elements such as iron, aluminum, copper, and lead which exist in high quantities but the precious metals are in low concentrations [44]. Therefore, e-waste is exposed to lead smelting and copper smelting routes to cause the two elements to separate individually and leave precious metals. The roasting process is considered to be the oxidization of metal sulfides resulting in metal oxides and sulphur dioxide and therefore an exothermic reaction [47]. As a result, roasting is considered to be a surface reaction where the oxide layer is initially created and continues to remain as a porous layer where oxygen is able to go into the unreacted inner sulfide section of the particle and sulphur dioxide gas released [48]. Heat assists in keeping the roaster at the needed temperature and so the procedure can be persisted with some external heat from the fuel [49]. As a result, sulfide roasting is considered to be an autogenous practice that extra heat is not needed [49]. Sulfide is not minimized with the most often incorporated reducing agents such as hydrogen and carbon, since the free energy alteration for the reaction is positive due to the minimal stability of carbon disulfide and hydrogen sulfide [48]. The sulfide reduction with metals is not considered to be quite economical. As shown in Figure 7, large amounts of air are often augmented with oxygen when combined with the sulfide mineral concentrate during roasting. The process occurs at raised temperatures when oxygen mixes with sulfur creating sulfur dioxide and the metals, further forming oxides, sulfates, and the rest. Oxidation has to occur without melting the charge to avoid reduction of particle surface-oxidizing gas contact region. Once the charge is stirred in a certain way, it ensures the exposure of all particle surfaces to the oxidizing gas [48].

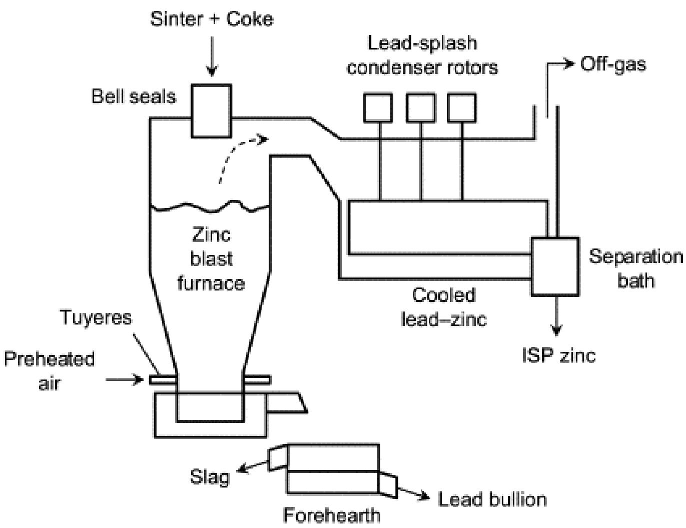

Figure 7. Schematic diagram of pyrometallurgical smelting process [54].

There are six types of roasting in application: oxidation roasting, salt roasting, chlorination roasting, reduction roasting, volatilizing roasting and sinter roasting [48]. Oxidation roasting is considered to be the process in which changing metallic entities in waste elements into oxides by incorporating oxidants [50]. An oxide is obtained to allow the next step of smelting. Incorporated in sulfide ore smelting, this is used to eliminate antimony, arsenic, sulphur ore and other destructive contaminants in the ore [48]. The main aim of salt roasting is to change metallic oxides or sulfides in the material into soluble salts that can be dissolved in dilute acids or water under regulated conditions. The chlorination and sulfuric acid roasting process are the average examples of salt roasting [48]. The primary manipulation situations of sulfuric acid roasting are the volume of air and heat

Table 5. Summary of end processing.

Methods	Advantages	Disadvantages
Hydrometallurgy	Low energy requirement, easy accomplishment, rapid and highly efficiency	Highly corrosive environment, toxicity of regents and by products
Pyrometallurgy	High efficiency rate	Release of toxic fumes, air pollution and high energy demand
Biometallurgy	Eco friendly and economical	Low leaching rate, selectivity, contamination possibilities

temperature. Sulfuric acid roasting is implemented to the process with copper concentrate and low-grade metal elements. Reduction roasting is considered to be the lowering of oxygen content in ores by heating it in a reducing atmosphere using carbon monoxide. The carbon monoxide is supplied by mixing carbonaceous material such as coal or coke with the ore [51]. Volatilizing roasting is understood as the cautious oxidation at raised temperatures of the ores to remove impurities in the structure of their unstable oxides [52]. Samples of the stated forms of volatile oxides include arsenic trioxide, antimony trioxide, sulfur oxides, and zinc oxides. Excessive oxidation creates nonvolatile oxides necessitating the need for controlling the oxygen content [48]. The final form of roasting is sinter roasting, which contains heating the fine ores at high temperatures, resulting in oxidation and agglomeration of the ores. For instance, lead sulfide ores are exposed to sinter roasting continuously after froth floatation to turn the fine ores into workable agglomerates for additional smelting processes.

