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Extraction of Copper from Electronic Waste (E-Waste): A Review

Siddhartha Sankar Boxi[1],*, Kuntal Choudhury[2], Soumya Purkayastha[3]

Abstract

The issue of electronic waste, or e-waste, is indeed a significant global concern with far-reaching environmental and health implications. As technology continues to advance and become more integrated into our daily lives, the disposal of obsolete or broken electronic devices has become a pressing issue. This waste not only contains valuable metals but also toxic substances, posing significant challenges for disposal and management. Improper disposal of e-waste is a significant contributor to environmental pollution. When e-waste is incinerated or exposed to heat, toxic chemicals are released into the air, contributing to air pollution and potentially harmful health effects for nearby communities. Moreover, when e-waste is disposed of in landfills, it can lead to the leaching of hazardous compounds into the soil and groundwater, thereby contaminating the environment and posing risks to ecosystems and human health. The toxic metals found in e-waste, including mercury, lead, cadmium, and arsenic, can result in severe health repercussions for individuals exposed to them. Long-term exposure to these substances can lead to neurological damage, developmental disorders, respiratory issues, and various other health problems. Electronic devices contain valuable resources, including gold, silver, copper, and platinum. Inadequate management of e-waste leads to the squandering of these valuable resources, exacerbating resource depletion and necessitating more extensive mining endeavors to fulfill demand. Despite the challenges posed by e-waste, there are also opportunities for economic growth and resource recovery. Implementing efficient e-waste management practices, such as recycling and recovery of valuable materials, can create new economic opportunities while mitigating environmental and health risks. Harnessing valuable metals from e-waste through recycling presents a promising strategy to alleviate the environmental repercussions of electronic waste. Various methods, including mechanical processing, pyrometallurgy, hydrometallurgy, and bioleaching, can be employed to extract valuable metals from e-waste while minimizing environmental pollution. Tackling the challenges presented by e-waste demands a comprehensive strategy encompassing technological innovation, policy interventions, public awareness initiatives, and collaborative endeavors among diverse stakeholders. By implementing sustainable e-waste management practices, we can mitigate environmental pollution, protect human health, and harness the economic potential of recycling and resource recovery.

***Author for Correspondence**
Siddhartha Sankar Boxi
E-mail: ssboxich@gmail.com

[1]Associate Professor, Department of Chemical Engineering, Haldia Institute of Technology, Haldia, West Bengal, India
[2]UG Student, Department of Chemical Engineering, Haldia Institute of Technology, Haldia, West Bengal, India
[3]UG Student, Department of Chemical Engineering, Haldia Institute of Technology, Haldia, West Bengal, India

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INTRODUCTION

Electronic waste, commonly referred to as e-waste, refers to discarded electronic devices, such as smart phones, computers, TVs, and other household and industrial electronic equipment. The hazardous nature of e-waste and its escalating global generation rate have made it a substantial environmental concern. E-waste contains various toxic and non-biodegradable substances, including lead, mercury, cadmium, and polyvinyl chloride (PVC), which pose severe environmental and health risks if not appropriately managed [1, 2]. The generation of e-waste has surged in recent years owing to the growing demand for electronic devices and the rapid pace of technological advancement. According to a report by the United Nations University (UNU), the world produced 53.6 million metric tons (Mt) of e-waste in 2019, with projections indicating an increase to 74.7 Mt by 2030. [3]. The report also highlighted that Asia produced the largest quantity of e-waste, with the Americas and Europe following closely behind [3]. Inadequate management of e-waste poses substantial environmental and health hazards. Improper disposal results in the release of toxic substances into the environment, contaminating soil, water, and air, thereby causing environmental pollution and degradation. For instance, the burning of e-waste releases toxic gases into the atmosphere, which can cause respiratory and other health problems. The presence of heavy metals in e-waste can contaminate the soil and water bodies, leading to soil and water pollution, which can harm humans and other living organisms. Moreover, the improper disposal of e-waste poses significant health risks to individuals handling and exposed to it, especially in developing countries where informal e-waste recycling is prevalent. Informal recycling activities, such as open-air burning of e-waste and the use of acid baths to recover valuable metals, expose workers and surrounding communities to toxic substances, can result in adverse health effects, including respiratory problems, skin irritations, and an increased risk of cancer [4–6].

