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A Review of E-Waste Treatment Technologies from the Perspective of Heavy Metal Release: Efficiency, Mechanisms, and Environmental Risks from Informal Acid Leaching to Formal Smelting

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ABSTRACT

The global proliferation of electronic waste (e-waste) has raised critical environmental and public health concerns, primarily stemming from the liberation of toxic heavy metals during recycling operations. This comprehensive review provides a systematic comparative analysis of two dominant e-waste treatment pathways—informal acid leaching and formal smelting—evaluating their metal release efficiencies, underlying mechanisms, and associated ecological consequences. Informal acid leaching, widely practiced in developing regions through the application of concentrated acids, facilitates metal extraction but leads to extensive soil and aqueous contamination, owing to unregulated effluent discharge and absent mitigation measures. Formal pyrometallurgical smelting, conversely, employs regulated thermal treatment in enclosed environments, augmented by sophisticated gas cleaning and residue management systems, achieving high metal recovery rates while substantially curtailing environmental emissions. Nevertheless, widespread implementation of formal techniques is impeded by operational heterogeneities, divergent pollution monitoring methodologies, and contextual socioeconomic constraints. The study underscores the necessity of developing harmonized assessment protocols, blended policy instruments, and flexibly scalable technological interventions to alleviate heavy metal pollution and advance sustainable e-waste management strategies worldwide.

KEYWORDS

E-waste recycling; Heavy metal mobilization; Hydrometallurgical extraction; Pyrometallurgy; Environmental contamination; Informal sector recycling

1 Introduction

The global accumulation of electronic waste has become one of the most pressing environmental challenges of our time. Recent estimates reveal that worldwide e-waste generation reached 53.6 million metric tons in 2019 - equivalent to the mass of 350 cruise ships - with only 17.4% being properly recycled through formal channels [1]. This staggering disparity represents not just a failure of resource recovery, but more importantly a significant environmental hazard due to the presence of toxic heavy metals including lead (Pb), cadmium (Cd), and mercury (Hg) in discarded electronics. Current projections indicate this volume may escalate to 74.7 million metric tons by 2030, exacerbating existing environmental and health concerns. The situation is particularly acute in developing nations where formal recycling infrastructure is often lacking or inadequate, leading to the proliferation of informal recycling operations that frequently employ environmentally damaging methods.

In developing economies, informal recycling dominates the sector, handling an estimated 60-90% of total processing activities. Nigeria's situation provides a telling example, where annual imports of used electrical equipment range between 60,000-71,000 tons, with approximately 19% being non-functional and consequently entering informal recycling streams [2]. Major processing sites like Agbogbloshie in Ghana employ around 5,000 workers who daily perform hazardous manual dismantling, open burning, and acid-based extraction without adequate safety measures or environmental controls. These practices have created severe local environmental degradation while providing crucial livelihoods in communities with limited economic alternatives. The health impacts on workers and nearby residents have been well-documented, yet the economic realities continue to drive participation in these dangerous activities.

The environmental contamination pathways created by informal e-waste recycling are complex and multifaceted. Heavy metals enter ecosystems through soil infiltration, groundwater penetration, and atmospheric dispersion, with each processing method creating distinct contamination profiles. Acid leaching operations, which use strong acids to extract precious metals from circuit boards and components, facilitate toxic substance migration into hydrological systems through runoff and improper waste disposal. Conversely, open burning - a common pyrometallurgical approach - releases particulate matter containing Pb, Cd, and arsenic (As) into the atmosphere [3]. These metals then deposit onto soils and water bodies, entering agricultural systems and food chains. Of particular concern is the differential accumulation of these metals in food crops, with leafy vegetables demonstrating particularly high metal uptake capacity, thereby posing direct risks to consumers through dietary exposure.

The ecological magnification effect significantly compounds these environmental hazards. Cadmium and lead undergo progressive concentration through trophic levels, with studies demonstrating increasing metal concentrations at each successive level of the food chain [4]. This biomagnification ultimately leads to dangerous concentrations in human food supplies, particularly in communities that rely on locally grown produce near recycling sites. The resulting health impacts are already evident in exposed populations. Research conducted at Agbogbloshie revealed that 12.3% of direct e-waste handlers exhibited blood lead levels (BLLs) exceeding 5 μg/dL, while paradoxically, peripheral workers such as food vendors registered slightly higher mean BLLs (3.54 μg/dL) than direct handlers (3.49 μg/dL) [5]. This phenomenon confirms the widespread nature of environmental contamination from recycling activities and underscores the urgent need for comprehensive evaluation of exposure risks and mitigation strategies.

