


Pyrometallurgical Recovery of Metal from E-Waste: A Comprehensive Review

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Abstract: In most developing and developed countries, e-waste or Used Electronic Equipment (UEEE) is gradually becoming one of the fastest-growing waste streams. Despite the challenges posed by improper disposal of e-waste, there is hidden wealth in these materials, including precious metals such as gold, silver, copper, and palladium, which can be extracted through pyrometallurgy. This review comprehensively analyses pyrometallurgical processes for the recovery of valuable metals from UEEE, waste electrical and electronic equipment (WEEE), or e-waste. The increasing global volume of e-waste presents both a significant environmental challenge and an opportunity for resource recovery. Pyrometallurgical methods, including refining, roasting, smelting, and the use of fluxes, are explored in detail, highlighting their efficiency, scalability, and economic and environmental implications. The review also addresses challenges such as the generation of toxic emissions, energy consumption, implications on global climate change, and the need for improved process control. Finally, emerging advancements in pyrometallurgy for e-waste recycling are discussed, emphasizing sustainability and the potential to integrate these technologies into circular economies.

Keywords: pyrometallurgy; e-waste; precious metal; smelting; WEEE; UEEE.

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1. Introduction

The lifestyles of humans in the past few decades have improved drastically following the Industrial Revolution and the digitalization of the world. This industrialized and digital world offers relief to humans in many aspects of their lives through the provision of electrical and electronic equipment (EEE). The more relief is aimed at humans, the more innovative electrical and electronic gadgets that are produced. Consequently, more of the waste of electrical and electronic equipment (WEEE) or used electrical and electronic equipment (UEEE) would be produced. WEEE refers to any remains of electrical or electronic equipment derived from the usage of electrical or electronic equipment and its parts [1]. In 2002, E-waste was defined as any electronic or electrical equipment that no longer adds value to the user or has reached the end of its useful life [2]. E-waste consists of discarded computers, smartphones, televisions, and household electrical and electronic appliances. The demand for sophisticated EEE and the need for relief among the world's population have led to exceptional and

significant growth in global E-waste. An estimated 53.6 million metric tons of E-waste was generated in 2019 [3], and an estimated value of about 350 metric tons of unrecycled e-waste as of August 2024, with an expected increase in the amount of WEEE generation in the years to come [4]. According to Adepitan *et al.* [1], precious metals such as Silver, Palladium, Gold, and Chromium are present among the metal composition of these discarded wastes. E-waste, or WEEE, typically contains a variety of materials, including polymers, metals, and ceramics, which are heterogeneous. These components are referred to as integral technological elements because of their basic functionality in appliances [5]. The unequal distribution and scarcity of reserves of these metals globally lead to a high associated value [6].

These wastes, however, pose a critical danger to human well-being when improperly discarded, as they contain harmful substances such as mercury, lead, and cadmium [1, 6]. These dual traits of e-waste pose a critical challenge in managing their disposal, and there is a need for an innovative, effective, and sustainable approach to address the impending danger [2]. Most technological components are built on a metal foundation, from electrical circuits to their body frames. Extraction of metals from their ores can be expensive, energy-intensive, and environmentally harmful, but extracting these metals from secondary sources such as E-waste provides a viable option that can minimize reliance on mining while also reducing environmental impacts. Metal recovery from e-waste is not only financially beneficial but also contributes to global sustainability goals, such as reducing resource depletion and waste. Figure 1 shows the life cycle of rare earth elements (REEs) in device production and their recovery from e-waste. However, it is expedient that efficient recovery methods address issues such as the complexity of e-waste composition, the dispersion of valuable metals in these wastes, and the exposure to harmful byproducts during the process.

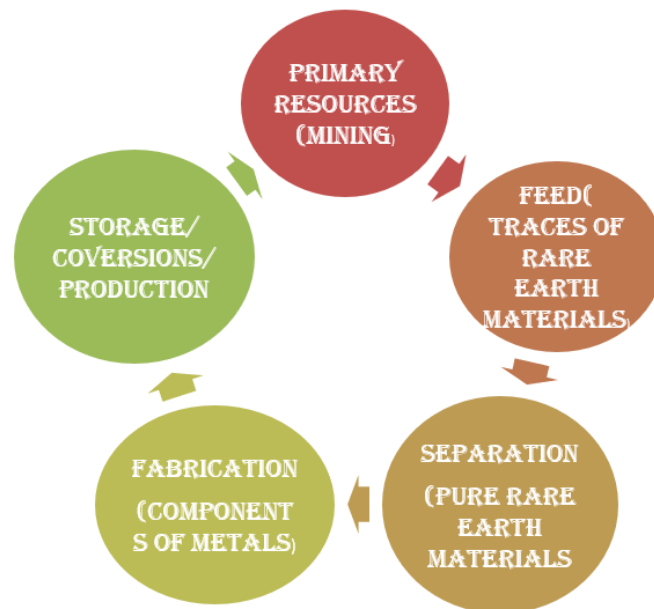


Figure 1. The lifecycle of rare earth elements (REEs) in device production and their recovery from e-waste.

