detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

MINING ALUMINUM FROM LANDFILLS: CHALLENGES, TECHNOLOGIES, AND THE CASE FOR PRE-LANDFILL INTERVENTION

Daniel Amponsah-Berko [1,*], Rebecca Kwofie [1], Timothy Eisele [1] and Jonathan Robins [2]

[1] *Department of Chemical Engineering, Michigan Technological University, 1400 Townsend Dr, Houghton, MI 49931, USA*
[2] *Department of Social Sciences, Michigan Technological University, 1400 Townsend Dr, Houghton, MI 49931, USA*

Article Info:
Received:
26 September 2025
Revised:
19 February 2026
Accepted:
6 March 2026
Available online:
31 March 2026

Keywords:
Primary aluminum production
Secondary aluminum production
Landfill mining
Aluminum recycling
Separation technologies
Used beverage cans

ABSTRACT

Aluminum, a critical mineral in modern industry and energy transition, presents substantial environmental and economic burdens when produced through primary methods due to its high energy consumption and associated emissions. Although secondary production through recycling offers significant energy and emissions savings, it is widely believed that a large volume of aluminum still ends up in Municipal Solid Waste Landfills, particularly in the form of used beverage cans (UBCs) and other post-consumer products. This paper explores the feasibility and challenges of recovering aluminum from landfills through landfill mining (LFM). It presents an in-depth review of the historical and current state of aluminum waste generation in the United States, highlighting the growing accumulation of aluminum in landfills and the limitations of existing recycling practices. The study evaluates the physiochemical conditions of landfills affecting aluminum stability and outlines key technologies for material recovery, including air classification, magnetic separation, eddy current separation, electrostatic separation, sink-float techniques, optical sorting and LIBS. Despite technological advances, the recovery of aluminum from landfills remains hindered by numerous barriers such as technical inefficiencies, contamination, oxidation, high operational costs, regulatory ambiguity, and public opposition. Crucially, a techno-economic assessment demonstrates that standalone aluminum recovery from landfill is profoundly uneconomic under any plausible combination of parameters. The findings emphasize the importance of pre-landfill aluminum recovery as a more viable and sustainable strategy. By diverting aluminum from disposal before landfilling, the environmental, economic, and logistical burdens of post-disposal recovery can be substantially mitigated. This review advocates for upstream integration of aluminum recovery into waste management systems as a pathway toward resource efficiency, landfill space conservation, and reduced reliance on energy-intensive primary production.

1. INTRODUCTION

Aluminum, crucial for its properties and the third most abundant element in the earth's crust, was first utilized in the 19th century (Ashkenazi, 2019). Its extraction, initially hindered by its high affinity for oxygen, became viable with the Hall-Héroult process in 1886 (Rabinovich, 2013). Today, aluminum production is dominated by the combined Bayer and Hall-Héroult processes, and is an important metal in many industries (Ashkenazi, 2019).

1.1 Aluminum as a critical mineral and its relevance in the energy transition

Although aluminum is abundant in the Earth's crust, it is classified as a critical mineral under the U.S. Energy Act of 2020 because it is essential to economic and national security and has a vulnerable supply chain (Fortier et al., 2018). Aluminum requires a considerable amount of energy to be converted to its metallic state from its oxide (Al_2O_3), making availability in the metallic form more important than availability of the ore. Most of this energy must be provided in the form of electricity, not just heat. The energy-intensive nature of aluminum production is a key factor in its classification as a critical mineral (Energy, 2023). Due to high energy costs, especially in the United States and Europe, multiple smelters have been forced to shut down or reduce their production output of primary aluminum, leading to a reduced number of operational smelters in some regions. In response, the industry is pursuing significant innovations, including the development of inert

* Corresponding author:
Daniel Amponsah-Berko
email: damponsa@mtu.edu

https://doi.org/10.31025/2611-4135/2026.19573

anode technology and other process improvements aimed at drastically lowering energy consumption and achieving near-zero direct emissions from the smelting process (Ahmad et al., 2025; Munshi). Concurrently, there is a trend for some primary production facilities to integrate or transition towards secondary aluminum production to improve economic and environmental sustainability.

1.2 Aluminum Production

Aluminum production consists of primary production (from bauxite) and secondary production (recycling scrap) (Padamata et al., 2021). Primary aluminum is produced through the Bayer process, which refines bauxite into alumina, followed by the Hall–Héroult electrolytic process, which reduces alumina to metallic aluminum (Buffington, 2012). These processes are highly energy intensive, requiring approximately 23–24 kWh per kilogram of aluminum, largely in the form of electricity for electrolysis (Choate & Green, 2003). According to literature, for every 4kg bauxite, 2 kg of aluminum oxide can be obtained and 1kg of aluminum metal produced (David & Kopac, 2013). Approximately, 23.8 kWh (comprising heat energy for Bayer refining and electrical energy for Hall-Heroult smelting) is required to produce a kilogram of aluminum from bauxite under the conventional method of aluminum production (Choate & Green, 2003). As a result, primary aluminum production contributes roughly 1% of global CO_2 emissions, with life-cycle emissions ranging from 14.98 to 23.96 tons CO_2-eq per ton of aluminum, depending on the energy source (Ali Hasanbeigi, November 21, 2017; Shen & Zhang, 2024). Research is actively pursuing decarbonization, notably inert anodes that could eliminate direct CO_2 emissions from electrolysis if powered by renewables (Saevarsdottir & Kvande, 2025). While not yet commercially widespread, this technology represents a critical pathway for reducing the future carbon footprint of primary aluminum (Chen et al., 2025). Waste generation, particularly red mud from the Bayer process, is another major issue: 1-1.5 tons of highly alkaline residue per ton of alumina, with ~117 million tons generated annually (Archambo & Kawatra, 2021; Wen et al., 2024).

The challenges associated with primary aluminum production has shifted the world's focus on secondary aluminum production (Tabereaux & Peterson, 2024). Secondary aluminum production is basically collecting and recycling aluminum scrap into usable aluminum (Capuzzi & Timelli, 2018). This type of aluminum production is 95.0% more energy-efficient than primary aluminum production (Green, 2007). This is because in secondary aluminum production, the energy intensive processes (Bayer and Hall-Heroult) in primary aluminum production are eliminated. Modern recycling achieves material yields >95.0%, with oxidation losses as low as 1-5% (Al-Alimi et al., 2024b; Capuzzi & Timelli, 2018). Producing one ton of secondary aluminum requires only 750-1500 kWh (directory, 2025), with CO_2-eq emissions of ~0.32 metric tons, compared to 14.98-23.96 tons for primary aluminum (Ali Hasanbeigi, November 21, 2017; Shen & Zhang, 2024).