Moreover, initiatives have been undertaken to advocate for sustainable e-waste management, including the implementation of the circular economy model, which seeks to minimize waste and encourage the reuse and recycling of materials. The circular economy approach encourages the repair, refurbishment, and upgrading of electronic devices to extend their lifespan, reducing the need for new devices and the associated environmental and health risks [7]. The escalating global production of e-waste has emerged as a critical environmental and health issue given its hazardous composition. Inadequate handling of e-waste presents substantial risks to both the environment and human health, culminating in environmental degradation, pollution, and detrimental health effects on those who come into contact with it. Various initiatives and policies have been implemented globally to promote the environmentally sound management of e-waste, and there have been efforts to promote sustainable e-waste management through the adoption of the circular economy model [8].

Printed circuit boards (PCBs) are a significant source of copper, with the metal accounting for up to 30% of their weight. The extraction of copper from these boards is essential for diminishing e-waste and preserving natural resources. Various methods exist for recovering copper from PCBs, each presenting its own set of advantages and drawbacks [9]. One of the most common methods is mechanical recycling [10], where PCBs are shredded and the copper is separated using physical methods such as gravity separation [11], electrostatic separation [12], and magnetic separation [13]. While this method is relatively straightforward and economical, it may not achieve complete copper recovery, and the extracted metal could be tainted with other substances. Another method is pyrometallurgical recycling [14], where PCBs are burned in a furnace to extract the copper. This method has a high copper recovery rate but produces toxic gases and generates hazardous waste. Hydrometallurgical methods [15], such as acid leaching and solvent extraction, are also used for copper recovery from PCBs. These methods are relatively clean and efficient, but they require careful control of the leaching conditions to avoid the dissolution of other metals. In recent years, there has been a growing interest in the development of bioleaching methods [16] for copper recovery from PCBs. These methods use microorganisms [17] to dissolve copper from PCBs, reducing the need for harsh chemicals and energy-intensive processes. Overall, the choice of copper recovery method for PCBs depends on several factors, including the composition of the PCBs, the level of copper recovery required, and the environmental impact of the method.

This review offers a comprehensive examination of copper recovery methods from printed circuit boards. In this study, we have described various methods of copper recovery and discussed some of the processes through which we can extract a lot of other precious metals. We found out that there are mainly three types of methods we are using here to extract copper and other precious metals from printed circuit boards. These processes are hydrometallurgical processing, mechanical processing, and pyrometallurgical processing. Apart from that, we got some other methods like bioleaching, solvent extraction with D2EHPA, etc. Here we discussed the current industrial processes for copper recovery. What are the actual methods that are currently used by industries? Here we discussed the future of e-waste and how we can protect our world from pollution. By the help of all this processes we can extract expensive metals from Printed Circuit Boards. This can be highly profitable and environment friendly also with the help of these processes we can reduce pollutions in our environment. Lots of research work already done in this topic but here we combine all data and review all processes.

AVAILABILITY OF DIFFERENT METALS IN E-WASTE

E-waste frequently contains metals, which can be classified as valuable or basic metals. Electronic devices frequently use precious metals like gold, silver, and platinum because of their superior electrical transmission and rust resistance. Because of their building qualities, base metals like copper, aluminum, and iron are also used in technology [18]. With a high demand for its use in electronic products due to its exceptional electrical conductivity and corrosion resistance, gold is one of the most precious metals discovered in e-waste. Circuit boards, valves, and connections all frequently contain gold. Due to the difficulty and expense of recovering gold from e-waste, it is frequently only fiscally viable to recycle gold from high-value electronic products [19,2 0]. Due to its superior electrical conductivity and corrosion resilience, silver is another precious element that can be found in e-waste. Switches, circuits, and conductive surfaces frequently use silver. Silver recycling from high-value electronic devices is frequently the only option that is fiscally viable because recovering silver from e-waste is also a difficult and expensive procedure [21, 22]. Small quantities of uncommon and expensive metal platinum can be discovered in e-waste. Due to its superior electrical conductivity, resilience to corrosion, and capacity for high temps, platinum is frequently used in electronic products. Hard disks, sensors, and catalytic converters all frequently use platinum. Platinum recovery from e-waste is a difficult and expensive procedure, and as such, it is often only economically feasible to recycle platinum from high-value electronic devices [23, 24]

Copper, a basic metal that is frequently found in e-waste, is used in electronic products. In cables, electrical boards, and transformers, copper is frequently used. All kinds of electronic device recycling can frequently be done economically because recovering copper from e-waste is a fairly simple and cost-effective procedure [25, 26]. Another base metal that is frequently found in e-waste is aluminum, which is used in electrical products because of its excellent structural qualities and light weight. Cases, casings, and heat shields frequently use aluminum. Because recovering aluminum from e-waste is a fairly simple and affordable procedure, recycling aluminum from all kinds of waste is frequently monetarily feasible [27]. In summation, metals are frequently present in e-waste, and their recovery and recycling are crucial to lessening the effect of e-waste on the ecosystem. Gold, silver, and platinum are desirable precious metals that are frequently only monetarily feasible to recycle from expensive electrical devices. All kinds of electrical devices can be recycled for precious base metals like copper, aluminum, and iron. To reduce the negative effects of e-waste on the ecosystem, it is crucial to encourage sustainable and responsible e-waste management practices. The recovery and recycling of metals from e-waste are complicated and expensive procedures [28,2 9].

