Advances in E-Waste Recycling: Physical and Chemical Treatment Methods

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Abstract. The unprecedented rise in production and consumption of electronic devices has resulted in staggering amounts of electronic waste (e-waste). Improper recycling and disposal of e-waste can cause severe environmental and public health repercussions due to the presence of toxic substances like lead, mercury, and flame retardants. This article introduced advanced e-waste recycling technologies, focusing on physical and chemical treatment methods. Physical treatments such as gravity separation, electrostatic separation, and inverse flotation enable efficient and cost-effective recovery of precious metals like gold, silver, platinum, and rare earth metals from e-waste components. These physical processes are often environmentally friendly, scalable, and can handle diverse e-waste streams. Chemical treatments, including the dimethylformamide technique, supercritical fluid technique, and pyrolysis, allow for separating hazardous substances and recovering valuable materials not amenable to physical processes. Supercritical CO_2 fluid destroys toxic organic compounds while enabling metal recovery. Pyrolysis converts plastics into liquid oil and gas products. By enhancing the separation and purification of valued materials, these physical and chemical e-waste recycling techniques provide more profitable, efficient, and sustainable solutions to ever-growing e-waste volumes.

Keywords: E-waste recycling, physical treatment methods, chemical treatment methods, environmental impact mitigation.

1. Introduction

E-waste is a growing problem, encompassing a wide range of electronic products, from household appliances to computers [1]. In 2019, 53.6 million metric tons of e-waste were generated globally, with the average person producing 7.6 tons annually [2]. Predictions indicate that by 2030 the world will produce 74 Mt of e-waste [2]. EEE contains harmful substances, such as lead, which can harm human health, especially in children [3]. Research has shown that children in areas with e-waste recycling have worse lung conditions [4]. E-waste also causes environmental damage, contaminating soil and water when disposed of in landfills and emitting toxic pollutants when burned [5]. While there is potential for recycling [6], only about 17.4% of e-waste is currently recycled due to complexity and low public willingness [2]. Most of the e-waste still needs to be recycled [3]. Therefore, to minimize the pollution of e-waste to humans and the environment and increase the economic value of e-waste recycling as much as possible, mature, and economic e-waste recycling technology was invented.

Informal e-waste recycling emerged in the 1970s and 1980s, with scrap dealers extracting metals from discarded electronics without standards. In the 1990s, countries like Switzerland and Sweden pioneered formal e-waste recycling systems and regulations to handle growing volumes [7]. The early 2000s saw a significant increase in e-waste volumes globally, leading developed countries to establish nationwide recycling while developing countries became hubs for crude recycling [7]. The 2006-07 Basel Convention expansion brought e-waste under its hazardous waste framework to prevent illegal dumping [7]. Since then, recycling has become more advanced and regulated, with extended producer responsibility being a key policy [8]. While developed countries now utilize high-tech recycling, developing countries focus on growing formal sectors and phasing out informal processing [7]. Despite progress, managing increasing global e-waste sustainably through better collection, technological innovation, and universal regulations remains an ongoing challenge [7]. The techniques can be roughly separated into three different types of treatments based on their treatment methods [8].

Physical treatments separate e-waste using physical methods. These techniques are the cheapest and most used techniques in the world [8]. Thus, most e-waste is recycled using physical treatments due to their cheap price [8]. Chemical treatments, on the other hand, use chemicals to separate and recycle e-waste [9]. Chemical treatments can recycle harmful substances that physical treatments cannot, thus chemical treatments are used to recycle harmful substances [9]. Bioleaching treatments are treatments that recycle and extract metals like Cu, Ni, Au, and Ag from e-waste using bacteria-as-sited reactions [8]. They are more green and clean treatments and cost less than chemical treatments [8].

This article will introduce e-waste two types of recycling treatments which are physical and chemical approaches to provide insights into current advances in e-waste recycling.

2. Physical Treatments

Physical recycling is the simplest of all recycling methods and has the lowest cost of equipment and energy requirements [8]. At the same time, physical methods also have great potential because the mechanics of physical methods can improve over time. The most used e-waste recycling method in developed countries such as the European Union and the United States is physical recycling [8]. Here are three of the most used and by far the most mature methods of physical treatments, including supergravity separation, electrostatic separation, and inverse flotation.