Secondary aluminum production can be effective tool to reduce aluminum importation in countries that depend heavily on aluminum imports, such as the United States of America. Currently, the production of primary aluminum has decreased significantly in the U.S., and and the U.S. imported 5.54 million tons in 2023 (Chen & Graedel, 2012). Data from the EPA suggest that 3.9 million tons of aluminum waste was generated in 2018, of which about 2.7 million tons was landfilled (EPA, 2023). This suggests that improving the recycling industry in the USA can significantly reduce the amount of aluminum waste landfilled and consequently reduce the USA's dependency on other countries for raw aluminum.

1.3 Aluminum recycling as a share of total aluminum consumed is declining, even in states with container deposit laws

Despite the long-standing environmental and economic advantages associated with aluminum recycling, recent data indicate a concerning downward trend in the share of recycled aluminum relative to total aluminum consumption in the United States. This decline persists even in states that have adopted policies specifically designed to promote recycling behaviors, such as container deposit laws.

1.3.1 Trends and Data on Aluminum Recycling

According to the U.S. Geological Survey, the United States recovered approximately 3.2 million tons of aluminum from purchased scrap in 2021. This amount includes both new (manufacturing) scrap and old (post-consumer) scrap, with new scrap accounting for 53.0% and old scrap making up 47.0%. Notably, aluminum recovered from old scrap was equivalent to just about 30.0% of the nation's apparent consumption. This data reveals a critical gap that a substantial portion of aluminum scrap from post-consumer products, is not being recycled (Center-USGS, 2022).

Aluminum recycling in the United States is assessed using multiple metrics, each targeting different components of the recycling system. End-of-life (EOL) indicators such as the Collection Rate (CR) and Recycling Rate (RR) measure how much post-consumer aluminum is recovered and recycled. The Domestic Recycling Rate (DRR) refines this by excluding exports, offering a clearer view of materials retained and processed within the U.S. system. Recycling Input Rates (RIRs) evaluate the proportion of recycled aluminum in manufacturing inputs but can be inflated by the inclusion of pre-consumer (new) scrap, which does not reflect actual recovery from waste. The Old Scrap Ratio (OSR) addresses this limitation by quantifying only post-consumer recycled content (Association, 2024).

More recently, the Consumer Recycling Rate, which stood at 43.0% in 2023, has been emphasized for its accuracy in capturing domestic recycling behavior, as it excludes imported scrap. In contrast, the Industry Recycling Rate, reported at 57.0%, includes imported used beverage cans (UBCs) and exported material recycled abroad. The Aluminum Association includes imported UBCs to reflect total scrap processed by U.S. producers; however, this approach may overstate domestic recycling effectiveness. For evaluating material circularity and national policy outcomes, DRR, OSR, and the Consumer Recycling Rate offer more relevant and transparent indicators than industry-aggregated rates (Association, 2024; Institute, 2024).

1.3.2 Aluminum Beverage Cans: A Case Study in Declining Recovery

Aluminum Used Beverage Cans (UBCs) have historically played a central role in aluminum recycling due to their ubiquity and ease of collection. Recycling of UBCs in the U.S. peaked in 1992 with a rate of approximately 65.0%. According to the Aluminum Association and the Can Manufacturers Institute (CMI), the national recycling rate for aluminum cans fell to 43.0% in 2023, marking one of the lowest levels in recent decades. This rate represents a significant decline from the long-term average recycling rate of approximately 52.0% recorded since 1990. The reported statistics are derived from a comprehensive survey of aluminum can manufacturers and recyclers, complemented by governmental and other relevant data sources (Association, 2024). This downward trend coincides with a decrease in the inflation-adjusted market value of used aluminum cans, which has reduced the economic incentive (deposit) for collection and recycling.

A major issue lies in the recycled content of new aluminum cans, which typically ranges between 33.0% and 50.0%. Although it is technically possible to manufacture a can from 100.0% recycled material, doing so is considered inefficient within the current supply chain structure. This limitation arises from the inherently labor-intensive and disaggregated structure of the post-consumer collection system for used beverage cans (UBCs), which hinders efficient aggregation and processing at scale (Buffington, 2012). While aluminum cans are recycled at far higher rates than glass or plastic, these rates have fallen below 50% in recent years.

Despite aluminum's inherent recyclability and high material value, the U.S. continues to discard a vast quantity of used aluminum cans. In 2023, although approximately 46 billion aluminum cans were recycled, over 61 billion were discarded in landfills, resulting in an estimated loss of $1.2 billion worth of recyclable material (Association, 2024). This loss is equivalent to each person in the U.S. throwing away nearly 15 twelve-packs of aluminum cans annually, a striking indicator of the inefficiencies in the nation's recycling system.

Although aluminum still maintains a higher recycling rate than glass 39.6% and PET plastic bottles 20.0%, the recent decline represents a significant missed opportunity given aluminum's economic and environmental advantages (Association, 2024). Enhancing the collection, sorting, and processing of aluminum cans could yield substantial benefits in terms of resource efficiency, greenhouse gas reduction, and domestic material supply security (Gitlitz, 2002).

1.4 Scope of the Review

Given the persistent landfilling of large quantities of highly recyclable aluminum, this paper critically evaluates landfill mining (LFM) as a potential solution. We synthesize historical waste data, review separation technologies, and present a techno-economic assessment that quantifies the profound economic infeasibility of standalone aluminum recovery from landfills. We then analyze the environmental, technical, regulatory, and social barriers that render LFM impractical at scale. The central argument of this paper is that pre-landfill intervention – recovering aluminum before it is buried – is not merely preferable but necessary. Upstream recovery preserves material quality, avoids oxidation and contamination, eliminates the need for costly excavation, and aligns with circular economy principles. We conclude by outlining policy pathways and research priorities to shift the paradigm from post-hoc mining to proactive diversion.