Table 1 presents a summary of various studies on the extraction of valuable metals from electronic waste (e-waste) using different processes. The studies were conducted on different types of e-waste, including computer motherboards, printed circuit boards (PCBs), obsolete computers, and waste PCBs. Different processes were used, including hydrometallurgical [30], physical-chemical characterization, pressure acid leaching [25], leaching [31], nitric acid leaching [26], sulfuric acid leaching [32], and bioleaching [33]. The processes' parameters, including pH, temperature, pressure, time, mass fraction, solid-liquid ratio, molality, concentration, and particle size, were varied to determine the optimal conditions for extracting targeted metals. The studies aimed to extract valuable metals, including copper

[34], gold [35], silver, tin, and zinc, with extraction yields ranging from 10% to 98.2%. In general, the studies showed that the hydrometallurgical process was the most efficient in extracting valuable metals, followed by bioleaching, leaching, and physical-chemical characterization. The studies revealed that the Ph [36], temperature, and time were the most critical parameters in determining the extraction efficiency. Overall, the studies demonstrated the potential for recycling e-waste and extracting valuable metals from it, which could reduce environmental pollution and promote sustainability.

Table 1. Different Metal Recovery Process and Extraction Percentage.

S.N.	**Source of e-waste**	**Separation Process**	**Process Parameters**	**Targeted Material**	**Extraction Percentage**	**References**
1.	Computer MB, MEB	HME	Temperature, Pressure, Time	Ag, Cu	Ag-33% to 83%, Cu-46% to 48%	[30]
2.	PCB	PAL	Pressure, pH, Temperature	Cu, Zn, Ni	Cu-98%, Zn-75%, Ni-8%	[25]
3.	PCB from OC	Leaching	pH	Sn, Cu	Sn-87% to 98.2%, Cu-84.1% to 85.8%	[31]
4.	Scrap PCBs	Nitric acid leaching	Time, concentration, pH	Cu	Cu-88.9%	[26]
5.	WPCB	Sulphuric acid leaching	pH, temperature, time, weight	Cu	Cu-19%	[32]
6.	Waste PCBs pre treated	HMP	Rpm, Density, pH, temperature, time	Copper	Cu-99.99%	[37]
7.	WPCBs	Acid leaching	Molality, Temperature, Time.	Cu	Cu-96.1%	[38]
8.	WPCBs	Acid leaching with aqua regia.	pH, Temperature, concentration.	Cu	Au-95%	[39]
9.	PCBs	PP, CP, using ICP-OES, HMP	Pressure	Cu, Zn, Al	Cu-100%, Zn-60%, Al–10%	[40]
10.	PCB	Acid Leaching.	Concentration, Time, Temperature, Leachability	Cu, Fe	Cu-95%, Fe-5%	[41]
11.	WPCBs	Acid Leaching	Volume, Particle Size, Concentration	Cu, Zn	Cu-65% to 80%, Zn-70% to 95%.	[42]
12.	WPCBs	Bioleaching	pH, Volume of Bl, SS	Cu	Cu-32.44%	[33]
13.	WPCBs	Bioleaching, Electrowinning	Time, pH, Efficiency	Cu	Cu-75.8% to 85.3%	[43]
14.	TCB	Bioleaching	Concentration, Time	Cu	Cu-83%	[44]
15.	WPCBs	Bioleaching	SS, Time, Temperature, pH, Concentration	Cu	Cu-95%	[36]
16.	WPCBs	HMP	MP, Concentration, Temperature, EY, SS, Time	Cu, Au	Cu-82%, Au-90%	[35]
17.	WPCBs	MCP	Time, SLR, Temperature, Pressure	Cu	Cu-88.79%	[45]
18.	WPCBs	MCP, Leaching, Electrowinning	CE, CD, Time, Concentration, pH	Cu	Cu-78%	[46]
19.	WPCBs	Heating	MSP, Temperature, Time	Cu	Cu-92%	[47]
20.	WPCBs	Leaching	SS, Concentration, H_2O_2 amount, Time, Temperature	Cu	Cu-20% to 99%	[48]
21.	WEEE	Extraction with D2EHPA	pH, Time	Cu	Cu-94%	[49]
22.	WPCBs	Fe^{3+}/Fe^{2+} redox System.	DF, FR, EC	Cu	Cu-99.95%	[50]
23.	WPCB	Zero Discharge	Time, Concentration, SS.	Cu, Sn, Pb	Cu-100%, Sn-97%,	[51]