2.1. Supergravity Separation

Supergravity separation is an innovative method utilizing enhanced centrifugal force to separate and recover metals from waste materials efficiently. The high-intensity gravity field enables separation based on melting point differences. The technology has been successfully applied to recover rare earth metals, precious metals, aluminum alloys, and other metals from different industrial wastes [10]. This technique generates a strong centrifugal force called supergravity by rotating samples at high speeds. The supergravity field can be hundreds to thousands more potent than normal Earth gravity. When waste material containing different metals is subjected to supergravity, the metals can be selectively melted and separated based on their different melting points. The molten metal phase gets pushed to the periphery under intense centrifugal acceleration while the solid unmelted particles remain behind [10]. The separation gets better as the supergravity level is increased by rotating faster. The separated molten metal can then be collected after solidification. Supergravity separation provides rapid and efficient segregation of phases. The intense mixing and heat transfer under supergravity also results in fast homogenization and diffusion, improving separation efficiency. The process can operate continuously at high temperatures [10].

Meng et al. found that the gravity coefficient dramatically influenced separation, with Pb and Sn recovery increasing significantly from 1-1000x gravity, maxing at 50.48% and 36.85%, respectively, at 1000x. Temperature also strongly affected recovery, with optimal results obtained at 410 °C giving 54.41% Pb and 41.94% Sn recovery and a high purity Pb-Sn alloy of 94.84% [10]. Though Sn content was higher in initial PCBs, its lower recovery indicates the formation of Sn solid solutions during heating. Overall, the supergravity separation experiment successfully demonstrated efficient recovery of valuable Pb and Sn from electronic waste, with optimization of crucial parameters being critical to maximizing separation performance [10].

2.2. Electrostatic Separation

Electrostatic separation is an e-waste recycling technique that uses the theory of difference in electrical conductivity between the metal and non-metal particles in crushed WPCBs to selectively separate them. Electrostatic separation is particularly suitable for WPCB recycling because it recovers metals at high purity while preserving the bromine-containing non-metals intact for further recycling. It avoids the use of corrosive chemicals, heat, or abrasion which could damage the non-metals. The equipment has moderate capital and operating costs. Overall, this dry separation technique enables sustainable and comprehensive recycling of the distinct WPCB components [10].

The process starts with the size reduction of WPCBs into fine particles, typically less than 2 mm in size. This improves separation efficiency. The particles are then fed onto a grounded vibrating conveyor belt. Above the belt is a corona electrode which charges the particles by ion bombardment. As the particles fall off the conveyor, they pass through alternating electromagnetic fields created by rapidly rotating rolls. The non-conductive non-metal particles (like plastics and ceramics) retain the positive charge induced by the corona [10]. They are pinned to the rolls by electrostatic attraction and are carried sideways to be collected separately. The conductive metal particles like copper and iron quickly dissipate charge to the grounded rolls. They are unaffected by the electric fields and continue falling vertically down due to gravity into a different collection bin. Separation efficiency is governed by factors like particle size distribution, feed rate, electric field strength and roller rotation speed. Multiple separation stages are sometimes used to improve purity. The process can achieve over 90% separation of metals like Cu and Al at high throughput rates of 0.5-1 ton/hour [10].

2.3. Inverse Flotation

Inverse flotation is a froth flotation technique that can be applied to separate and recycle metals and plastics from electronic waste (e-waste). Inverse flotation allows relatively simple, cost-effective separation of plastics and metals from electronic waste. It takes advantage of the natural hydrophobicity difference between these components. In e-waste, metals, and plastics must be liberated through size-reduction processes like shredding and grinding. This produces a mixture of fine metallic and non-metallic particles. Inverse flotation selectively separates these particles by preferentially floating the non-metallic fraction [12]. For e-waste, inverse flotation is preferentially compared to direct flotation of metals or plastics because it isolates the minority metal fraction, avoiding yield losses. Metals generally comprise less than 30% of the weight of e-waste, while plastics make up over 30%. By floating plastics, metal recoveries are maximized [12].