1.5 Review Methodology

This review was conducted following a systematic approach to ensure comprehensive coverage and analytical thoroughness. Literature was identified through searches in the Scopus, Web of Science, and Google Scholar databases, using keyword combinations including "aluminum recycling," "landfill mining," "municipal solid waste aluminum," "aluminum recovery," "secondary aluminum," "used beverage cans," and "separation technologies." The search was not restricted by start date, with a cutoff in December 2024, to capture both foundational and recent developments.

Inclusion criteria prioritized peer-reviewed journal articles, authoritative industry reports and seminal books. Governmental and institutional data were included for quantitative analysis of waste generation and recycling trends (e.g., from the Aluminum Association, U.S. EPA, USGS). Exclusion criteria removed non-English publications, articles focusing solely on primary production without a waste/recovery link, and very short conference abstracts lacking substantive data. After screening titles, abstracts, and full texts, 114 sources were selected for in-depth analysis and synthesis. Evidence was synthesized thematically to address the core research questions: the scale of aluminum in landfills, the physicochemical fate of landfilled aluminum, the technological pathways for its recovery, and the associated economic and regulatory barriers. Quantitative data from U.S. agencies were harmonized and, where necessary, interpolated to construct cumulative time-series analyses. Findings from technological and case studies were compared to evaluate efficiency, readiness, and feasibility, leading to the critical assessment and advocacy for pre-landfill intervention presented in this review.

While previous reviews have provided broad overviews of landfill mining and material recovery challenges, often from global or European perspectives (Jain et al., 2023; Krook et al., 2012), this review offers a targeted and original contribution focused on the United States context. First, it presents a data-driven quantification of the historical accumulation of aluminum in U.S. landfills from 1960 to 2018, integrating fragmented national datasets to demonstrate the scale of aluminum resource loss. Second, the study bridges aluminum corrosion science with landfill biogeochemistry, using Pourbaix-based frameworks to assess aluminum survivability under realistic landfill conditions and to move beyond generic recovery potential toward a material-specific evaluation of recoverability. Third, the review provides a dedicated assessment of the economic and regulatory viability of aluminum landfill mining in the United States, explicitly contrasting U.S. policy and market conditions with the more established European experience. Collectively, these contributions culminate in a focused argument that upstream, pre-landfill aluminum recovery represents the most sustainable and practical pathway for improving resource efficiency, reducing environmental risk, and strengthening domestic material security within U.S. waste management systems.

2. STATE OF ALUMINUM WASTE MANAGEMENT IN THE U.S.

The U.S. has witnessed a substantial increase in aluminum usage over the past six decades, leading to a corresponding rise in aluminum waste (Chen & Graedel, 2012; Kulas et al.). While the U.S. Environmental Protection Agency (EPA) reports annual aluminum generation data, cumulative generation data over multiple decades are not directly provided (Agency, 2018a, 2018b, 2018c; Agency, 2020; Recovery, 2014). Therefore, this study calculated the cumulative aluminum generation from 1960 to 2018 by first using interpolation to estimate the amount of aluminum generated in the missing years and then summing them with the annual generation data reported by the EPA. This approach provides a more comprehensive perspective on the total aluminum generated over the decades.

Data from the U.S. EPA show that the total cumulative amount of aluminum generated from the early 1960s to 2018 exceeded 130 million U.S tons as shown in Figure 1. Annual generation rose from 340,000 U.S tons in the 1960s to nearly 4 million U.S tons by 2018. This growth is largely driven by increased consumption in packaging (especially beverage cans), durable goods (including appliances and electronics). The U.S. EPA did not provide specific data on the amount of aluminum from durable goods that was generated in their 2018 report.

To estimate this quantity, the annual aluminum generation from containers and packaging is subtracted from the total annual aluminum generation, with the remaining quantity attributed to durable goods. A graphical representation of this trend (Figure 1) shows exponential growth across all major aluminum generation categories, with containers and packaging leading the increase, reaching a cumulative 83 million U.S tons in 2018. While aluminum generation in the U.S. has increased exponentially, the amount of aluminum that ends up in landfills has also grown over the decades. This clearly highlights a gap in the aluminum recycling culture in the U.S.

The U.S. EPA did not provide specific data on the amount of aluminum from durable goods that ends up in landfills in their 2018 report. To estimate this quantity, the annual amount of aluminum landfilled from containers and packaging is subtracted from the total annual aluminum landfilled, and the remaining amount is attributed to durable goods. A similar methodology used to calculate cumulative aluminum generation from 1960 to 2018 was applied to estimate the cumulative amount of aluminum entering landfills, based on data reported by the EPA. The cumulative landfill data reveal a concerning buildup of aluminum waste, with over 90 million tons discarded by 2018. As shown in Figure 2, containers and packaging account for more than half of this accumulated waste, while durable goods represent a growing portion due to their increasing presence in consumer products (Agency, 2018a, 2018b, 2018c; Agency, 2020; Recovery, 2014).

2.1 Aluminum Waste by Type

Containers and packaging (beverage cans, food cans, food containers and foil) and durable goods (products that last three years or more) constitute the largest sources of aluminum in municipal solid waste. As shown in Figure 3, approximately 1 million U.S tons of containers and packaging ended up in landfills 2018, while the cumulative amount

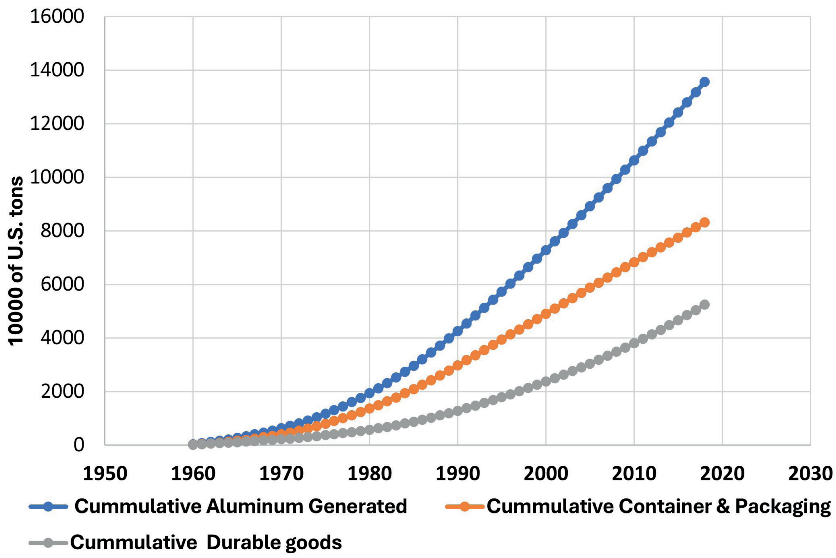

FIGURE 1: Cumulative aluminum waste generation in the United States from 1960 to 2018. Data are sourced from the EPA's 2018 report, Materials in the Municipal Waste Stream, with missing years interpolated using available data provided in the report (EPA, 2023).