Current methodologies for evaluating heavy metal release and recovery efficiency in e-waste processing face significant challenges due to fundamental differences in analytical approaches between dominant technologies. A persistent inconsistency exists in sampling protocols and analytical frameworks: hydrometallurgical studies typically focus on measuring metal concentrations in aqueous leachates and soil extracts, while pyrometallurgical investigations primarily examine atmospheric emissions and ash residues [6]. This methodological divergence produces fundamentally incompatible datasets that obstruct meaningful cross-method efficiency comparisons and comprehensive environmental impact assessments. Without standardized metrics and protocols, policymakers and researchers cannot accurately compare the relative risks and efficiencies of different processing methods.

Operational variability further complicates the measurement and comparison of metal release rates. In hydrometallurgical processes, studies have documented discrepancies of up to 40% in metal dissolution rates depending on operational parameters such as leachant composition (e.g., H_2SO_4 versus HCl), concentration gradients, and residence durations [7]. Pyrometallurgical data shows even greater variability due to combustion temperature differences and feedstock heterogeneity, with uncontrolled open burning demonstrating 2-3 times higher emissions of volatile metals (particularly Hg and Cd) relative to regulated smelting operations. This disparity is partially mediated by the thermal decomposition of brominated flame retardants commonly found in e-waste plastics [8]. Such wide variations in reported values make it difficult to establish reliable benchmarks for process efficiency or environmental impact.

The significant gap between controlled laboratory studies and real-world informal recycling operations remains a major unresolved challenge in the field. Conventional experimental approaches systematically underestimate metal release rates by excluding common informal sector practices such as partial recovery, plastic co-processing, and the use of non-standard reagents. Conversely, field investigations often face limitations in attributing observed contamination to specific processes within mixed-operation sites where multiple techniques are employed simultaneously [9]. This disconnect between laboratory data and field observations hinders the development of accurate risk assessment models and effective regulatory frameworks tailored to informal recycling contexts.

An additional layer of complexity arises from fundamental differences in toxicity assessment paradigms across studies. Research efforts have alternatively emphasized acute exposure metrics (e. g., airborne pollutant concentrations near burning sites) or chronic effect indicators (e. g., long-term biotic accumulation factors in local ecosystems), generating conflicting risk profiles that complicate comparative impact evaluations between thermal and chemical recovery pathways [10]. The lack of consensus on appropriate assessment methodologies has resulted in a fragmented knowledge base that impedes the development of comprehensive, science-based e-waste management policies. Establishing unified protocols for environmental and health impact assessment therefore represents a critical priority for advancing sustainable e-waste management solutions.

2 Informal and formal e-waste treatment pathways

2.1 Heavy metal release from informal acid leaching: mechanisms and environmental consequences"

The widespread adoption of unregulated acid leaching techniques in informal e-waste recycling operations has emerged as a significant environmental and public health concern. Current research documents the extensive use of highly concentrated mineral acids, particularly nitric acid and cyanide compounds, in these uncontrolled processing environments. Analytical data from Ghana reveals alarming contamination levels, with surface dust samples containing lead concentrations 19.2 times higher than China's Soil Standard Grade II limits, while copper and cadmium levels exceeded regulatory thresholds by factors of 326 and 203 respectively [11].

The underlying contamination mechanisms involve complex physicochemical processes. Acidic solutions effectively solubilize metallic constituents from electronic components, while the subsequent infiltration of untreated effluent induces significant alterations in soil geochemistry. This pH modification substantially enhances the mobility of heavy metal contaminants, facilitating their migration through both vertical percolation into groundwater systems and horizontal dispersion via surface runoff pathways. Environmental monitoring at Agbogbloshie, Ghana has identified extreme soil contamination, with lead concentrations reaching 1100 μg/g, copper levels up to 1500 μg/g, and zinc measurements as high as 5200 μg/g - all substantially exceeding established safety guidelines [12].

Controlled laboratory investigations of soil remediation techniques demonstrate promising results. Sequential extraction protocols employing organic acids (oxalate or citrate) followed by EDDS chelation have achieved 30-50% reductions in metal leachability, with copper recovery rates of 60-80% under optimized conditions [13]. However, field observations from informal operations reveal markedly different outcomes. Processing sites in India's Moradabad region typically exhibit metal recovery efficiencies below 50%, primarily due to inconsistent acid concentrations and the complete absence of purification steps in the recycling workflow [14].

The environmental consequences of these practices extend well beyond immediate processing zones. The conceptual framework of spatial boundaries becomes particularly relevant, as contaminants routinely transcend physical containment areas. In Agbogbloshie, measurable soil pollution has been detected in residential and agricultural zones up to 10 kilometers from primary processing sites, demonstrating the extensive reach of contamination from informal operations [15].

Several critical knowledge gaps require urgent attention:

(1) Development of economically viable leachate treatment systems suitable for developing regions

(2) Comprehensive longitudinal studies on heavy metal bioaccumulation dynamics

(3) Implementation of scalable solutions to address India's substantial e-waste processing deficit, where annual generation (22×10^5 tons) far exceeds formal sector capacity (11.1×10^5 tons) [16].

