Technological and environmental aspects of electronic waste recycling

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Abstract
This article reviews recent literature related to electronic waste (E-waste) processing. The extraction of precious metals is shown as the main economic driver of E-waste processing. The study methodology is based on collecting and analyzing statistical data and performing comparative analytical methods. The theoretical aspect is based on a critical analysis of the research of Russian and international authors.
This article highlights the current pyro-, hydro-, and biometallurgical processing methods used for extraction of precious metals from E-waste. A comparative analysis of known technologies for E-waste processing is performed; their advantages and disadvantages are shown to achieve a cleaner waste disposal process.
The technological and environmental aspects of E-waste processing, as well as the effect of toxic substances and harmful components in E-waste processing, have been subjected to a detailed analysis. According to the analysis results, existing technologies must be revised for a comprehensive solution to environmental problems. The increasing E-waste formation demonstrates the necessity of new approaches and the development of innovative technologies for E-waste processing. The use of E-waste as an additional source of raw materials to produce precious and other valuable metals seems very promising.

Keywords Electronic waste · Collection · Processing · Raw materials · Precious metals · Ecology · Toxic substances · Environment

Introduction

Waste electronic and electrical equipment (WEEE) includes all devices that have lost their consumer properties and whose operation depends on an electric current and/or electromagnetic field. In global practice, the abbreviations WEEE and electronic waste (E-waste) denote this type of waste. Currently, the main options for managing E-waste are reuse, recycling, incineration, and landfilling. In many cases, electronic equipment that is no longer useful to the original consumer may still have value to others, i.e., they can be resold or donated to schools or charity without any modifications.

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Reusing end-of-life electronic equipment is of utmost importance when managing E-waste. This importance is due to a reduction in the volume of processed waste resulting from increasing the service life of aftermarket equipment. WEEE recycling is a batch manufacturing process in which used products or cores are disassembled, cleaned, repaired or upgraded, reassembled, and tested to produce new or similar equipment [1]. WEEE recycling involves recycling materials for their original purpose or other purposes and the dismantling and/or disposal of end-of-life equipment to recover the materials.

The main economic driver of E-waste processing is the extraction of precious metals. In global practice, various established approaches to solving this problem have already been developed. European countries have advanced in the issue of processing E-waste, where a systematic approach has been applied to provide a solution at a high state and public level. The current Directive No. 2012/19/EU of the European Parliament and the Council of the European Union on WEEE sets per capita standards for the recycling and recovery of WEEE. The desire to recycle E-waste is quite obvious.

In European countries, where no reliable mineral resource base is available for the production of gold and other valuable metals, the issue of processing E-waste to obtain gold is of particular importance.

Conservation and sustainable development of the environment is a common problem that is inherent in all countries. From the standpoint of processing and disposing man-made waste in general and E-waste containing hazardous toxic and harmful substances in particular, this topic is becoming pressing. When developing and organizing methods (technologies) for processing E-waste, environmental issues and human health safety should be placed at the forefront.

The feasibility of choosing a processing method (technology) for E-waste should consider technological and environmental aspects equally.

In this work, on the basis of a critical analysis of E-waste processing, the authors focus on problems that are not fully discussed in the scientific literature. In particular, these problems are related to the integrated use of raw materials with the extraction of a wide range of valuable metals from E-waste, which forms the basis for economic diversification. Despite their high manufacturability, technologies accepted for implementation must ensure "zero waste" and prevent new secondary waste formation. Unfortunately, according to practice results, currently used E-waste processing technologies do not always meet these requirements.

This work mainly aims to provide a comprehensive overview of the E-waste problem, E-waste management strategies, and various physical, chemical, and metallurgical processes for recycling E-waste.

Generation, collection, and recycling of E-waste worldwide

In 2019, 53.6 million tons of E-waste were produced worldwide, an average of 7.3 kg per capita [2, 3]. Of this total volume (53.6 million tons), the accumulation of E-waste in the regions is presented in Fig. 1.