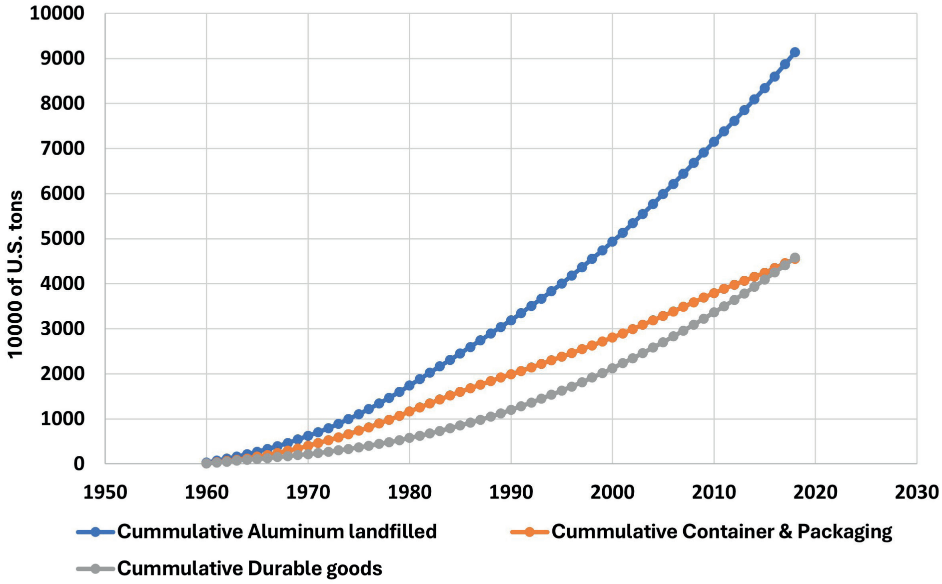

FIGURE 2: Cumulative aluminum landfilled in the United States from 1960 to 2018. Data are sourced from the EPA's 2018 report, Materials in the Municipal Waste Stream, with missing years interpolated using available data provided in the report (EPA, 2023).

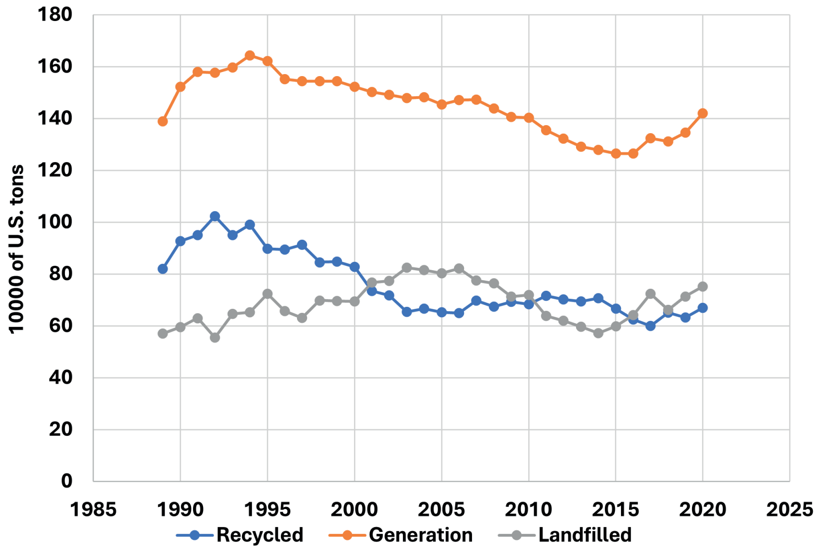

FIGURE 3: Generation, recycling, and landfilling of used beverage cans (UBCs) in the United States. Data exclude imported UBCs and are sourced from the Aluminum Association (Agency, 2020).

is 45.5 million U.S. tons, with beverage cans contributing the most to this total (Agency, 2020). As illustrated in Figure 2, the cumulative quantity of aluminum from durable goods disposed of in landfills has increased substantially over the decades, reaching approximately 45.8 million U.S. tons by 2018. In that same year, the annual landfill contribution from durable goods was estimated at 1.6 million U.S. tons.

Despite the high recyclability and economic value of aluminum, a substantial portion of aluminum waste, particularly in the form of Used Beverage Cans (UBCs), continues to be disposed of in landfills annually in the United States. Data from the Aluminum Association over the past three decades indicates a consistent increase in the volume of aluminum UBCs being landfilled since the early 2000s. In 2018 alone, approximately 660,000 U.S. tons of aluminum UBCs were landfilled, representing nearly half of the total generated as shown in Figure 3 (Agency, 2020). Between 1995 and 2015, UBCs waste generation declined from over 1.6 million to around 1.3 million U.S. tons. This may be due to lightweighting of aluminum cans by manufacturers and innovations in beverage cans design incorporating other materials such plastics.

The persistent landfilling of nearly half of all generated aluminum UBCs, despite their high economic value and recyclability, points to systemic failures in the U.S. recycling system. Several interconnected factors likely contribute to this gap. Economically, the fluctuating market price for scrap aluminum and the relatively low (and inflation-eroded) deposit value in bottle bill states can weaken financial incentives for consumer recycling and for municipalities to operate robust collection programs. Logistically, the reliance on single-stream recycling, while convenient, often leads to contamination of material streams, reducing the quality and value of collected aluminum (Morawski, 2010). Furthermore, the absence of a federal container deposit law (only 10 states have such laws) means a majority of the U.S. population lacks a direct economic incentive to return cans. Public awareness and convenience also play a role; recycling rates are often lower in multi-family housing and public spaces where access to recycling bins is limited (Buffington, 2012; Gitlitz, 2002). Addressing this issue requires a multi-pronged strategy involving policy (e.g., extended producer responsibility, modernized deposit laws), investment in sorting technology, and public education.