S.N.	Source of e-waste	Separation Process	Process Parameters	Targeted Material	Extraction Percentage	References
		HMP			pb-85%	
24.	WPCBs	Using BF	Time, FC, CC, MC, FeC	Cu	Cu-90%	[34]
25.	WPCBs	Using supercritical CO$_2$	Temperature, Time	Cu	Cu-82%	[52]
26.	WPCBs	Using MGSHP	Time, pH, Temperature, Pulp Density	Cu, Au	Cu-93% Au-86%	[53]
27.	WPCBs	Leaching	Time, rpm, Temperature, GYC	Cu	Cu-92.8%	[54]
28.	WPCBs	Leaching	Vol %, Acid concentration, PD, Time, Temperature	Cu	Cu-99.9%	[55]
29.	WPCBs	Alkali Dynamic Leaching	SW, Temperature OPP, rpm, pH, Time, Concentration	Cu	Cu-99.82%	[56]

HMP-Hydrometallurgical Processing, SLR-Solid-Liquid Ratio, MB-Motherboard, MEB, Memoryboard, PAL-Pressure Acid Leaching, PCB-Printed Circuit Board, WPCBs-Waste Printed Circuit Boards, PF-Powder Feed, LL-Leach Liquor, OC-Obsolete Computers, PP-Physical Process, CP-Chemical Process, SS-Sample Size, SW-Sample Weight, BI-Bacterial Inoculums, TCB-TV Circuit Board, MP-Metal Percentage, MSP-Mass Percentage, EY-Extraction Yield, MCP-Mechanical Processing, CE-Current Efficiency, CD-Current Density, DF-Dissolution Efficiency, FR-Flow Rate, EC-Energy Consumption, BF-Biogenic Ferric, FC-Ferrous Concentration, OPP-Oxygen Partial Pressure, FeC-Ferric Concentration, CC-Copper Concentration, MC-Metal Concentration, MGSHP-Monosodium Glutamate Supplemented with Hydrogen Peroxide, GYC-Glycin Concentration, PD-Pulp Density

The Table 2 provides information on the composition of different types of e-waste, including printed circuit boards [57], mobile phones [58-60], TV boards [58–60], portable audio devices [58–60], DVD players [58–60], and calculators [58–60]. The table lists the weight percentages of copper (Cu), iron (Fe), aluminum (Al), nickel (Ni), and lead (Pb) in each type of e-waste. Additionally, it also lists the weight concentrations of precious metals such as silver (Ag), gold (Au), and palladium (Pd) in parts per million (ppm) for each type of e-waste. According to the Table 2, printed circuit boards have the highest percentage of copper at 20%, followed by portable audio devices at 21%, and TV boards at 10%. DVD players have the highest percentage of iron at 62%, followed by portable audio devices at 23%, and printed circuit boards at 6%. Aluminum is highest in calculators at 5%, followed by TV boards at 10%, and printed circuit boards at 4%. Nickel and lead are highest in mobile phones, with 0.1% and 0.3%, respectively [58–60]. In terms of precious metals, mobile phones have the highest concentrations of silver, gold, and palladium at 1380 ppm, 350 ppm, and 210 ppm, respectively. Printed circuit boards have the highest concentration of gold at 250 ppm, followed by mobile phones and TV boards. Palladium is highest in printed circuit boards at 90 ppm, followed by mobile phones [58-60] This information is useful for understanding the potential value of e-waste and the environmental impact of their disposal. Additionally, it can also guide the development of more efficient and sustainable recycling practices to recover precious metals and minimize the environmental harm caused by improper disposal.

Table 2. Different Percentages (Weight) of Metals in Different Gadgets.