The main objective of this review is to systematically examine the processes of valuable metal recovery through pyrometallurgy from e-waste by highlighting the current process of pyrometallurgy, its efficiency, economic implications, and environmental impact. To achieve these, the possibility of resource conservation, some difficulties encountered in scaling the process internationally and increasing economic growth through the pyrometallurgical process will be identified.

2. E-waste

The term e-waste refers to waste generated by electrical or electronic devices after their life cycle has ended. These e-wastes range from large devices such as refrigerators, televisions, and washers to portable devices like laptops and smartphones. The classification of e-waste by the International Telecommunication Union (ITU) is divided into 6 categories because it consists of mixtures of materials such as plastics, ceramics, glass, and metals [7]. Some of these classifications are: screen and monitor devices like televisions and computers; temperature exchange devices like refrigerators, air conditioners, and heat pumps; and lamps, including LED lamps, fluorescent bulbs, and other lighting devices. Large equipment includes washers, dryers, and solar panels. Although many of these discarded devices (e-waste) are waste, there are a few valuable materials (metals) like gold, silver, copper, palladium, and rare earth elements (REES) in these discarded devices, which are fundamental to the functioning of many modern devices and renewable technologies in the energy sector [8].

Small equipment includes toasters, cameras, and electrical tools, and Small IT and telecommunications equipment includes mobile phones, routers, and pocket PCS. This classification helps streamline waste management processes, ensuring that the diverse components within these devices are properly handled and processed. Each category presents unique challenges and opportunities for material recovery, particularly regarding metal content and recyclability [9].

China, India, and the United States of America are among the countries with the greatest amount of generated e-waste [10]. Global e-waste generation is speedily increasing by the year, with a percentage as high as 4-6%. In 2019, global e-waste generation was estimated at about 53.8 Mt, a 22% increase from the previous year, and is expected to skyrocket to about 74% by 2030 [11,12]. E-waste generation varies from country to country, and levels in developed countries differ from those in developing and underdeveloped countries. This can be attributed to the high level of digitalization. Just like other wastes generated by humans, e-waste poses hazards to human health.

Various countries and international organizations have promulgated strict laws to reduce the influx of UEEE, as it's a potential source of e-waste due to its short lifespan. A developing country like Nigeria, with a dense population, faces illegal dumping of UEEE or WEEE in most of its urban regions [1]. This illegal dumping of WEEE materials can be hazardous to human health due to their components, which can pose negative health risks when they enter water bodies. E-waste contains metals and hazardous components. E-waste is very heterogeneous, containing precious metals as well as harmful chemicals. Table 1 presents components (pollutants) of e-waste, their sources, and their potential risks to human health. According to [13], most e-waste components contain about 50% iron, about 20% polymeric material, and non-ferrous materials, which include some precious metals. Excessive exposure to WEEE, either through occupation or environmental accident, has been reportedly linked to the cause of many cancers [14]. Proper management of E-waste through recycling or precious metal recovery (pyrometallurgy) would not only improve public health in the immediate vicinity but also boost the economic growth of the inhabitants.

Table 1. Some components of e-waste and their potential risk to human health [1].

Components (Pollutants)	Sources	Potential health risk
Mercury	Batteries (clocks, phones, calculators), LCDs, steam iron, etc.	Negative effects on the nervous system, irritability

Components (Pollutants)	Sources	Potential health risk
Lithium	Batteries of mobile phones, video games, and photographic equipment	Muscle weakness, fatigue, and heart disease (in high percentage)
Chrome	Dyes and pigments, switches, etc.	Damage to the Liver and skin irritation
Cobalt	Batteries of mobile phones and insulators	Respiratory disorder
Nickel pigments: Skin irritation	Batteries, semiconductors	Pigments: Skin irritation
PCBs (polychlorinated biphenyls)	Transformers and capacitor components, paint, glue, and plastic as softeners	Damage to the Liver and skin irritation and exposure to pregnancy can result in behavioural deficits in newborns
Selenium	Pigments in phones, Photoelectric cells, and photocopiers	Skin irritation. Excessive hair loss, nails, and lack of mental alertness
Cadmium	Monochrome cathode ray tubes (CRTs) and batteries in phones and laptops. Pigments, solder, metal alloys, and electrical circuit boards	Disruption in bone composition

3. Pyrometallurgy

An important aspect of e-waste recycling is the metal recovery process, given the high value of the metals in the equipment's composition. E-waste processing is complicated due to its heterogeneity [15]. Valuable metals are frequently scattered in minute quantities throughout devices, necessitating improved recovery methods. For example, a single smartphone may include up to 60 elements from the periodic table, each with a specific functional purpose [16,17]. Most e-waste consists of polymeric materials (plastics), ceramics, and precious metals from electrical or electronic devices. Mechanical means are often employed in the separation of metallic components and plastic components. The separated plastics can be recycled for other purposes, such as pyrolysis and gasification, while the other parts, which are metals such as iron, aluminum, and silver, are separated using suitable methods, such as biological, physical, and chemical methods. All these processes, however, are challenging due to the complexity and heterogeneity of the metal's composition [7].