Only 17.4% of the total volume of E-waste has an officially documented status as being properly collected and recycled. Moreover, if this volume has increased by 1.8 million tons since 2014, then the total generation of E-waste has increased by 9.2 million tons, i.e., recycling production has not kept pace with the global growth of E-waste [2–4].

In 2019, the highest amount of E-waste was recorded in Asia (24.9 million tons), followed by America, Europe, Africa, and Oceania with 13.1, 12, 2.9, and 0.7 million tons, respectively [5].

Europe produces the most E-waste per capita (16.2 kg), followed by Oceania (16.1 kg per capita), America (13.3 kg per capita), Asia (5.6 kg per capita), and Africa (2.5 kg per capita).

Data presented in [3–5] show that the volume of E-waste is growing at an alarming rate, by almost 2 million tons per year (~200%) (Fig. 2). These data suggest that recycling has not kept pace with the global increase in E-waste.

E-waste contains a range of valuable metallic and nonmetallic materials. The production of mobile phones and PCs consumes a considerable proportion of the gold, silver, and palladium mined annually around the world. A total of 43% of all gold produced worldwide is used in electronics. Computer circuit boards contain the highest

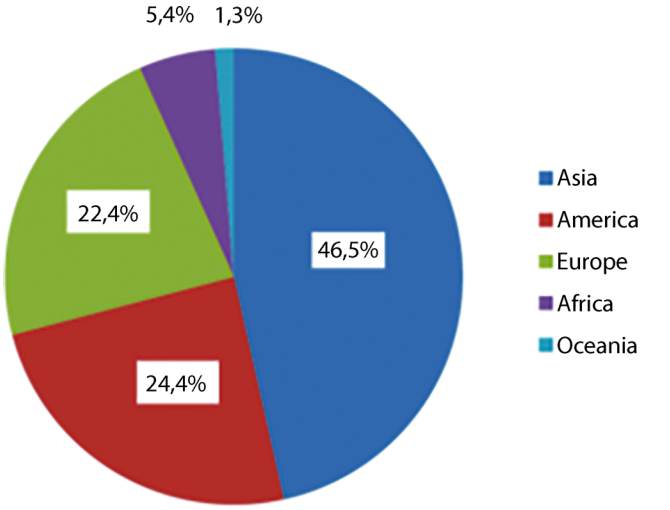


Fig. 1 Accumulation of E-waste worldwide [3]

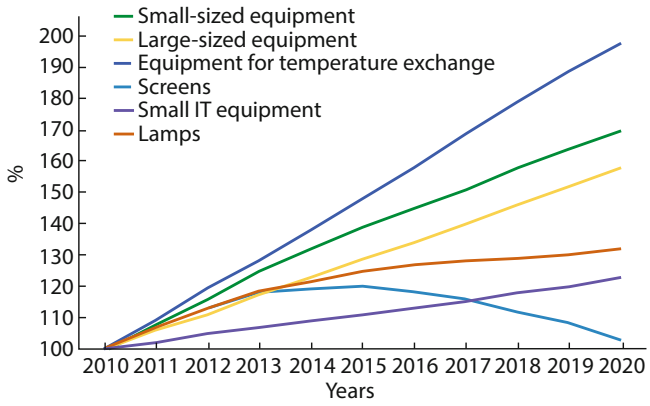


Fig. 2 Growth rates of electronic waste by main streams [5]

proportion of precious metals. As printed circuit boards become more complex and compact, the amount of materials they contain changes constantly. One ton of printed circuit boards can contain 80–1500-g gold and 160–210-kg copper. These concentrations are 40–800 times the amount of gold in Au ore and 30–40 times the concentration of copper in copper ore mined in the United States.

Worldwide, the electronics industry annually consumes 267.3 tons of gold and 7275 tons of silver [6]. According to the 2019 E-waste report of the United Nations Organization, approximately 300 tons of gold are recovered annually, and the E-waste market is worth $ 52 billion. E-scrap recycling is profitable, although its precious metal content (Au, Ag, and Pd) steadily decreases.

In terms of composition, E-waste can be identified as a material containing various metals, particularly copper and aluminum, attached to, coated with, or mixed with plastics and ceramics of various types [7]. Precious metals are widely used to manufacture electronic devices and as contact materials because of their high chemical stability and good conductive properties. Platinum group metals are used, among other things, in switching contacts (relays, switches) or as sensors for determining an electrical measured variable as a function of temperature [8].