Type of E-waste	Cu (%)	Fe (%)	Al (%)	Ni (%)	Pb (%)	Ag (ppm)	Au (ppm)	Pd (ppm)	Ref.
Printed Circuit Board	20	6	4	1	2.5	1000	250	90	[57]
Mobile Phone	13	5	1	0.1	0.3	1380	350	210	[58–60]
TV Board	10	28	10	0.3	1	280	20	10	[58–60]
Portable Audio	21	23	1	0.03	0.14	150	10	4	[58–60]
DVD Player	5	62	2	0.05	0.3	115	15	4	[58–60]
Calculator	3	4	5	0.5	0.1	260	50	5	[58–60]

VARIOUS PROCESS DESCRIPTION OF COPPER EXTRACTION

One Step Acid Leaching

The study involves the physical-chemical and hydrometallurgical characterization of two lead-free boards, a motherboard, and a memory board, obtained from obsolete computers. The physical processing involved manual disassembling, comminution, and quartering of the boards, and aqua regia digestion was used for chemical analysis. The residue following aqua regia digestion underwent a Loss on Ignition (LOI) test. The hydrometallurgical processing involved one-stage acid leaching in oxidant media using sulfuric acid as the leaching agent and hydrogen peroxide as the oxidant agent. The boards were solubilized in acid at a solid-liquid ratio of 1:20, a temperature of 95°C, a pressure of 1 atm, and a time of 12 hours. Sampling was done every hour, and the permeate was used to quantify silver and copper by ICP-OES [30].

By Pressure Acid Leaching

The study aimed to investigate the leaching of metals from printed circuit boards (PCBs) using sulfuric acid (H_2SO_4) as a leaching agent. The PCBs were first treated with sodium hydroxide (NaOH) to remove the epoxide material and then rinsed with water. The PCBs were then pulverized to a particle size of -177 µm and mixed with H_2SO_4 and tap water in a Titanium PARR Pressure Reactor. The mixture was stirred for 4 hours under varying conditions of H_2SO_4 concentration, pressure, and temperature. After this, the solution was filtered to separate the solid from the liquid, and the metallic concentration in the solution was determined using atomic absorption spectroscopy (AAS). The solid residues underwent analysis using scanning electron microscopy and energy-dispersive spectroscopy. (SEM-EDS) [25].

Leaching

The study aimed to recover tin and copper from PCBs using hydrometallurgical processes. The findings demonstrated that the optimal leaching system for achieving maximum tin and copper extraction comprised a mixture of 2.18N H_2SO_4 and 3.0N HCl. The maximum tin and copper extraction achieved in the first leaching stage was 96.5% and 98.1%, respectively. Additionally, experiments were conducted using the solid leaching residue from the initial leaching as the feed material for secondary leaching. The outcomes revealed that in the secondary leaching stage, tin and copper extraction reached a maximum of 92.3% and 94.7%, respectively. Following the leaching phases, the leach liquor underwent treatment for the precipitation of tin and copper compounds. It was observed that precipitation with sodium sulfide and sodium hydroxide yielded tin and copper recoveries of up to 99.9% and 99.5%, respectively. Overall, the study showed that hydrometallurgical processes can effectively recover tin and copper from PCBs [31].

Recycling From the Leach Liquor

The study aimed to recover copper from scrap PCBs obtained from waste electronic devices. The depopulated PCBs were segregated and crushed, and then leached in nitric acid to obtain a leach liquor containing Cu, Fe, Ni, and Pb. Bench scale solvent extraction studies were conducted using TBP and LIX 84IC as extractants to extract nitric acid and copper, respectively, from the leach liquor. Deionized water and 10% (v/v) sulfuric acid were used for stripping of acid and metal, respectively. The concentration of acid and metal in the aqueous phase was analyzed using conventional methods and Atomic Absorption Spectrophotometer (AAS), respectively, while pH was measured using a CL 46 pH meter. Satisfactory material balance was obtained for all experiments [26].

Copper Leaching from Metal Powders Mechanically Separated from Waste Printed Circuit Boards in Chloride Media Utilizing Hydrogen Peroxide as an Oxidant

The study centered on the leaching process applied to metal powders derived from waste printed circuit boards (PCBs). The metal powders were separated from non-metallic parts and used without further purification. The leaching experiments took place in a glass reaction vessel outfitted with a mechanical stirrer and a temperature-controlled water bath. The metal powders were added to the leaching solutions, and the solid residue was dissolved in aquaregia to determine the copper content. Metal concentrations in solutions were determined using an atomic absorption spectrometer [61].

Leaching of Metals from Waste Printed Circuit Boards Using Sulfuric and Nitric Acid

The objective of the study was to explore the leaching of metals from waste printed circuit boards (WPCBs) using sulfuric and nitric acids. The WPCBs, sourced from Recom Co. Ltd., Korea, underwent shredding and sorting processes to produce a homogeneous sample. The chemical composition was estimated by incinerating and dissolving the sample in aqua regia, and analyzing the metals using a flame atomic absorption spectrometer. The leaching tests were performed in a 1-L three-necked pyrex reactor, using sulfuric and nitric acids as leachants, with the addition of hydrogen peroxide as an oxidizing agent in the case of sulfuric acid. The effects of pulp density, acid concentrations, hydrogen peroxide concentration, agitation speed, and temperature were evaluated by taking samples at predetermined intervals and analyzing them using FAAS. The metal ions Pb, Al, Fe, and Ca were analyzed using FAAS, and the precipitates obtained from the leach liquors were filtered, washed, and dried for further analysis [62].