The thermal process of metal recovery from or extraction from a component is known as pyrometallurgy. Pyrometallurgy is a metal extraction process that involves high temperatures for recovering metals from ores, concentrates, or secondary sources such as UEEE or WEEE. Unlike hydrometallurgy, which uses chemical solutions to extract metals, pyrometallurgy uses thermal energy to drive phase transitions, chemical reactions, and separations, typically making it more efficient for a given feedstock [18]. The process of pyrometallurgy is generally regarded as the conventional method of metal recovery from e-waste material, especially from non-ferrous elements.

3.1. Smelting.

One of the most common pyrometallurgical processes is smelting [19]. The process involves dismantling, shredding, and smelting materials to produce bullion copper, which can then be further refined by an electrolytic process to achieve a purer form of copper. Figure 2 summarises an overview of the smelting process. Smelting is a form of extractive metallurgy that involves the heating of ores to extract base metals. The process typically involves a furnace in which the ore is combined with a reducing agent, often carbon, to facilitate the extraction of the metal. The result is the production of a molten metal that can be further refined. Smelting requires very pure feed (rich in copper and precious metals) and high energy.

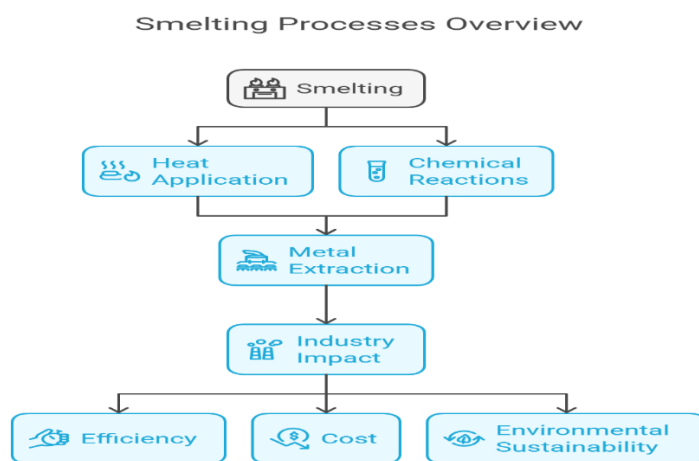


Figure 2. An overview of the smelting process.

Pyrometallurgical methods excel at recovering metals when applied to e-waste from complicated matrices, such as printed circuit boards and solder compounds, where metals are intricately bound with non-metallic components [20]. According to Cui *et al.* [21], despite the economic advantage of metal recovery from e-waste, the main challenge of this process is the non-homogeneity of e-waste composition.

The pyrometallurgical process of metal removal from ores or components has been in existence for many years and can be traced back to metalworking, when crude smelting procedures were used to remove metals such as copper and iron from their ores [19]. Over millennia, these processes have evolved dramatically, driven by technological advances and rising metal demand. The Industrial Revolution was a watershed moment, introducing large-scale blast furnaces and refining techniques capable of efficiently processing massive amounts of ore. There are many core pyrometallurgical processes beyond smelting, and each is unique.

3.2. Roasting.

One other process of pyrometallurgical recovery of precious metals is roasting. Roasting is done in a high-temperature process that involves heating e-waste or its intermediates in the presence of oxygen [22]. The goal is to oxidize metal sulfides, convert volatile compounds into gases, and prepare materials for further processing [20]. This process is unique in the removal of impurities such as sulfides, chlorides, and arsenic compounds, which are mostly found in e-waste components such as PCBs (Printed Circuit Boards), etc. [12, 23]. In the recovery of copper from e-waste, for instance, roasting is used to oxidize copper sulfide (CuS) to copper oxide (CuO), which can then be reduced in the smelting process [24]. Roasting also helps reduce the volume of the waste, making it easier to handle during subsequent smelting stages. Figure 3 provides an overview of the pyrometallurgical roasting process, including its advantages, limitations, byproducts, applications, and environmental controls.

The pyrometallurgical process is another method for recovering precious metals from electronic waste. These techniques are primarily used to recover metals such as gold, copper, and iron, as well as lithium-ion battery materials. Figure 4 shows an overview of the thermal method of pyrometallurgy, which comprises heating, chemical reaction, separation, cooling, and collection. Over the years, thermal methods have become efficient for recovering valuable metals from spent lithium-ion batteries. Recent studies have focused on optimizing these processes to enhance metal recovery rates and reduce environmental impacts [25,26].