E-waste varies considerably depending on its age, origin, and manufacturer. Scrap has no average composition; even the values given as typical averages actually represent scrap of a certain age and manufacturer. This is due to the drop in the power consumption of modern switching circuits and the increase in the clock frequency (surface conductivity). If, in the 1980s, the contact layer thickness was 1–2.5 µm, it presently ranges from 300 to 600 nm (gold plate) in modern devices [8].

Precious metals account for more than 70% of the cost of cell phones, calculators, and waste printed circuit boards and approximately 40% of television circuit boards and DVD players. The precious metals are followed by copper and zinc, with Al, Pb, and Fe having lower values.

Technological aspect of the issue

Recycling E-waste conventionally includes three main stages: (1) selective disassembly aimed at separating hazardous or valuable components for special processing, a mandatory process when processing E-waste; (2) modernization, i.e., the use of mechanical processing and/or metallurgical processing to improve the quality of materials, i.e., preparation of materials for processing; and (3) refining, i.e., metallurgical processing and purification of the final metal [9].

Three main E-waste recycling methods include pyrometallurgy, hydrometallurgy, and biohydrometallurgy. In general, all types involve shredding, crushing, and grinding the waste down to particles that are 100–300 microns in size, with sieving and subsequent physical separation of the plastics when possible. However, the latter is not always possible because the metal parts are embedded in plastic on a much smaller scale (several microns).

Pyrometallurgical processing includes combustion and smelting, which are accompanied by high-temperature gas-phase reactions [10]. Over the past two decades, pyrometallurgy has become a traditional method for extracting precious metals from E-waste. In this technology, crushed waste is burned in a furnace or melt bath to remove plastics, and refractory oxides form a slag phase. Pyrometallurgy has two advantages. First, almost all precious metals are extracted, even if their content is only 1 ppm. Second, the method implementation does not require special preparation. However, the implementation of pyrometallurgical technology for processing E-waste requires the presence of a copper smelter and, less often, a lead plant for smelting metals, which is an important factor limiting its development. Consequently, E-waste must be collected and transported over very long distances. With over 99.9% of E-waste having little commercial value, the cost of extracting gold using pyrometallurgy becomes quite high. In addition, the direct combustion of E-waste entails major environmental problems.

In the last two decades, hydrometallurgical processing has been the most active area for extracting metals from electronic scrap. Hydrometallurgy is based on a sequence of acid and alkaline leaching operations to separate gold from other metals, followed by the separation of liquid and solid phases and purification of the final metal produced [11, 12]. Hydrometallurgical technologies are becoming widespread for gold extraction worldwide because they are very energy efficient. However, hydrometallurgical technologies require the use of large quantities of hazardous chemicals such as cyanide and/or thiourea. The use of hydrometallurgy to recover gold from E-waste has two main hindrances. First, hydrometallurgical processes are highly optimized for a specific type of feedstock. Recovery of gold from E-waste, which varies in content, highly depends on the type of pretreatment and often requires very fine grinding ($<100\,\mu m$). Thus, gold recovery rates vary greatly depending on the type and composition of the processed batch. Second, hydrometallurgical processes are accompanied by a large yield of highly toxic liquid waste. Increasingly stringent requirements for waste treatment make only huge hydrometallurgical plants competitive, resulting in waste collection and transportation costs becoming crucial, similar to pyrometallurgical technologies.

One of the new areas includes biohydrometallurgy, which is based on reactions involving bacteria. This technology is widely used to process ores with high sulfide content (“refractory” ores), which are unsuitable for cyanide or thiourea leaching. This technology is relatively inexpensive and minimizes the amount of chemical or biological residue [13]. Despite its advantages, biohydrometallurgy is not suitable for processing E-waste. This unsuitability is due to the presence of gold in E-waste as alloys and surface coatings. Extracting gold from such materials using bacteria does not provide the desired high economic effect.