This situation demands immediate interdisciplinary solutions that address both technical processing challenges and broader socioeconomic factors driving informal recycling practices.

2.2 Heavy metal release and mitigation in formal pyrometallurgical processing

Formal smelting is defined as a regulated pyrometallurgical process for treating waste electrical and electronic equipment (WEEE), fundamentally differing from informal acid leaching through its implementation of high-temperature operations in enclosed reactors coupled with advanced gas cleaning systems to mitigate pollution [17]. The standardized industrial workflow begins with pretreatment—a crucial phase involving dismantling, shredding, and mechanical separation via magnetic and eddy current techniques—to concentrate metallic fractions and remove impediments like plastics and ceramics which could otherwise hinder furnace operation or generate problematic emissions. This prepared feedstock is then smelted in specialized furnaces such as IsaSmelt or Kaldo units operating between 1150°C and 1500°C, where organic combustion provides a portion of the process energy, metals coalesce into a molten bullion phase, and oxides combine with added fluxes to form a separate, stable slag phase designed to encapsulate impurities [18]. A subsequent and essential refining stage, predominantly through electrolytic processes, purifies the base metal and recovers precious metals from the resultant anode slimes. The key advantage of this integrated, multi-stage approach is its demonstrated capability for large-scale, efficient resource recovery, as evidenced by operations processing substantial tonnages of material annually and successfully recovering a wide spectrum of elements from complex waste streams, thereby transforming a potential environmental liability into a valuable source of secondary raw materials [19].

The release and distribution of heavy metals during formal smelting operations are governed by an intricate interplay of thermodynamic equilibria, kinetic constraints, and physical partitioning behaviour. The migration pathways of specific elements are primarily determined by their relative volatility. Metals exhibiting high vapour pressure and comparatively low boiling points, such as mercury (Hg) and cadmium (Cd), are preferentially volatilised under process conditions and consequently become enriched in the particulate matter captured by subsequent gas cleaning apparatus [20]. This predominantly physical mechanism operates in concert with chemical transformation processes, where high-temperature reduction-oxidation (redox) reactions, heavily influenced by the prevailing oxygen potential, critically dictate elemental speciation and subsequent allocation between co-existing phases.

The partitioning behaviour of lead (Pb) throughout the smelting process serves to illustrate these complex interactions. Although its inherent volatility accounts for a considerable degree of metal transfer into the flue dust stream, a significant proportion also reports to the slag phase. Within this silicate-based matrix, the chemical stability and incorporation of lead are principally governed by the structural formation of the slag network and the influence of network modifiers such as iron oxide [21]. Furthermore, the in-situ generation of volatile metal species constitutes another major release route. This is particularly evident in chlorination reactions, wherein chlorine originating from halogenated plastics facilitates the formation of volatile chlorides, thereby promoting the transfer of certain metals into the gaseous phase. Collectively, these mechanisms underscore how formal smelting systems are designed to strategically exploit differences in volatility and chemical affinity to affect a separation between economically valuable metals and hazardous constituents.

Ultimately, the final distribution of metallic elements is a product of the competition between these concurrent physical and chemical pathways. Key operational parameters—including temperature profile, oxygen partial pressure, and the overall furnace atmosphere—are meticulously controlled to steer metal partitioning behaviour. This precise management enables the effective recovery of valuable metals via scientifically optimised release mechanisms, which are central to minimising the environmental footprint of the process while simultaneously maximising resource efficiency [22].

2.3 Pollution control

Modern formal smelting facilities employ sophisticated end-of-pipe treatment technologies specifically engineered to address the heavy metal contamination of terrestrial ecosystems and soils, a serious environmental issue thoroughly documented in regions affected by informal e-waste processing activities [23] and conventional industrial operations[24]. These integrated abatement systems are designed to simultaneously target particulate emissions, acidic gases, and volatile metal compounds through a coordinated series of physical and chemical processes that effectively prevent the discharge of hazardous substances into the environment.

The emission control methodology utilizes a multi-stage purification approach to achieve exceptional removal efficiencies. Initial fabric filter systems (baghouses) physically capture more than 99% of particulate matter, including metal-containing dusts, through surface filtration mechanisms. Subsequent wet scrubbing units then chemically remove acid gases and sub-micron aerosols via absorption and neutralization reactions employing alkaline reagents. For particularly volatile heavy metal species (e. g., cadmium and lead vapors), the injection of powdered activated carbon ahead of fabric filtration provides substantial adsorption capacity, effectively trapping these contaminants and markedly reducing atmospheric emissions that would otherwise contribute to terrestrial pollution through deposition pathways [25]. These technologies are systematically combined into advanced treatment sequences that are continually optimized through automated process control systems. However, this technical sophistication entails significant economic considerations, including substantial capital investment and ongoing operational expenditures related to energy consumption, reagent utilization, and the management of hazardous collected residues. The comprehensive pollution control infrastructure is fundamentally designed and rigorously operated to meet strict emission limit values mandated by regulatory authorities, thereby ensuring that contemporary formal smelting practices avoid creating the severe soil contamination patterns historically associated with unregulated e-waste recycling and conventional metallurgical operations.