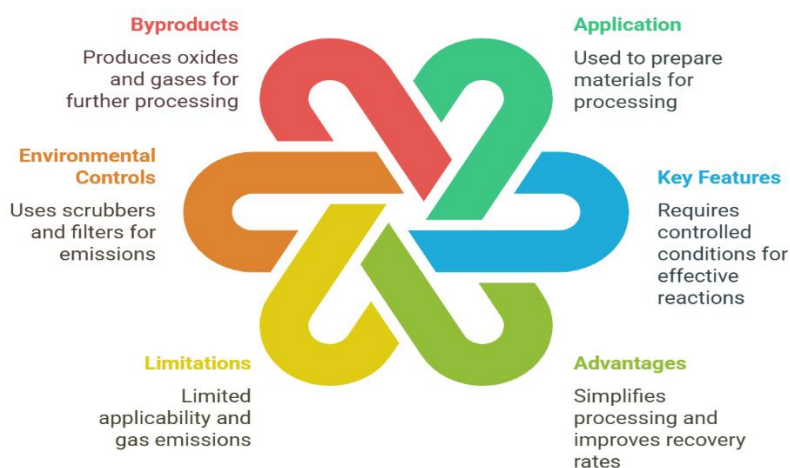


Figure 3. Overview of the roasting process in pyrometallurgy.

Studies are being conducted on the utilization of greener reactants such as hydrogen, biofuels, ammonia, and biochar to reduce carbon footprints and promote a safer environment and sustainability. This has led to the design of more efficient reactors and process control. For instance, a novel reactor developed at Montanuniversitaet Leoben utilizes an inductively heated bed of graphite cubes to recover lithium and phosphorus in the gas phase, thereby enhancing the efficiency of metal recovery [27,28]. However, some e-waste materials are composed of compounds; that is, multiple elements are chemically combined to achieve the engineering characteristics needed for electrical purposes. Such compounded materials are best separated or recovered by thermal decomposition.

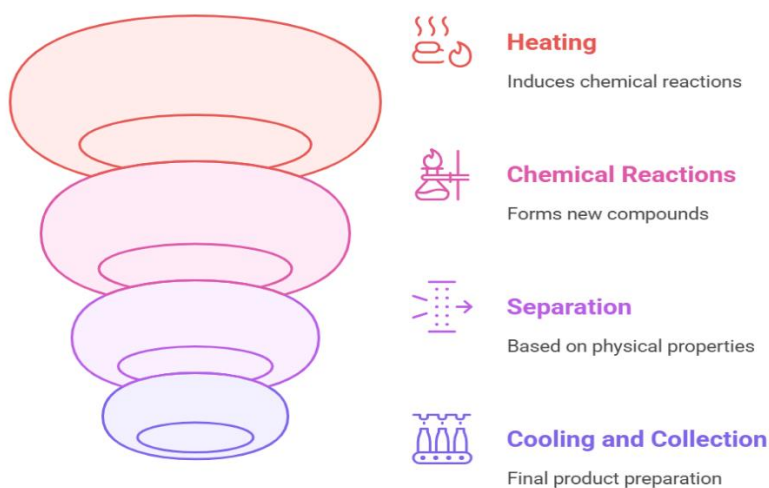


Figure 4. Overview of the thermal method.

3.3. Thermal decomposition.

Thermal decomposition is a crucial process in pyrometallurgy, in which a chemical compound is broken down into simpler substances by applying heat. This process is key to metal extraction, purification, and refining from ores, as well as to the removal of impurities [29]. This method is used in pyrometallurgical processes like calcination and roasting, as well as in the preparation of certain metals from their impurities (ores). Thermal decomposition primarily involves the decomposition (breakdown) of metal carbonates, sulfides, or other compounds into their oxides, elemental metals, and other by-products, often in the presence of

a reducing agent or oxygen [30]. The thermal decomposition reactions are usually carried out at high temperatures, ranging from 300°C to 1000°C or more. The operational temperature depends on the type of metal or material involved. Figure 5 shows the processes involved in thermal decomposition and metal recovery in e-waste material. Thermal decomposition has few advantages as a type of pyrometallurgy process. The following are a few advantages of thermal decomposition over other forms of pyrometallurgical processes [31,32].

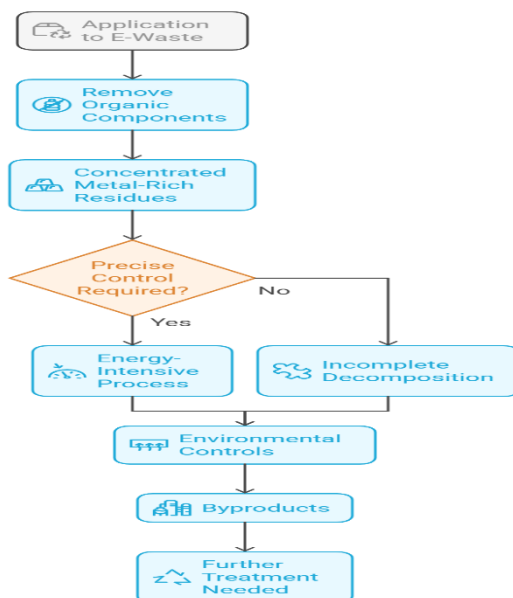


Figure 5. Processes involved in the thermal decomposition of metals from e-waste.