By 2021, the gap between generation, recycling, and landfilling had further narrowed, with landfilling and recycling rates approaching equivalence. This trend signifies a significant missed opportunity for material recovery. Aluminum cans are among the most energy-intensive materials to produce from virgin resources, yet they can be recycled indefinitely without any degradation in quality. The landfilling of this material not only contributes to environmental degradation but also results in the loss of substantial embodied energy and economic value (Al-Alimi et al., 2024a; Gaines, 1981; Green, 2007; Miteva & Hodjaoglu).

3. EFFECTS OF LANDFILL PHYSIOCHEMICAL PROPERTIES ON ALUMINUM

The substantial accumulation of aluminum in municipal solid waste landfills represents a potentially significant secondary resource; however, its recovery potential depends not on total buried mass but on the fraction that retains its metallic form. The long-term preservation of metallic aluminum is governed by the dynamic and heterogeneous physicochemical environment within landfill systems, where evolving pH, redox potential (Eh), moisture availability, and waste composition control corrosion processes and material stability (Stark et al., 2012).

Landfill conditions evolve as organic waste undergoes biodegradation, producing spatial and temporal variations in temperature, moisture, oxygen availability, and chemical composition (Igwegbe et al., 2024). Depth strongly influences these conditions: shallow zones experience greater oxygen intrusion and moisture fluctuations, while deeper layers are typically compacted, saturated, and anaerobic. These gradients regulate pH and Eh, which together determine aluminum stability.

The Pourbaix diagram for aluminum provides a thermodynamic framework for interpreting these processes (Pourbaix, 1974). Higher Eh values indicate oxidizing environments associated with aerobic activity, whereas lower Eh values reflect reducing anaerobic conditions. Aluminum remains corrosion-resistant within a pH range of approximately 4-9 due to formation of a protective oxide layer. Outside this range, the oxide film destabilizes. Acidic environments (pH < 4), generated during acidogenic decomposition, and highly alkaline conditions (pH > 9), often associated with ash residues or concrete degradation, both promote aluminum dissolution and oxidation (Pourbaix, 1974).

Moisture further accelerates degradation by enabling electrochemical reactions and microbial activity. Organic matter decomposition produces carbon dioxide and organic acids that promote pitting corrosion. Under alkaline anaerobic conditions, aluminum may react directly with water:

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2\uparrow$$

forming aluminum hydroxides and hydrogen gas (Calder & Stark, 2010; Stark et al., 2012). Field observations of hydrogen generation and localized heating confirm that aluminum oxidation can persist for decades after burial. These reactions progressively convert metallic aluminum (Al^0) into hydroxides and aluminosilicate phases that are unrecoverable through conventional separation or remelting (Calder & Stark, 2010).

Beyond oxidation, Al^{3+} released during corrosion can complex with humic and fulvic substances in landfill environments, forming stable organo-aluminum species that persist in leachate or become incorporated into fine fractions (Lee et al., 2023). Because this aluminum is no longer metallic or conductive, it cannot be recovered through conventional mechanical separation technologies (Parrodi et al., 2018). Recovery would require energy- and chemical-intensive hydrometallurgical treatment, rendering it economically unattractive (David & Kopac, 2013). This pathway represents an additional irreversible loss mechanism, further reducing practical recoverability and strengthening the case for pre-landfill recovery.

Material characteristics also influence degradation rates. Thicker, coated used beverage cans (UBCs) corrode relatively slowly, whereas thin, uncoated aluminum foils rapidly degrade and fragment into fine particles that become incorporated into soil-like fractions. Because aluminum is recyclable only when its metallic structure is preserved, such transformations directly reduce recoverable resource potential (Alicia Vallejo-Olivares, October 7th,2020; Guide, 2025)

The cumulative effect of these degradation pathways is quantifiable in actual landfill mining operations. A Belgian landfill mining study reported recovery of approximately 70% of aluminum as metallic concentrate, while about 30% was lost to fine residues due to corrosion and particle size reduction (Lucas et al., 2019; Wen et al., 2025). This loss reflects irreversible chemical transformation rather than processing inefficiency. Recovery rates are highly site-dependent: landfill age and hydrogeological conditions control moisture exposure and long-term chemical evolution (Wen et al., 2025). Younger landfills generally retain more metallic aluminum, whereas older sites expose materials to decades of chemically aggressive conditions, progressively reducing recoverable fractions.

Consequently, aluminum recovery potential varies widely across landfill environments and cannot be inferred from disposal quantities alone. Evidence suggests that in mature landfills, up to roughly 30% of aluminum mass may already be irreversibly lost through corrosion, with the remaining fraction representing an upper bound for recovery.

In wetter or more chemically aggressive settings, losses may be greater (Lucas et al., 2019).

These findings shift landfill mining evaluation from theoretical resource estimation toward conditional recoverability. Although metallic aluminum persists in landfills, progressive degradation imposes an inherent reduction in recoverable material over time, reinforcing the importance of upstream recovery and pre-landfill intervention to preserve aluminum in its recyclable metallic state.

4. LANDFILL MINING

Landfill mining (LFM) is an emerging and innovative waste management strategy that focuses on the extraction and recovery of resouces from landfills (Krook et al., 2012). With the tremendous amount of UBCs and other aluminum waste in landfills, mining landfills to recover these aluminum waste can serve as a way to mitigate conventional aluminum mining and greatly reduce the U.S. dependence on imports. Primarily there are two types of landfill mining, which are in-situ landfill mining and ex-situ landfill mining (Jones et al., 2013).

In-situ landfill mining involves the recovery of resources from landfills without physical excavation (Burlakovs et al., 2017). While historically focused on methane extraction, recent technological advances have expanded the focus to include the extraction of dissolved metals and nutrients from leachate. Although significant research and pilot-scale innovation over the past decade demonstrate the technical feasibility of recovering resources like ammonia, phosphorus, and metals, these processes have not yet achieved widespread commercial adoption (Wang et al., 2024). However, this method is not suitable for aluminum recovery intended for recycling. Aluminum present in leachate exists in ionic or oxidized forms and cannot be directly recycled. Instead, it would require electrolysis to be converted back into its metallic state, a process akin to primary aluminum production, which is highly energy-intensive and costly. Therefore, in-situ mining is not a practical approach for recovering recyclable aluminum from landfills.

Ex-situ landfill mining, however, involves material recovery from landfills by first excavating the landfill and processing them to recover valuable materials for recycling. Aluminum waste recovered through this type of landfill mining is suitable for recycling, provided the material has not undergone oxidation (Pecorini & Iannelli, 2020).