2.4 Research gaps

Despite significant advancements in formal pyrometallurgical processing for e-waste treatment—which have demonstrated considerable efficacy in heavy metal emission control through regulated high-temperature operations and integrated pollution abatement systems—several critical knowledge gaps persist in the optimization of its long-term environmental performance [26]. As established in previous sections, the technology's capacity to efficiently recover valuable metals while mitigating environmental hazards fundamentally depends on the precise control of thermodynamic equilibria and key operational parameters; however, substantial scientific and technical uncertainties remain inadequately addressed.

A particularly critical research gap concerns the behavior and fate of halogenated compounds (e.g., brominated flame retardants) during smelting. Their potential interactions with heavy metals such as lead and cadmium may significantly enhance metal volatility and elevate emission risks, yet these mechanisms are poorly quantified under industrial conditions [27]. Furthermore, the long-term leaching behavior and environmental stability of slags originating from e-waste smelting remain substantially overlooked. Current research emphasis lies predominantly on short-term metal recovery efficiencies, rather than on the residual contamination potential and geochemical evolution of these secondary residues over time. Additionally, comprehensive economic feasibility studies regarding advanced pollution control technologies—especially for small-to-medium scale smelting facilities in developing regions—are notably scarce, thereby hindering broader and more scalable adoption of best available techniques [28].

These knowledge deficiencies collectively impede evidence-based policy formulation and context-sensitive technological adaptation, as both regulators and industry operators lack robust empirical data to evaluate the critical trade-offs between process efficiency, economic viability, and long-term ecological safety. Consequently, the development and standardization of environmentally sound practices across diverse operational and regulatory contexts remains challenging.

Future research efforts should prioritize three interconnected domains: (1) systematic experimental and modeling studies on halogen-heavy metal interaction mechanisms during smelting to refine emission prediction models and control strategies; (2) long-term leaching assessments and geochemical characterization of slags to establish scientifically-grounded criteria for their safe disposal or beneficial reuse; and (3) integrated cost-benefit and techno-economic analyses of pollution control technologies tailored to resource-constrained operational settings. Near-term research objectives should include pilot-scale tracking of bromine-induced metal volatilization, while long-term goals ought to focus on creating region-specific technical and regulatory guidelines for sustainable e-waste smelting operations.

3 Conclusion

This analysis has delineated the fundamental operational and environmental distinctions between informal acid leaching and formal smelting processes for electronic waste treatment, with particular emphasis on heavy metal liberation dynamics, ecological ramifications, and mechanistic foundations. Informal recycling methodologies, defined by the uncontrolled application of corrosive reagents and rudimentary metal recovery practices, yield suboptimal extraction efficiency while generating extensive ecological degradation. These activities provoke profound contamination of terrestrial and aquatic systems, elevating the mobility and trophic transfer of toxic metals including lead, cadmium, and copper, with clearly established consequences for local ecosystem integrity and public health.

Formal pyrometallurgical operations, conversely, constitute a technologically sophisticated paradigm, structured within regulatory frameworks emphasizing emissions mitigation and resource conservation. By incorporating sealed thermal processing units, preparatory material conditioning, and advanced multi-stage emission abatement technologies, formal smelting attains markedly higher metal recuperation yields across diverse elemental groups while substantially attenuating the release of hazardous fine particulates and volatile metal compounds. The process is underpinned by controlled thermodynamic and kinetic principles to direct metal partitioning into distinct output streams, thereby concentrating valuable components while sequestering harmful elements.

Notwithstanding these advantages, the progression toward globally sustainable e-waste processing is impeded by persistent obstacles. Key among these are inconsistent analytical methodologies for environmental impact evaluation across technological domains, socioeconomic constraints limiting the implementation of advanced emission controls in developing economies, and substantial research deficiencies pertaining to the long-term environmental stability of secondary residues and the transformation pathways of halogenated additives. Addressing these challenges mandates an integrated approach involving the creation of unified, technology-neutral assessment protocols, the innovation of economically viable pollution mitigation adaptations for small-scale applicatio, and dedicated interdisciplinary investigation into the complete lifecycle of metal species throughout recycling operations. Fundamentally, alleviating the environmental impacts of e-waste processing demands coordinated initiatives to embed formal technologies within a comprehensive, globally accessible circular economy framework for electronics.

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