Efficiency in Metal Extraction: Thermal decomposition processes like roasting and calcination provide an efficient means of converting ores into metal oxides or other useful compounds that can be more easily reduced or processed.

By-product Utilization: Gases produced during thermal decomposition (e.g., sulfur dioxide) can often be captured and converted into valuable by-products like sulfuric acid, which has significant industrial applications.

Scalability: Thermal decomposition processes are scalable and can be performed on a large industrial scale, making them suitable for the extraction of metals from a wide variety of ores.

Thermal decomposition plays an essential role in pyrometallurgy by breaking down ores and compounds into simpler substances that can be further processed to extract valuable metals. Whether through calcination, roasting, or other forms of thermal decomposition, these processes are fundamental to the extraction of metals such as copper, zinc, gold, and lead. While they offer efficiency and scalability, they also require careful management of energy use and environmental impact.

3.4. Refining.

In the pyrometallurgical process, the final stage is the refining of the extracted metal. This stage focuses on the purification of metals obtained from ores. The objective of refining is to ensure the metal product is free of impurities and of high quality, meeting the required standards for industrial or commercial use [33]. There are various pyrometallurgical methods for refining, including distillation, oxidation, melting, and reduction. These depend on the metal to be refined and the composition. Refining is important in metals like gold, silver, lead, and copper because these metals often contain a variety of impurities such as sulfur, arsenic,

iron, and zinc, other trace impurities that must be removed for the metal to have desirable properties, such as electrical conductivity or corrosion resistance [34,35]. Figure 6 provides an overview of key features, byproducts, advantages, limitations, and environmental controls of the metal refining process.

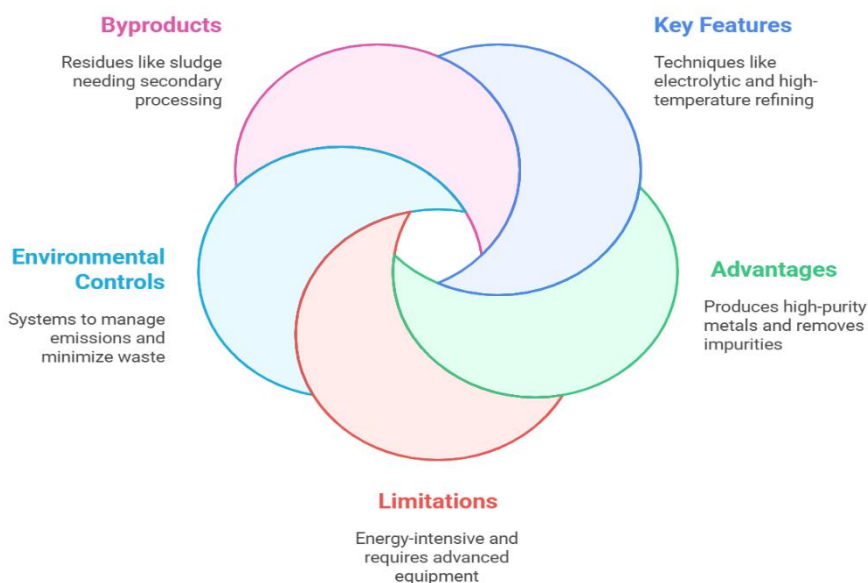


Figure 6. Overview of some of the key features of the metal refining process.

Metal refining plays a critical role in shaping the global economy and advancing environmental sustainability, providing cleaner environments and high-purity metals necessary for manufacturing and technological advancement [36]. Different refining methods, such as pyrometallurgy, hydrometallurgy, and electrolytic refining, each have advantages and challenges. While environmental concerns remain, advancements in refining technology continue to improve efficiency and sustainability [37].

Several factors impact metal recovery efficiency in pyrometallurgy, including feedstock composition, furnace design, and operating conditions. For example:

E-waste recovery rates may be affected by feedstock composition, including the types and concentrations of metals. Materials with higher concentrations of target metals usually yield better results.

Modern furnace designs, such as plasma-arc or electric-arc furnaces, provide better temperature and reaction control, resulting in higher yields.

Operating Conditions: Temperature, pressure, and flux are carefully controlled to optimize metal separation and minimize losses.

Characterizing e-waste protects the environment by identifying and appropriately managing hazardous components. Toxic compounds are properly segregated to prevent their release into the environment, reducing threats to human health and ecosystems [8]. As industries move toward more environmentally conscious practices, the future of metal refining will likely involve eco-friendly methods and innovations to minimize environmental damage.