Plastics inside e-waste tend to be naturally hydrophobic, while metals are hydrophilic. When air bubbles are introduced, the hydrophobic plastic particles adhere to the bubbles and float, while the hydrophilic metals stay in suspension. This allows the two fractions to be separated efficiently without using chemical additives. Direct flotation of metals would be inefficient due to their low natural hydrophobicity [12]. After separation, the plastic fraction can be collected and recycled. The concentrated metallic fraction is also much easier to process through subsequent hydrometallurgical or pyrometallurgical steps to recover specific metals like copper, gold, silver, palladium, etc. Inverse flotation is a relatively inexpensive physical separation method that avoids the costs and waste generation of aggressive chemical or thermal processing of bulk e-waste [12].

In inverse e-waste flotation, optimizing particle size and operating parameters is critical to efficiency. Fine grinding below 0.5 mm ensures adequate liberation of metallic particles from plastics. Using the proper agitation and air flow rates promotes bubble-particle contact and selective attachment of plastics [12]. Under optimized conditions, inverse e-waste flotation can typically achieve plastic purities over 90% in the concentrate, while metals are enriched to 50-60% or more in the tails. However, efficiency depends heavily on feed composition. Streams with very high plastic contents (>60%) will yield better results and material balances. The presence of other hydrophilic components like glass and ceramics may limit metal concentrate purity [12].

3. Chemical Treatments

Although physical treatments have advantages like cheap and low equipment requirements, physical treatment techniques cannot effectively separate hazardous substances such as halogens and heavy metals from e-waste [13]. Thus, chemical treatments that can effectively separate hazardous substances are needed. Here below are three of the most used chemical treatments including dimethylformamide technique, supercritical fluid technique, and pyrolysis.

3.1. Dimethylformamide

Dimethylformamide is a newly introduced method for recycling waste printed circuit boards (WPCBs). The key innovation in this technique is using the organic solvent dimethylformamide (DMF) to selectively dissolve the brominated epoxy resin (BER) that bonds layers of metals and glass fiber in WPCBs [14]. This novel process minimizes harmful emissions while efficiently separating the metals, glass fiber, and BER. The recovered components can then undergo conventional recycling methods. Additionally, the optimization data provides critical insights into the dissolution kinetics that could help simulate and scale up this sustainable e-waste recycling technique. The process takes advantage of DMF's ability to form hydrogen bonds with BER above its glass transition temperature of 130°C [14]. Heating WPCBs in DMF to an optimized temperature of 135°C provides the energy to increase vibrations and breakage of BER bonds, enhancing its interaction with DMF. A high WPCB with DMF ratio of 300g/L ensures maximum contact between the WPCBs and solvent for efficient dissolution. Reducing the WPCB size to 1cm x 1cm increases the cross-sectional surface area exposed to DMF, further improving BER dissolution. Under these optimized conditions, the BER completely dissolves and delaminates the copper, glass fiber, and other layers in 1cm2 WPCBs within 150 minutes. The used DMF is easily regenerated by evaporation, and the dissolved BER is recovered as a residue, allowing their reuse [14].

Verma et al. experimented. While exact efficiency metrics were not provided, the collective optimization and validation results indicate that this DMF process significantly improves the extraction, separation, and recovery of valuable materials from WPCBs compared to conventional methods. Using the dissolution kinetics data could further optimize conditions and maximize yields. Overall, this study presents strong evidence that using DMF to dissolve BER enables more efficient, sustainable e-waste recycling [14]. The results provide strong evidence that using DMF to dissolve brominated epoxy resin (BER) selectively enables more efficient separation and recovery of metals, glass fiber, and BER from WPCBs compared to existing methods. Under the optimized conditions of 135 °C temperature, 300 g/L WPCB: DMF ratio, and 1 cm x 1 cm WPCB size, the problematic BER was dissolved entirely, allowing the copper, glass fiber, and other layers of 1 cm2 WPCBs to be fully delaminated and separated within 150 minutes. This rapid and thorough delamination suggests high efficiency in separating the components. Additionally, the used DMF solvent was shown to be regenerated with zero loss of BER dissolution performance through at least five reuse cycles [14]. This implies highly efficient recycling of the solvent, minimizing waste. Furthermore, SEM, EDS, and FTIR analysis demonstrated that the dissolved BER was recovered as a residue in high yields with composition closely matching untreated BER from WPCBs [14].