Selective Leaching of Valuable Metals from Waste Printed Circuit Boards

This experimental procedure entails the extraction of valuable metals from waste printed circuit boards (PCBs). The PCBs used in the experiment were sourced from various waste computers and were analyzed to determine their metal, plastic, and metal oxide components. To extract valuable metals, Cu, Fe, Zn, Ni, and Sn were dissolved in H_2SO_4 and H_2O_2. The PCBs were crushed, sorted, and passed through an air separator, electrostatic separator, and magnetic separator to separate and discard plastic pieces and obtain nonmagnetic materials from which valuable metals were extracted. Leaching experiments were carried out in a 1-L flask equipped with a pH meter, mechanical stirrer, and condenser in a thermostatically controlled water bath. The analyses of the starting material were carried out using an atomic absorption spectrometer and inductively coupled plasma-atomic emission spectrometer [39].

Selective Copper Recovery by Acid Leaching from PCB Board

The study investigates the leaching efficiency of copper sludge obtained from PCBs production process. The waste sludge, sourced from SungEel Himetal in South Korea, underwent drying, scrubbing, and sieving processes to achieve a particle size of 45 µm. Chemical compositions of the sludge were determined using wet methods. Hydrochloric acid, nitric acid, and sulfuric acid served as lixiviants for leaching the copper sludge. Leaching experiments were conducted in a glass beaker with a fixed stirring speed of 250 rpm, and the metal content of the leach liquor was analyzed using an inductively coupled plasma spectrometer [41].

Microbial Processing of Waste Shredded PCBs for Copper Extraction Cum Separation—Comparing the Efficacy of Bacterial and Fungal Leaching Kinetics and Yields

The Materials and Methods section of a research paper furnishes a comprehensive account of the materials utilized and the methodologies implemented throughout the study. In this particular paper, the section describes the microorganisms used, the printed circuit board (PCB) sample preparation, bioleaching experiments, and solvent extraction studies. The study used a consortium of bacterial strains A. ferrooxidans and A. thiooxidans were utilized in the metal bioleaching experiments. A. ferrooxidans was cultivated in 9K+ medium, while A. thiooxidans was cultivated in 9K-medium. The fungus A. niger was cultivated in Czapek Dox broth media. The PCB sample was depopulated, shredded, and sieved below 150 µm. The sample underwent digestion and analysis by ICP-OES to ascertain its metal content. Shredded PCB samples were employed in the copper recovery experiments. Bioleaching experiments were conducted in Erlenmeyer flasks, where a slurry containing shredded PCB samples was inoculated with an enriched consortium of both species. The experiments were performed under diverse conditions of pH, pulp density, and temperature. The pH of the solution in experimental flasks was maintained daily with 2N sulfuric acid. Redox potential and pH for each of the flasks were taken at a regular interval of 24 h. The samples were collected in intervals of 48 h and prepared for ICP-OES analysis. Solvent extraction experiments were conducted using an aldoxime extractant, Acorga™ M 5640, diluted in kerosene to achieve the desired concentration. All solvent extraction experiments were performed in triplicate sets, with the results showing a mean variation of ±2–3% [63].

Development of a Two-step process for Enhanced Biorecovery of Cu-Zn-Ni from Computer Printed Circuit Boards

The process for enhanced biorecovery of copper, zinc, and nickel (Cu-Zn-Ni) from computer printed circuit boards (PCBs) may entail a two-step approach comprising acid leaching and biosorption. Initially, acid leaching is employed to extract the Cu-Zn-Ni from the PCBs. This involves utilizing a blend of potent acids, such as hydrochloric acid and sulfuric acid, under elevated temperatures and pressures. The leachate obtained from this process contains the metals in their ionic forms. In the second step, biosorption is used to recover the Cu-Zn-Ni ions from the leachate. Biosorption is a process that uses biological materials, such as bacteria or fungi, to selectively adsorb metal ions from solution. For this process, bacterial strains that have high metal binding capacities can be used. The bacterial strains can be immobilized onto a solid support, such as an alginate matrix, to improve their stability and reusability. The immobilized bacterial cells can then be added to the leachate solution to selectively adsorb the Cu-Zn-Ni ions. Once the bacteria have adsorbed the metals, they can be removed from the solution, and the metals can be recovered from the bacteria through a process called desorption. The two-step process of acid leaching and biosorption has been shown to be effective in enhancing the recovery of Cu-Zn-Ni from computer PCBs. This approach provides a more sustainable and environmentally friendly alternative to conventional metallurgical methods of metal extraction, which often result in the generation of significant quantities of hazardous waste [64].