4. Pyrometallurgy and Other Forms of Metal Recovery Methods

The pyrometallurgical, the classical high-temperature route, excels at processing large quantities with excellent recovery, but usually involves high energy use and emissions. For example, copper smelting often employs pyro routes for its speed and flexibility [38].

Hydrometallurgy offers a lower-energy alternative, especially suitable for low-grade ores and selective metal extraction, though it introduces challenges in chemical waste management [36]. Meanwhile, bioleaching uses microorganisms to dissolve metals under ambient conditions, creating an eco-friendly process with minimal emissions; however, it is slower and less efficient for some metals compared to the other two methods mentioned earlier [38].

In summary, each recovery strategy presents a trade-off between energy intensity, environmental impact, operational cost, and recovery efficiency. Pyrometallurgy is optimal for high-throughput needs but incurs environmental costs; hydrometallurgy balances energy use with chemical handling concerns, whereas bioleaching offers green credentials but requires patience and infrastructure for scalability. Table 2 gives a concise distinction between the three methods of metal recovery mentioned.

Table 2. Overview of the differences between pyrometallurgy, hydrometallurgy, and bioleaching [36,38].

Methods	Advantages	Disadvantages
Pyrometallurgy	<ol style="list-style-type: none"> 1. Mature, large-scale industrial use 2. High recovery rates (>98 %) 3. Able to treat diverse feedstocks 	<ol style="list-style-type: none"> 1. High energy consumption 2. Significant CO₂ and gas emissions 3. Often needs extra steps for purification [38]
Hydrometallurgy	<ol style="list-style-type: none"> 1. Lower energy requirements 2. Good impurity control and selectivity 3. Suitable for low-grade ores [38] 	<ol style="list-style-type: none"> 1. High chemical usage; corrosive 2. Generates contaminated wastewater 3. Slower separations [38]
Bioleaching	<ol style="list-style-type: none"> 1. Environmentally benign 2. Minimal energy input 3. Very low greenhouse gas emissions [36] 	<ol style="list-style-type: none"> 1. Slow process kinetics 2. Lower recovery rates 3. Higher costs for scaling fungal systems

5. Economic and Environmental Implications

Proper e-waste management will generate appreciable revenues for any country and, consequently, provide a cleaner environment. According to Adepitan *et al.* [1], countries such as Iceland, Norway, and Estonia, which have advanced e-waste management technology, have benefited from e-waste management that ranges from metal extraction, reuse, recycling, and reduction, generating annual revenue of over \$48,000 million. The e-waste recycling market is estimated to be worth over \$1.5 billion by 2030 [1]. It is estimated that about 50 million tonnes of e-waste are generated annually [38]. Although about 20% of the produced e-waste is being properly recycled and reused, leaving about 80% unused [39,40]. \$62.5 billion worth of materials are extracted from e-waste alone, which serves as a significant global economic boost [37]. Thus, making metal extraction, recycling, and the reuse of e-waste economically viable. Countries like Germany, the UK, China, Japan, and France have e-waste recycling rates of 52%, 57%, 16%, 22%, and 56%, respectively [1, 37]. These countries derive economic benefits from recycling and metal recovery systems from e-waste, thereby boosting their economies.

However, to develop a proper e-waste recovery system, a better understanding of e-waste composition is an integral factor for an effective and efficient system [39]. Furthermore, a precise understanding of e-waste composition aids in the creation of recycling legislation and standards, promoting a more sustainable approach to resource management. For example, one metric ton of printed circuit boards can contain up to 800 grams of gold, far exceeding the concentration found in primary ores [40]. Evaluation of the economic and environmental impacts of current e-waste disposal and recovery methods is essential [15, 39, 40]. The ultimate goal is to identify ways to optimize e-waste management to maximize economic value while minimizing negative environmental impacts. Table 3 shows three leading companies in metal recovery from e-waste.

Table 3. Companies, locations, and special features in metal recovery from e-waste.

Company	Location	Core Operations	Special Features
Umicore	Belgium (Hoboken)	Advanced e-waste pyrometallurgical recycling	- State-of-the-art smelting technology - Advanced emissions control systems - Integration with downstream refining [41]
Aurubis AG	Germany (Hamburg)	Recycling e-waste and complex waste streams for copper and precious metals	- Innovative slag management - Byproduct repurposing for industrial use [41,42]
DSR Corporation	South Korea	E-waste recycling for rare earth elements and base metals	- Energy-efficient processes - Minimal environmental impact - Supported by government policies and public-private partnerships [43,44]

While the pyrometallurgical method offers economic benefits by reclaiming valuable metals from WEEE or UEEE, it also poses several environmental challenges [45]. Pyrometallurgical processes can release harmful substances into the environment, such as heavy metals like lead, mercury, and cadmium, that could find their way into soil and water bodies, leading to contamination. The high temperatures involved can generate particulate matter, contributing to air pollution and posing health threats to nearby inhabitants [46,47]. Figure 7 provides a descriptive account of the high-temperature demand of the pyrometallurgical process on the ecosystem. High temperature is necessary for the process due to the material's high melting point, which will lead to a high energy demand. Globally, the world depends mostly on fossil fuels as its main source of energy, thereby contributing significantly to climate change [48]. Table 4 presents the emissions challenges and mitigation measures associated with the pyrometallurgical process.