3.2. Supercritical Fluid

Supercritical fluid (SCF) treatment is an emerging technology that can recycle hazardous e-waste like waste PCBs in an environmentally friendly manner. The critical advantage of SCF treatment is that it provides fast, complete, and green decomposition of hazardous organics like brominated flame retardants while also liberating metals for recovery [15]. It involves treating the e-waste with solvents like water, CO_2, or alcohol under conditions above their critical point. At supercritical conditions, the fluids have unique properties that allow them to dissolve and react entirely with organics in the waste. For treating PCBs, SCF oxidation using supercritical water is often used. The PCB is first heated and pressurized above water's critical point of 374°C and 22 MPa. Under these conditions, water behaves like an organic solvent, and the organic contaminants and polymers in the PCB can dissolve and react homogeneously. Oxygen is added to oxidize the organics, breaking them down into simpler and less toxic compounds like CO_2, water, and inorganic acids. The metals and other inorganic components remain solids and can be easily separated. SCF extraction using CO_2 is also applied, where supercritical CO_2 acts as a solvent to extract organics from the PCB [15] selectively.

Li et al. demonstrated that SCF can achieve excellent destruction of hazardous organic contaminants in PCBs while also freeing up metal components for recycling. The supercritical water provided a fast, homogeneous reaction environment to completely oxidize organics [15]. Future work

is still needed to design reactors for continuous industrial-scale operation. However, the batch results validate that supercritical fluids can enable effective e-waste recycling [15]. The results showed that over 90% of the original organics in the PCB, including flame retardants and polymers, had been oxidized into carbon dioxide, water, and acetic acid. The total organic carbon content had reduced from an initial 4.5% in the PCB to just 0.3% after SCWO treatment. The metals initially present in the PCB, including copper, silver, and gold, remained in the reactor as solids. They were found to be very effectively liberated from the PCB's epoxy resin and fiberglass matrix. Overall metal recovery rates exceeded 95% [15].

3.3. Pyrolysis

Pyrolysis is a thermochemical decomposition process that breaks down organic materials by heating them to high temperatures, typically between 300-1200°C without oxygen. It offers various waste management, energy production, and chemical processing benefits through the selective thermal decomposition of organic matter without oxygen [16]. The lack of oxygen prevents combustion, allowing the long molecular chains that make up plastics, biomass, and other organic matter to break apart into simpler fragments and compounds. As heat is applied, the material undergoes a series of complex chemical and physical changes - polymer chains unzip, molecules crack into smaller hydrocarbons, gases are released, and the material gets thermally decomposed into various solid, liquid, and gaseous products [16]. The relative amounts of the pyrolysis products can be varied by carefully controlling parameters like temperature, heating rate, pressure, and residence time. The liquid fraction known as pyrolysis oil contains complex hydrocarbons and oxygenated hydrocarbons that can be refined into fuels and chemical feedstocks [16]. Gasses like methane, hydrogen, and carbon monoxide have calorific values and can be collected as syngas or fuel gas. The solid char residue is mostly carbon and ash, which can be used as an adsorbent, fertilizer, or fuel. The pyrolysis technique can transform waste materials like plastics and biomass that have low-energy-density into higher-energy-density fuels. It also allows the recovery of valuable chemicals from waste streams [16]. Pyrolysis provides more excellent selectivity and control than other thermal processes like gasification or incineration. Currently, pyrolysis is being extensively researched to recycle electronic waste and recover metals from them while reducing harmful emissions like dioxins and furans compared to primitive disposal methods like incineration [16].

4. Summary

In conclusion, this paper summarized advanced physical and chemical treatment methods for e-waste recycling. Physical techniques like supergravity separation, electrostatic separation, and inverse flotation enable efficient and cost-effective recovery of precious and rare earth metals from e-waste components in an eco-friendly manner. Chemical methods, including dimethylformamide, supercritical fluid, and pyrolysis, allow the destruction of hazardous organic substances in e-waste and the liberation of embedded metals.