4.1 Theoretical Framework: Landfill Mining in the Context of Circular Economy

The concept of landfill mining must be understood within the broader framework of the circular economy, which seeks to decouple economic growth from resource consumption through closed-loop systems (Kirchherr et al., 2017). Traditional linear economic models follow a 'take-make-dispose' pattern, while circular economy principles emphasize waste prevention, resource efficiency, and material recovery (Sariatli, 2017). Landfill mining represents a 'retroactive' circular strategy, attempting to recover value from already discarded materials. However, this approach conflicts with the circular economy's emphasis on upstream design and prevention. This tension creates a critical paradox: while landfill mining recovers resources, its necessity signals failure in upstream circular systems. Evaluating landfill mining through circular economy metrics, such as material circularity indicators, resource productivity, and system-level impacts, reveals that pre-landfill interventions align more closely with circular principles by preventing waste generation rather than remediating it (Goh et al., 2025; Jones et al., 2013; Kirchherr et al., 2017).

The comparative analysis in Table 1 reveals significant international variation in approaches to aluminum recovery and landfill mining. European countries, particularly Sweden , have pioneered landfill mining primarily as an environmental remediation strategy, with aluminum recovery as a secondary benefit (Johansson et al., 2017);(Krook & Baas, 2013; Vollprecht et al., 2021). In contrast, developing economies often achieve higher aluminum collection rates through extensive informal sectors (waste pickers, itinerant waste buyers and small-scale scrap shops), though with significant environmental and social costs (Ferronato & Torretta, 2019). Japan's approach demonstrates that high recycling rates (exceeding 90% for aluminum cans) can be achieved through integrated policy frameworks, advanced technology, and strong public participation, reducing the need for landfill mining (Pereira, 2025). The United States occupies a middle ground, with advanced technological capacity but fragmented policies that result in suboptimal recovery rates. Meanwhile, China's state-driven approach – under the National Sword Policy and Circular Economy Promotion Law – emphasizes "urban mining" through government-backed demonstration projects, with recycling rates estimated at 50-60% and rising, though constrained by quality control and energy-intensity challenges (Li et al., 2020; Lindstrom, 2024). These international comparisons highlight that successful aluminum recovery requires context-specific integration of technological, economic, and policy factors (Cadavid, 2025).

4.2 Techniques employed in recovery of aluminum waste

Following landfill excavation, the next phase is the separation stage, which involves removing ferrous metals, nonferrous metals (such as copper and aluminum), plastics, and other materials from the waste stream using various separation technologies. Given the heterogeneous nature of landfill waste, a preliminary shredding process is typically employed to reduce the size of waste materials followed by a screening process, thereby enhancing the efficiency and effectiveness of the separation operations (Quaghebeur et al., 2013). Typically, a combination of two or more separation technologies is employed to selectively recover aluminum from the waste stream.

4.2.1 Air Separation

Air separation is primarily applied as a pre-concentration step to enhance downstream aluminum recovery by removing low-density contaminants such as fines, paper, textiles, and light plastics from excavated landfill material. By reducing the mass of organics and soil-like fines going to subsequent separation stages, air classification improves the efficiency and recovery of aluminum (Brooks

TABLE 1: International policy frameworks for aluminum recovery and landfill mining.

Country/Region	Policy Framework	Aluminum Recycling Rate	Landfill Mining Status	Key Innovations	Major Challenges
United States	Market-driven approach; state-level regulations; 10 states with container deposit laws	47% for aluminum cans (2024);	Limited to remediation projects; few states have regulations; not yet adopted for resource recovery	Advanced MRF technologies; private sector R&D; efficient eddy current separation	Fragmented policy; contamination in single stream; low economic incentives
European Union	Circular Economy Action Plan; Landfill Directive (1999/31/EC); Extended Producer Responsibility (EPR)	60-75% (varies by member state); EU target: 50% by 2025	Most advanced; multiple pilot & operational projects; viewed as resource recovery within CE framework	Integrated circular economy approach; landfill mining pilot projects (e.g., BELGIUM, SWEDEN); standardized metrics	Regulatory ambiguity; high operational costs; public acceptance issues
Japan	Sound Material-Cycle Society; Home Appliance Recycling Law; Container & Packaging Recycling Law	>90% for aluminum cans; ~98% for automotive aluminum	Limited activity; focus on "urban mining" from active waste streams rather than historic landfills	Sophisticated collection & sorting systems; high public participation; advanced urban mining	Limited landfill space; high operational costs; focus on prevention over remediation
Developing Countries (e.g., Brazil, India)	Informal sector dominant; evolving EPR frameworks; limited formal regulations	60-95% (highly variable; often high due to informal collection)	Rare as formal engineering projects; extensive informal scavenging at active dumpsites	Low-cost, labor-intensive networks achieve high collection rates; adaptive informal technologies	Significant environmental & health costs; low quality of scrap; lack of worker protection
China	National Sword Policy; Circular Economy Promotion Law; "Urban Mining (demonstration bases)	50-60% (estimated, improving rapidly)	Emerging focus; government-backed pilot projects; emphasis on "urban mining" from industrial waste	Large-scale implementation potential; state investment; integration with manufacturing supply chains	Quality control; environmental compliance in processing; energy-intensive recovery

et al., 2019; Gesing & Wolanski, 2001). Air separators are capable of handling particles as small as 50-1000 µm, making them suitable for preparing landfill-derived waste for aluminum-focused recovery circuits (Shapiro & Galperin, 2005).

4.2.2 Magnetic Separation

Magnetic separation is used to remove ferrous metals from the waste stream before targeting non-ferrous aluminum recovery (Brooks et al., 2019). A permanent magnet positioned beneath or above a conveyor belt attracts iron and other ferrous metals, which are diverted into a separate collection stream, as depicted in Figure 4 (Kelly & Apelian, 2016). Although magnetic separators do not recover aluminum directly, they play a critical supporting role by eliminating ferrous materials that would otherwise interfere with eddy current separation of aluminum. Additionally, recovered ferrous metals represent a valuable co-product that can partially offset landfill mining operational costs.