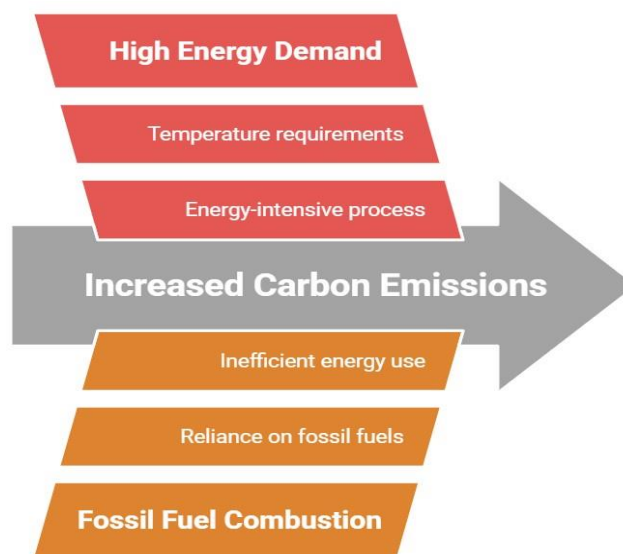


Figure 7. Environmental Implications of fossil fuels in the pyrometallurgical process.

Table 4. Key emissions challenges and mitigation measures. [49,50]

Challenges	Possible Outcomes
Greenhouse Gases	Processes like smelting often rely on fossil fuels, making them significant sources of CO ₂ emissions.
Toxic Metal Vapors	Ethers with low boiling points may volatilize and escape into the atmosphere, posing health and environmental risks.
Particulate Matter	Fine particles generated during operations can contribute to respiratory issues if not effectively captured.
Acidic Gas Emissions (e.g., SO ₂)	The release of gases like sulfur dioxide can cause environmental harm and acid rain.

The recovery of metals through pyrometallurgy has been a tremendous success; however, it somewhat threatens the atmosphere through emissions of gases such as CO₂, SO₂, and NO_x

due to the high temperatures involved. Consequently, volatile substances (metals) such as mercury, cadmium, and lead can be released if not properly controlled. Despite the economic advantages of pyrometallurgy, its environmental and health challenges are of concern to scientists. However, there are two alternatives to mitigate the challenges posed by pyrometallurgical techniques: hydrometallurgy and electrochemical processes [49]. Unlike pyrometallurgy, hydrometallurgy has a lower environmental impact. To further curb the environmental impacts of pyrometallurgy, there is a need to regulate, promote eco-friendly practices, and adopt clean e-waste recovery methods [50-51]. Plants involved in the metal recovery business using the pyrometallurgical process should be subject to stricter environmental safety and sustainability rules. Many countries are adopting rules and regulations for pyrometallurgical industries to control emissions, manage trash, and safeguard worker safety, promoting a more responsible approach to metal recovery [52-55].

6. Industrial Scenarios

There have been some successful stories around the world regarding the process of pyrometallurgy for metal recovery from WEEE. However, a few of the scenarios are highlighted below. Three scenarios of pyrometallurgy for metal recovery are presented, each with its scale, environmental advantages, and innovations, as summarised in Table 5.

6.1. Biochar-assisted pyrometallurgy for copper slag.

A 2024 study at Aalto University and the University of Oulu investigated the pyrometallurgical reduction of copper slag utilizing biochar as a renewable reductant in place of traditional carbon sources. Operating at elevated temperatures, the research demonstrated efficient metal recovery through thermodynamic optimization, achieving substantial copper extraction from non-ferrous slag [60]. This method aligns with sustainability goals, as biochar is derived from biomass and sequesters carbon. The study reported copper extraction efficiencies of 90–95% with a reduced carbon footprint compared to conventional coke, showcasing the promise of green reductants in modern metallurgy.

6.2. Industrial E-waste recovery via ISASMELT/ISA smelting.

In electronic-waste recycling, European smelters like Rönnskär (Kaldo furnace) and Umicore (ISASMELT technology) employ high-temperature pyrometallurgy to reclaim copper, precious metals, and REEs [56-57]. Processing >100,000 tonnes of WEEE annually, these plants recover >95% of precious metals (Au, Ag, Pd) and base metals (Cu, Ni), while off-gases are captured for sulfuric acid production [58-59]. The ISASMELT process is noted for its turbulent bath, efficient zinc fuming (>80%), low flux usage, and enhanced furnace energy efficiency. These large-scale operations showcase how pyrometallurgical reactors can integrate high capacity, high yield, and circular-economy principles on an industrial scale [60].