The plastics of the shredded components and the metal oxides from a slag phase are burned in a molten bath or furnace [31]. Polyvinyl chloride and flame retardants from e-waste release toxic vapor when smelted, and thus special emission controls are required to reduce the harm to the environment and human [7]. In a case of processing PCBs, pyrometallurgy typically gives faster and sharper separation than hydrometallurgy in expense of high energy input [42]. The non-metallic materials in printed circuit board are based on the supercritical fluid de-polymerization, pyrolysis and gasification to produce fuels and chemical substances. For instance, the metals in a printed circuit board can be recovered, while the non-metal materials are able to be used in pyrometallurgy as reducing agents and fuels [37].

In application, pyrometallurgical methods are considered to be quite high in costs and high energy consumption [55]. As a result, hydrometallurgy has been increasingly considered to be an astute option over the pyrometallurgy based on the high energy demand required by the pyrometallurgy. Thus, hydrometallurgy is quite efficient since it is able to control the various levels of impurity in various stages and low energy requirement to handle the chemicals in several stages [55].

4.3.3 Bio-metallurgy

Bio-metallurgy refers to the biotechnological process that refers to interactions between metal-bearing minerals and microorganisms [12] as shown schematically in Figure 8. Biometallurgy is an environmentally friendly process that uses microbes to leach metals out of shredded e-waste. Studies have showed that, biometallurgy has been more popular for leaching gold and copper ores in the last 20 years [7, 15].

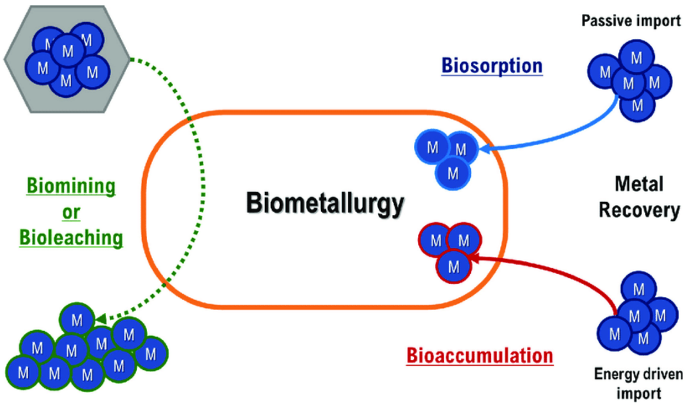

Figure 8. Schematic diagram of biometallurgy process [56].

Bioleaching is one of the biomining process which is used to leach solid metal from ores (i.e. gold and copper) into extractable and soluble elements to be recovered. Research has found bioleaching can be used to recover copper, zinc, nickel and cobalt, but full recovery of gold and silver are not achieved with this. In the bioremediation process, biosorption method is used to accumulate precious metals with the use of yeasts, bacteria, algae and fungi. These microbes are used as adsorbents to absorb the precious and heavy metals from aqueous solutions

[35]. Biomining enables the recover and remove metals from e-wastes or ores, while bioremediation eliminates or immobilizes dangerous contaminants such as heavy metals or radionuclides from the polluted locations. Thus, bio-metallurgy is able to create serval contributions to a sustainable globe that would rapidly eclipse current biomining and bioremediation applications [12]. A relative comparison of various techniques used during end processing is summarized in Table 5.

5 Discussion and Future Aspect

Recycling is a solution to address the existing e-waste problem that continues to fester and worsen environmental issuses. A factor that posses to be an increasing problem is that collection methods are more difficult than recycling. It falls on the original device's user to properly dispose of an electronic to find its way to the proper recycling facilities. Ideally, for the aforementioned to happen, there has to be extensive public education to be made and government intervention. Recycling has been properly broken down with the right machinery and methods being considered. However, the collection of old electronics is still a factor that does not have the appropriate methods or organizations devoted to the activity. At the same time, recycling is not a full-proof solution to the problem, requiring that people in society be educated about the ongoing problem and the potential problems if a better approach is not considered. At the same time, society needs to consider heavily investing in research and development concerning the best recycling methods. Without proper recycling methods, the amount of e-waste being piled up in the environment continue to increase. Electronic manufacturing companies need to be incentivized to invest and use recycled materials as a way to motivate them to take care of the environment. At the same time, it would be appropriate to find better and biodegradable materials to use in the production of electronics.

Apart from looking for the existing effect of e-waste on the environment, future research should look for the possible more effective ways and methods to recycle and recover e-waste. In the recycling process section, some pros and cons for the methods used were listed. Thus, future research should consider discovering techniques available to maximize the advantages and minimize the disadvantages.

6 Conclusion

In general, e-waste recycling consists of three main processes which are manual dismantling, pre-processing and end-processing. The advantages of recycling e-waste outweigh the disadvantage of it. E-waste recycling not only reduces the harm to the environment, it also can be considered as a profitable business. Printed circuit boards are one of the largest sources that constitue 3-6% by weight of total e-waste. Moreover, printed circuit boards contain significate amount of precious metals including palladium, gold and silver which can be extracted. The gold from the printed circuit boards can be recovered by the hydrometallugical leaching process. The research found that about 280 gram of gold could be recoverd from 1 tonnes printed circuit boards which could be 40 times higher than the gold found in ores in the United States.

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Ethical Approval and Consent to Participate

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