Pyrometallurgy is the most widely used method for processing E-waste, which, along with high technological indicators for the extraction of precious metals, has a significant negative impact on the environment and human health.

Pyrometallurgical processing, common in Russia, includes electric arc and anode smelting or reflective and shaft smelting, followed by conversion and fire refining. The most appropriate recycling method depends on the type of E-waste and its material composition. Processing of secondary raw materials in the Russian Federation mostly focuses on copper smelters and reduces to converting electronic scrap containing precious metals into an alloy with copper. Next, blister copper is subjected to electrolytic dissolution of the anodes, during which an anode slurry enriched with precious metals is formed [14].

A schematic of electronic scrap recycling in Russia is presented in Fig. 3.

Russia generates only 3.75% of the global E-waste, but this field is gradually developing and becoming profitable. The introduction of effective technologies in Russia is restrained because large nonferrous metallurgical enterprises are aimed at exclusively producing precious metals. To improve the economic performance

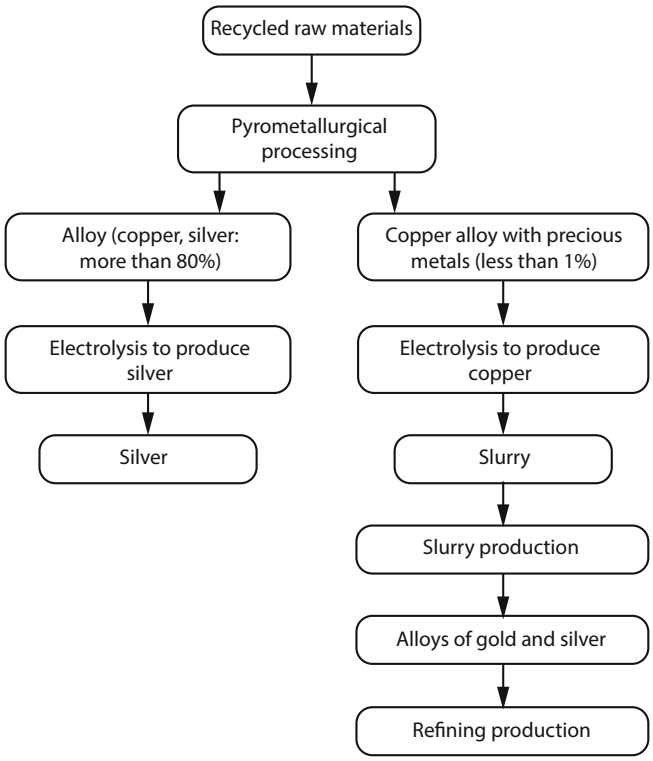


Fig. 3 Schematic of electronic scrap recycling in Russia [14]

of enterprises and maximize profits, complex processing technologies must be introduced to extract not only precious metals but also various other valuable metals.

According to the above analysis, none of the technologies considered for processing E-waste fully solve environmental issues. Technologies are designed such that successive complex operations are required to extract gold, which cause great harm to the environment. This result necessitates the search for new scientific approaches and the development of innovative technologies for processing E-waste, which can soon become a stable additional secondary raw material for the production of precious and other related valuable metals. At the same time, any new technology must ensure minimal release of toxic and harmful substances into the environment.

Environmental aspect

Currently, more than 70% of E-waste is disposed of in landfills where toxic heavy metals are washed out. The current state of E-waste processing seems ineffective. In particular, recycling using traditional municipal solid waste incinerators is unacceptable. For example, copper, which forms the basis of the E-waste matrix, catalyzes the formation of dioxins during the combustion of fire-retarding agents. This attribute is of particular concern when burning brominated fire-retarding agents at low temperatures.

The incineration of E-waste produces heavy metal fumes and toxic gases, which are also released into the environment. E-waste accounts for almost 2% the of total solid waste and contains 70% of the total toxic materials.

Toxic substances in E-waste

In European countries, annual emissions of mercury and cadmium into the environment from the combustion of E-waste are calculated to be 36 tons and 16 tons, respectively [15].