4.2.3 Eddy current separator

Eddy current separators (ECS) constitute the core technology for recovering aluminum from mixed waste streams. High-speed rotating magnetic rotors induce eddy currents in electrically conductive, non-ferrous metals such as aluminum, generating repulsive forces that eject these materials away from non-conductive waste (Smith et al., 2019) as shown in Figure 5. As a result, aluminum packaging, beverage cans, and foil are selectively recovered into a concentrated non-ferrous metal fraction. ECS performance strongly influences aluminum recovery efficiency in landfill mining and material recovery facilities, making it the most critical unit operation for aluminum separation (Padamata et al., 2021; Smith et al., 2019).

After non-ferrous metals have been separated from the waste stream, additional processing steps are required to selectively recover aluminum from the mixed nonferrous fraction. The following are some of the technologies commonly employed to achieve selective aluminum recovery, this normally takes place in a material recovery facility.

4.2.4 Electrostatic separation

Following ECS, the recovered non-ferrous fraction often contains a mixture of aluminum and copper. Electrostatic separation exploits differences in electrical conductivity to further refine aluminum purity as shown in Figure 6 (Dascalescu et al., 2016). When mixed metal is exposed to a high-voltage field, highly conductive metals such as copper exhibit greater deflection than aluminum, enabling their separation into distinct streams (Veit et al., 2005). This step is particularly important for producing aluminum fractions that meet smelter-grade purity requirements. Effective operation requires fine particle sizing and low moisture content, which may increase preprocessing costs. The main disadvantages of this separator are that the materials must be finely sized and be completely dry for effective separation.

4.2.5 Sink float method

SSink-float separation can be applied as a secondary refining step to separate aluminum from heavier non-ferrous metals and residual inorganics based on density differences as illustrated in Figure 7. Aluminum, with a density of ~2.7 g/cm³, preferentially floats in suitable media, while copper and other heavy metals sink (Padamata et al., 2021). Although effective, the use of heavy liquids and the need for post-separation drying increase operational complexity and cost, limiting widespread application in landfill mining unless high-purity aluminum recovery is required.

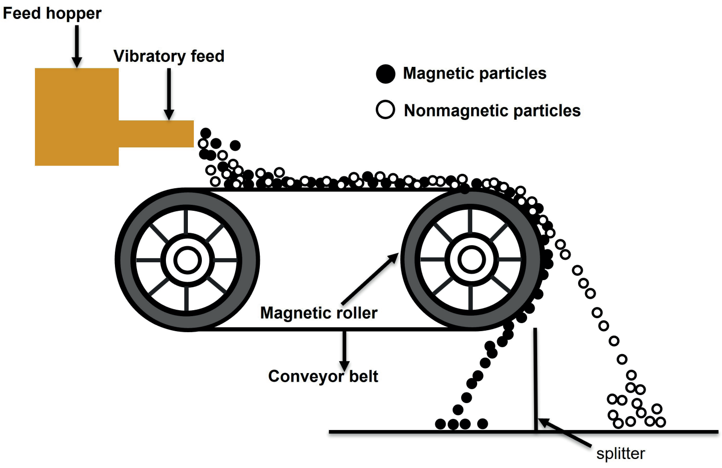

FIGURE 4: Schematic diagram of a magnetic separator comprising a vibratory feed hopper, conveyor belt, magnetic roller, and splitter for the separation of ferrous materials from non-magnetic particles.

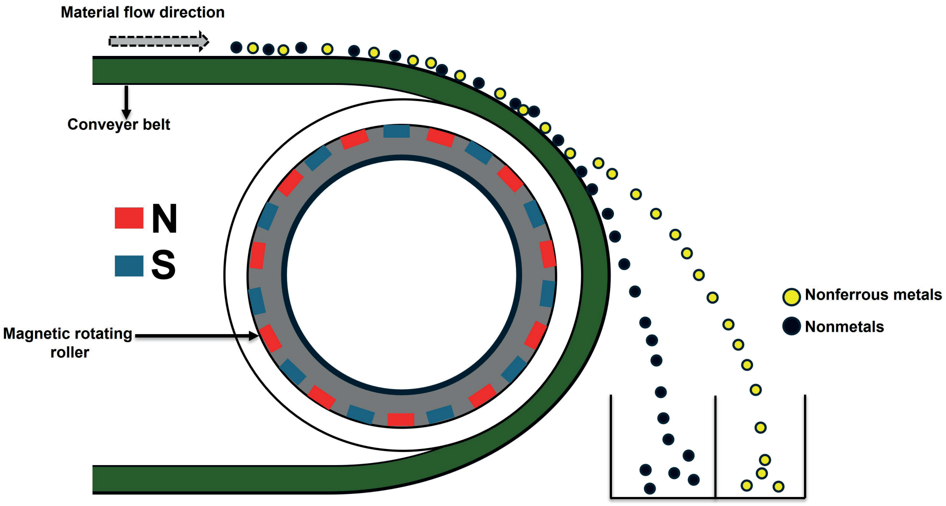

FIGURE 5: Schematic diagram of an eddy current separator comprising a conveyor belt and magnetic rotating roller consisting of alternating north and south poles.

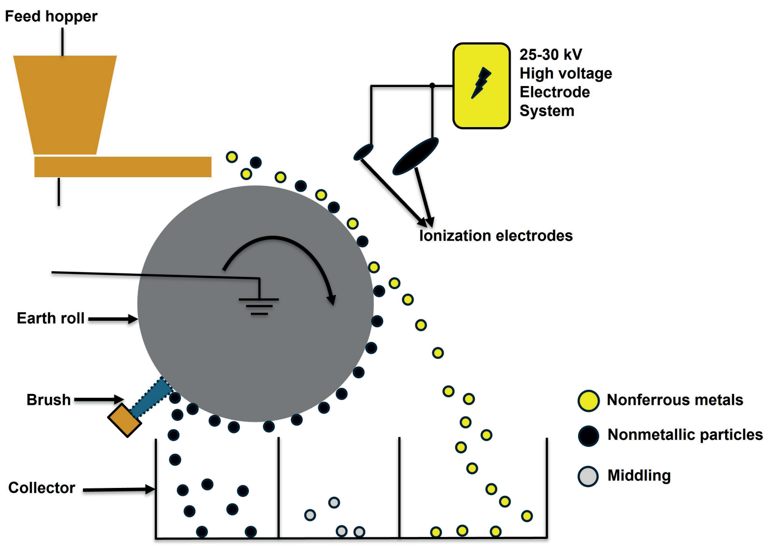

FIGURE 6: Schematic diagram of an electrostatic separator consisting of a vibratory feed hopper, high-voltage electrode system, earth roll, and collection chamber for product separation.