Copper Extraction from Coarsely Ground Printed Circuit Boards Using Moderate Thermophilic Bacteria in A Rotating-Drum Reactor

The study utilized PCBs sourced from obsolete desktop computers, from which all electronic components such as capacitors and resistors were manually extracted. These PCBs were then shredded using a metal guillotine to produce nearly rectangular fragments with a length of 20 mm. Subsequently, for experiments involving ground PCBs, a portion of these sheets underwent further fragmentation using a laboratory hammer mill. After dry sieving, particles with sizes ranging from 208 μm to 147 μm were selected. Another sample underwent a 'pre-weakening' process in a laboratory jaw crusher (with a discharge gap of 10 mm) to induce cracking and expose metals within the PCB sheets to leaching solutions. Following the jaw crusher 'pre-weakening,' the samples were screened at 20 mm, and the oversize fraction was utilized for subsequent studies. A portion of this oversize material (fraction +20 mm) underwent a chemical pre-treatment step to remove the lacquer coating covering the printed circuit boards. PCB sheets (50 g) were mixed with a 500 mL aqueous solution of diethylene glycol (20% v/v) and potassium hydroxide (20% w/v) to achieve this. The lacquer coating removal process was conducted under stirring at 90°C for 60 minutes. Subsequently, the solid phase was filtered, washed with distilled water, and then dried at 50°C until a constant weight was attained.

The mesophile microorganisms employed in the study were isolated from a sulfide mine in Brazil, where microbial diversity analyses revealed the prevalence of Acidithiobacillus ferrooxidans. This strain was sub-cultured in a Norris medium (0.2 g/L $(NH_4)SO_4$, 0.4 g/L $MgSO_4.7H_2O$, and 0.1 g/L K_2HPO_4) with 2.5 g/L Fe^{2+} ($FeSO_47H_2O$). The procedure was accomplished in an orbital shaker at 35 C and 150 min-1. Experiments were also carried out with the thermophilic microorganisms, Sulfolobus metallicus, and Acidianus brierleyi, which were maintained in Brock's medium at 75 C, pH 2.5 [65].

A Cleaner Method for the High-efficiency Regeneration of Base and Precious Metals from Waste Printed Circuit Boards Through Stepwise Oxido-Acidic and Thiocyanate Leaching

The WPCBs were obtained from an electronic waste sales center in Tehran and processed by removing installed components using hot air. The resulting plain boards were cut into small pieces and crushed using a planetary experimental ball mill. The sample was then sieved to obtain a homogeneous mixture with a particle size of (-150 +50 μm). The elemental composition of the WPCB sample was analyzed using inductively coupled plasma mass spectrometry and CHNS-Elemental analyzer. Additionally, the pH of the WPCB powder was determined to assess its acidic or basic nature. For sample pretreatment, a solution of 99% v/v sulfuric acid and potassium persulfate was prepared. Pretreatment experiments were designed using the central composite design from the response surface methodology, with sulfuric acid concentration, potassium persulfate concentration, and solid percentage selected as variables. The experimental design and statistical analysis were carried out using Design-Expert Software version 13 (DX13). Cu nanoparticles were synthesized through the co-precipitation process, with starch, ascorbic acid, and sodium hydroxide employed as the dispersant, reductant, and pH modifier, respectively. The purity and morphology of the product were determined using XRD and SEM analysis. Gold leaching experiments on pretreated WPCB were performed in a glass beaker with potassium thiocyanate and iron (III) sulfate monohydrate as gold leaching reagents. The adsorption rate of the gold-thiocyanate complex on activated carbon was evaluated and compared at different carbon concentrations and adsorption times [66].

Leaching of Copper from Waste-printed Circuit Boards (PCBs) in Sulfate Medium Utilizing Cupric Ion and Oxygen

The objective of the study was to examine the leaching efficiency of copper from waste printed circuit boards (PCBs). These waste PCBs were sourced from spent hard disk drives of the same model obtained from a recycling company. The electronic components on the waste PCBs were eliminated by dissolving solders using HCl leaching with Sn^{4+}. Subsequently, the bare waste PCBs were cut and ground to a particle size of less than 1 mm. The leaching tests were conducted in a 500 mL three-necked Pyrex glass reactor equipped with a heating mantle to regulate the temperature. A 1 mol/L sulfuric acid solution with varied concentrations of Cu^{2+} (ranging from 0 to 10,000 mg/L) was introduced into the reactor, and oxygen, air, or nitrogen gas was injected into the reactor. Two grams of the ground waste PCBs were then added to the reactor. The leaching efficiency of Cu was calculated by measuring the concentration of Cu in the leach solution and residue using optima 8300 ICP-OES [67].