These cutting-edge e-waste recycling technologies significantly enhance the separation, purification, and recovery of valuable materials compared to conventional recycling. This improves the economic viability and sustainability of e-waste recycling while reducing environmental and health impacts. The article highlights the immense promise of emerging physical and chemical treatments to handle continuously growing e-waste volumes through more profitable and ecologically sound recycling. Further work is still needed to scale up and implement these technologies at an industrial level. Techno-economic assessments considering factors like capital and operating costs would aid in selecting and integrating suitable techniques into e-waste recycling facilities. Research into continuous reactor and process design could enable large-scale applications. Nevertheless, the rapid progress in advanced e-waste recycling approaches underscores their potential to transform current crude recycling practices into a multi-billion-dollar industry that minimizes waste while unlocking the hidden treasure trove of resources inside disposed electronics.

References

[1] Basel Action Network, https://www.ban.org/e-waste, last accessed 2023/8/25.

[2] Forti Vanessa, Baldé Cornelis, Kuehr Ruediger, et al. The Global E-waste Monitor 2020.

[3] Perkins Devin, Drisse Marie-Noel, Nxele Tapiwa, et al. E-Waste: A Global Hazard. Annals of Global Health 2014, 80: 286 - 295.

[4] Grant Kristen, Goldizen Fiona, Sly Peter, et al. Health consequences of exposure to e-waste: a systematic review. Lancet Glob Health, 2013, 1: e350 – 61.

[5] Gaidajis G., Angelakoglou K., Aktsoglou D. E-waste: Environmental Problems and Current Management. Journal of Engineering Science and Technology Review, 2010, 3 (1) 193 - 199.

[6] M. Shahabuddin, Uddin M., Chowdhury J., et al. A review of the recent development, challenges, and opportunities of electronic waste (e-waste). International Journal of Environmental Science and Technology, 2023, 20: 4513 - 4520.

[7] Singh Gaurav, Yadav P.K.S. Hazardous waste characteristics and standard management approaches. Hazardous Waste Management An Overview of Advanced and Cost-Effective Solutions, 2022, 145 - 164.

[8] Abdelbasir1 Sabah, El-Sheltawy Chakinaz, Abdo Dina. Green Processes for Electronic Waste Recycling: A Review. Journal of Sustainable Metallurgy, 2018, 4: 295 – 311.

[9] Salhofer Stefan. E-Waste Collection and Treatment Options: A Comparison of Approaches in Europe, China and Vietnam. Source Separation and Recycling. The Handbook of Environmental Chemistry, 2017, 63: 227.

[10] Meng Long, Gao Jintao, Zhong Yiwei, et al. Supergravity separation for recovering Pb and Sn from electronic waste. Separation and Purification Technology, 2018, 191; 375 - 383.

[11] Ning, C., Lin, C. S. K., Hui, D. C. W., et al. Waste Printed Circuit Board (PCB) Recycling Techniques. Top Curr Chem, 2017, 375: 43.

[12] Wang Zhe, Li Hong, Chen Haiyan, et al. Recovery of residual metals from − 0.5 mm non-metallic fractions in WPCBs using electrostatic separation enhanced by air classification. Journal of Material Cycles and Waste Management, 2022, 24: 980 - 991.

[13] Flores-Campos R., Estrada-Ruiz R.H., Velarde-Sánchez E.J., et al. Study of the physicochemical effects on the separation of the non- metallic fraction from printed circuit boards by inverse flotation. Waste Management, 2017, 69: 400 - 406.

[14] Verma Himanshu, Singh Kamalesh, Mankhand Tilak. Dissolution and separation of brominated epoxy resin of waste printed circuit boards by using di-methyl formamide. Journal of Cleaner Production, 2016, 139: 586 - 596.

[15] Li Kuo, Xu Zhenming. A Review of Current Progress of Supercritical Fluid Technologies for E-waste Treatment. Journal of Cleaner Production, 2019, 227: 794 - 809.

[16] Andooz Amirhossein, Eqbalpour Mohammad, Kowsari Elaheh, et al. A comprehensive review on pyrolysis of E-waste and its sustainability. Journal of Cleaner Production, 2022, 333: 130191.