Mercury is used in relays, switches, batteries, liquid-crystal displays, and gaseous discharge lamps (i.e., fluorescent lamps, scanners, and copiers). Each year, approximately 22% of mercury produced in the world is used in the electronics industry. The batteries contain Pb, Cd, Li, and Ni. In old televisions, personal computers, and cathode ray tubes, the cone glass, electron gun getter, and phosphors contain Pb, Ba, and Cd, respectively. Plastic bases contain Pb, Sn, and Sb in solder; Cd and Be are found in switches. Polyvinyl chloride (PVC) and brominated flame retardants are the main components of plastics. Chromium (Cr^{6+}) is present in floppy disks. Capacitors and transformers contain polychlorinated biphenyls. Chlorofluorocarbons are found in cooling devices and insulating foamed plastics. Americium (Am) is found in smoke detectors. LCDs include liquid crystals embedded between thin layers of glass and electrical controls. Liquid crystals represent a mixture of 10–20 substances belonging to the substituted phenylcyclohexane, alkylbenzene, and cyclohexylbenzene groups. These substances contain O, F, H, and C and are considered hazardous.

Influence of metals on human health

Lead damages the human central and peripheral nervous system, blood system, and kidneys. It also affects children's brain development. Chromium causes asthmatic bronchitis and DNA damage. Cadmium has a toxic irreversible effect on human health and accumulates in the kidneys and liver. It also damages the nervous system. Mercury causes chronic damage to the brain and respiratory system. Plastics and PVC, release dioxins when burned, which cause reproductive and developmental problems, damage the immune system, and interfere with regulatory hormones.

Proper management of E-waste is necessary for all countries because it pollutes groundwater, acidifies the soil, and releases toxic fumes and gases after combustion. E-waste, as practice shows, accumulates most quickly in municipal landfills and releases carcinogenic substances into the air.

The impact of the listed toxic and harmful substances, as well as metals, on human health indicates the need for a more systematic, thoughtful approach to E-waste processing. New technologies are required to minimize environmentally harmful stages such as combustion, smelting, and refining, which, while solving the technological aspect of E-waste processing, are emission sources of toxic and harmful substances that adversely affect the environment and human health.

E-waste recycling technologies should be aimed at converting E-waste into conflict-free, sustainable polymetallic secondary resources for the future. Recycling technology must be able to process E-waste in an environmentally friendly manner, with high efficiency and a minimal carbon footprint, and at a moderate cost associated with setting up high-cost smelters. Considering the depletion of our natural resources, this approach to mining offers many advantages, such as conserving resources, obtaining products with high liquidity, and reducing material costs. This approach will lead to increased energy efficiency and reduced demand for the extraction of new additional raw materials with a high content of valuable metals.

New approaches are required to organize the effective processing of E-waste. "Large" enterprises are often uninterested in obtaining small-scale by-products from their own waste until the accumulated waste begins to hinder the development of the main business. Issues of environmental payments and resource conservation are the prerogative of the state, and obtaining by-products is most interesting to small- and medium-sized businesses. Thus, an outsourcing scheme suggests itself when small enterprises on the territory of "large" enterprises produce highly liquid products from their waste [16].

Economic diversification is required. The state, relying on global experience in the E-waste processing field, should not organize production but develop mechanisms and create favorable conditions for small- and medium-sized businesses. With this approach, the business will appear on its own and find its place necessary for the production of valuable metals from E-waste.

Conclusions

Recycling of E-waste is an important issue in terms of not only waste treatment but also valuable metal recovery. A division of the value of various samples of electronic scrap shows that precious metals account for more than 70% of the value of cell phones, calculators, and scrap circuit boards and are still approximately 40% for television circuit boards and DVD players. The use of these wastes as an additional source of raw materials for the extraction of precious metals can be a major economic incentive for recycling.

Hydrometallurgical technologies can play a key role in the recovery of nonferrous and precious metals from E-waste, the recycling of which, from an economic and environmental standpoint can soon be a crucial sector for obtaining highly liquid metals.

Existing technologies, including hydrometallurgical technologies, used for processing E-waste require considerable modernization and/or the creation of new technologies that ensure environmental safety when processing E-waste that is complex in type and composition.

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