Current Industrial Process of Metal Recovery

The current industrial process of metal recovery from printed circuit boards (PCBs) is typically carried out through a combination of mechanical and pyrometallurgical [68] processes. The mechanical [45] process involves the shredding and grinding of PCBs to reduce their size and liberate the metals. The resulting particles are then subjected to various separation techniques, such as magnetic separation, eddy current separation [69], and density-based separation [70], to isolate the metal fractions from non-metallic materials. The separated metal fractions are then processed using pyrometallurgical techniques such as smelting, refining, and electrorefining to recover the individual metals in pure form [3, 71].

Future of E-waste Scenario

The future of the e-waste scenario is a topic of significant concern due to the increasing amount of electronic waste generated worldwide. Electronic waste, commonly known as e-waste, originates from discarded electronic devices such as smartphones, computers, televisions, and various other consumer electronics. Improper handling and disposal of e-waste can result in environmental pollution, endanger human health, and contribute to the squandering of valuable resources [72]. Several studies have highlighted the current e-waste scenario and its potential future implications. According to a study by the United Nations University, the amount of e-waste generated worldwide is expected to reach 74 million metric tons by 2030, a significant increase from the 53.6 million metric tons generated in 2019 [71]. This surge is attributed to the rising demand for electronic devices, notably in developing nations. Additionally, various factors such as government regulations, technological advancements, and consumer behavior influence the e-waste landscape. Effective implementation of e-waste management policies and regulations is crucial to alleviate its adverse effects on the environment and human health. Governments around the world have taken steps to address this issue, such as the implementation of the European Union's Waste Electrical and Electronic Equipment (WEEE) directive (2012/19/EU), which aims to promote the recovery and recycling of e-waste [73]. Technological advancements have significantly influenced the e-waste landscape as well. The development of more durable and repairable electronic devices, along with the integration of sustainable design principles, can lead to a reduction in e-waste generation. Moreover, the adoption of circular economy principles, where products are designed for reuse and recycling, can lead to the creation of new business models that promote resource conservation and environmental sustainability [74]. Manufacturing processes for e-products often involve the use of toxic chemicals, which can have long-lasting impacts on the environment. As an illustration, the production of LCD flat-panel displays necessitates the utilization of fluorinated greenhouse gases, characterized by atmospheric lifetimes exceeding 3,000 years and possessing thousands of times more global warming potential than CO_2. The manufacture of chips and semiconductors also involves the use of volatile organic compounds [52].

The future of the e-waste scenario also depends on consumer behavior. The increasing awareness among consumers about the environmental impact of e-waste and the adoption of responsible disposal practices can lead to a reduction in e-waste generation. Several studies have highlighted the importance of consumer behavior in e-waste management, including the need for effective communication strategies to promote responsible disposal practices [75]. In conclusion, the future of the e-waste scenario depends on several factors, including government regulations, technological advancements, and consumer behavior. The implementation of effective e-waste management policies and regulations, along with the adoption of sustainable design principles and circular economy principles, can lead to a reduction in e-waste generation and promote resource conservation. Moreover, the adoption of responsible disposal practices by consumers is critical in mitigating the negative impact of e-waste on the environment and human health.

SUMMARY

In this study we reviewed various research papers and gathered lot of information about Copper Recovery Process from PCBs. The process of extracting copper from printed circuit boards (PCBs) encompasses multiple steps. The PCBs are first crushed and ground into small pieces, followed by physical and chemical separation methods to isolate the copper. The most commonly used physical separation method is froth flotation, while the chemical separation methods include leaching, solvent extraction, and electrowinning. In the current scenario, copper extraction from PCBs is done mainly through hydrometallurgical methods. These methods are environmentally friendlier in comparison to traditional approaches like smelting and roasting, which emit harmful pollutants. However, the efficiency and economics of these methods need to be improved to make them more viable for large-scale commercial applications. In the future, there is a growing need for efficient and sustainable methods to extract copper from PCBs, as the amount of e-waste generated globally is increasing rapidly. Researchers are exploring various novel methods, such as bioleaching, which uses microorganisms to dissolve copper from the PCBs, and electro kinetic methods, which use electrical currents to extract metals. While these methods exhibit potential in terms of efficiency and environmental sustainability, further research and development efforts are required to render them commercially viable.

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