6.3. Pyrometallurgy in lithium-ion battery recycling.

A 2024 review highlights pyrometallurgical routes for recycling spent lithium-ion batteries (LIBs), including microwave-assisted pyrolysis and roasting. Pyrometallurgy enables the recovery of cobalt, nickel, lithium, and manganese with high efficiency (up to ~99% for Co and Li), but requires high temperatures (500–1000°C) [61]. The use of microwave heating especially enhances process heat efficiency and reduces reaction time. The technique simplifies

the matrix complexity of battery waste, producing metal-rich alloys that can undergo further hydrometallurgical treatment, offering a robust strategy for the circular economy in critical metal recovery [60].

Table 5. Comparative summary of the case study of pyrometallurgy.

Feature	Scenario 1 (Copper Slag)	Scenario 2 (E-Waste Smelters)	Scenario 3 (LIB Recycling)
Scale	Pilot lab-scale	Industrial (>100,000 t/year)	Industry + pilot microwave
Metal Recovery	~90–95% Cu efficiency	>95% Cu, Pd, Au, Ag	~99% Co, Li, Ni recovery
Environmental Advantage	Carbon-neutral reductant	Circular economy, gas capture	Lower toxic leachates vs hydro
Innovation Highlight	Use of biochar	ISASMELT, Kaldo for turbulent slag	Microwave pyrolysis for efficiency

These case studies illustrate the versatility of modern pyrometallurgical processes: from renewable reductants in copper slag to large-scale furnaces for e-waste recovery, and to advanced thermal treatments in lithium-battery recycling. Each uses high temperatures to recover valuable metals efficiently. When designed with sustainability in mind—such as employing biochar, heat recovery systems, and emissions controls—they offer high throughput, resource efficiency, and environmental benefit. These developments underscore pyrometallurgy's evolving role in the transition to a circular, low-carbon metals economy.

7. Conclusions

The pyrometallurgical recovery of metals from UEEE or WEEE is a promising approach for managing the growing global problem of e-waste disposal while recovering valuable materials. The rapid advancement of technology, driven by the global population's quest for comfort, has greatly influenced the volume of e-waste and the improper disposal and recycling techniques. However, due to the complexity and heterogeneity of metal recovery, pyrometallurgy has proven effective for metals such as gold, silver, copper, and palladium. Unlike hydrometallurgy, such as leaching, the smelting process tends to be faster for metal recovery [60]. The metal extraction process in smelting is due to the endothermic reactions involved in the extraction of ores. However, the hydrometallurgical process is often applied to low-grade metal. Moreover, pyrometallurgy is best applied to metal ores with a high metal concentration due to the high temperatures involved. Despite all the mentioned advantages of pyrometallurgical methods for the extraction of valuable metals from UEEE or WEEE. The negative impact on the environment, particularly the emission of greenhouse gases into the atmosphere, and the resulting unhealthy effects on humans. Additionally, the amount of energy involved in the process is enormous, consequently costing more for operation and contributing to the carbon footprint. All these disadvantages can be mitigated through advancements in technology and proper furnace design, as well as alternative sources of fuel to reduce GHG emissions and renewable energy, which can help cushion these negative impacts on the atmosphere and the cost of operation. Furthermore, the variability of e-waste composition is another challenge due to its heterogeneous nature. This variability tends to complicate the recovery of valuable metals from WEEE, thereby increasing processing costs and generating secondary waste streams that require careful management to avoid further environmental harm. As a result, integrating pyrometallurgical recovery with other complementary methods, such as hydrometallurgy or mechanical separation, could improve the overall efficiency and effectiveness of the recycling process.

In conclusion, the pyrometallurgical recovery of valuable metals from e-waste is a futuristic solution to the potential threat of e-waste pollution and offers substantial promise as a critical approach to both e-waste management and the recovery of valuable resources. While there are challenges related to environmental impact and process optimization, the ongoing development of more efficient and sustainable technologies continues to improve the viability of pyrometallurgical techniques in the recycling of electronic waste. The combination of innovation, policy regulations, and improved waste management strategies will play a key role in optimizing the use of pyrometallurgy for e-waste recovery, contributing to a more circular economy and reducing the environmental footprint of electronic waste disposal.

Author Contributions

Conceptualization, O.A. and O.A.T.; investigation, O.A. and B.E.-A.; data curation, O.A. and B.E.-A.; writing—original draft preparation, O.A. and S.S.; writing—review and editing, O.A. and O.A.T.; project administration, O.A.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
EEE	Electrical and Electronic Equipment
GHG	Greenhouse Gas
ITU	International Telecommunication Union
PCB	Printed Circuit Board
REE	Rare Earth Elements
UEEE	Used Electrical and Electronic Equipment
WEEE	Waste Electrical and Electronic Equipment

Abbreviation	Definition
LiB	Lithium-ion Battery

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