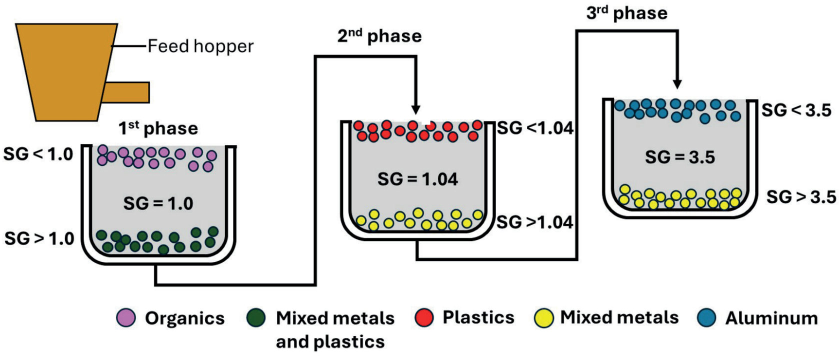

FIGURE 7: Schematic diagram illustrating the sink-float separation technique, highlighting the different phases involved in isolating aluminum from the waste stream.

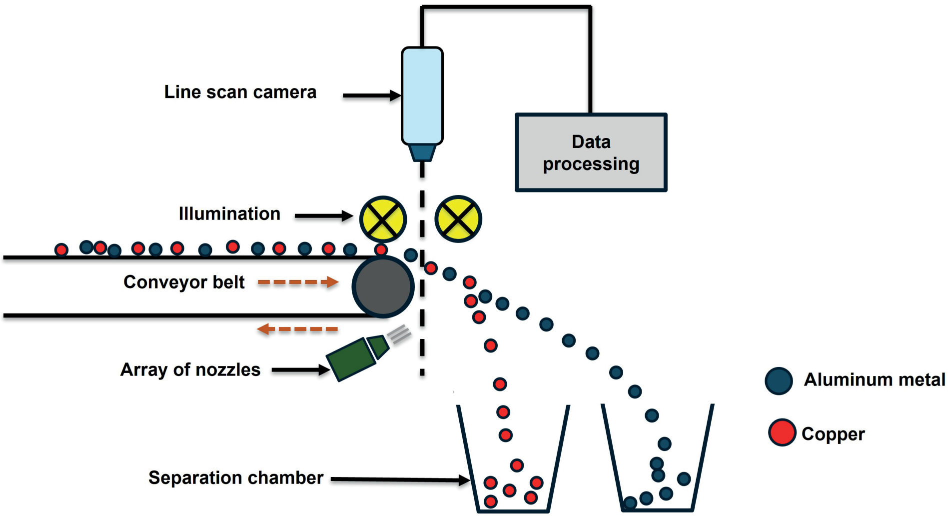

FIGURE 8: A schematic diagram of an optical separator consisting of camera, conveyor belt, nozzles and separation chamber, demonstrating the separation of aluminum from copper.

4.2.6 Optical based sorting

Optical based sorting systems enable targeted identification of aluminum based on surface color, spectral response, and inductive signatures (Mutz et al., 2005).These systems can selectively eject aluminum particles from mixed metal streams (Figure 8) using compressed-air nozzles and are increasingly applied where higher aluminum purity or alloy-specific sorting is desired. When integrated after ECS sensor-based sorting improves aluminum product quality and market value. This separator is suitable for separating materials with particle size above 10mm. Although optical separators are highly effective, they are associated with high operational costs.

4.2.7 Laser-Induced Breakdown Spectroscopy (LIBS)

Laser-Induced Breakdown Spectroscopy (LIBS) is an emerging technique for real-time, elemental identification of metals in mixed waste streams. By focusing a high-energy laser pulse on a particle, LIBS generates plasma whose emitted light spectrum reveals the elemental composition of the material (Cremers & Radziemski, 2006). When integrated downstream of ECS, LIBS can provide rapid, in-line detection and sorting of aluminum from residual copper, zinc, or other non-ferrous metals, enabling precise aluminum alloy-specific separation and recovery (Gurell et al., 2012). The key advantages of LIBS include high-speed analysis, minimal sample preparation, and the ability to detect trace contaminants that may affect smelter-grade purity. Limitations include higher equipment costs and the need for extensive calibration to handle heterogeneous landfill-derived materials effectively.

Each separation technology presents distinct trade-offs between recovery efficiency, operational requirements, and cost as shown in table 2. While individual technologies can achieve high recovery rates in a controlled settings, their effectiveness diminishes significantly in landfill mining applications due to material degradation, high moisture content, contamination, and heterogeneity (Xia et al., 2017). For instance, eddy current separation, typically achieving 85-95% recovery with clean industrial scrap, may achieve low recovery rates with landfill-aged aluminum due to oxidation and surface contamination (Huang et al., 2021). Similarly, electrostatic separation requires completely dry feed material, a condition that is rarely achievable for excavated landfill waste without extensive preprocessing. Excavated waste typically exhibits high moisture content and elevated relative humidity, necessitating energy-intensive drying steps that substantially increase operational costs (Silveira et al., 2018). This gap highlights that landfill mining cannot simply replicate MRF workflows but requires adapted or novel solutions. Emerging technologies such as artificial intelligence (AI)-driven optical sorters, robotic picking, and multi-sensor fusion systems offer potential pathways to better handle complex, degraded waste streams by making more nuanced material identifications. However, their high capital costs and unproven efficacy at landfill mining scale represent significant barriers (Gundupalli et al., 2017). Therefore, the central technological question for landfill mining shifts from what works in an MRF to what can be adapted or invented to work cost-effectively on low-grade, historical waste. These limitations explain why most successful landfill mining operations employ integrated, multi-stage separation systems, despite their higher capital requirements.

5. TECHNO-ECONOMIC ASSESSMENT OF ALUMINUM RECOVERY FROM LANDFILL: IDENTIFYING BREAKEVEN THRESHOLDS AND ECONOMIC CONSTRAINTS

This study presents a techno-economic assessment (TEA) of a commercial-scale aluminum recovery stream. By utilizing a base-case model derived from literature and realistic operational parameters, such as an annual project scale of 100,000 tonnes and a separation efficiency of 70%, we evaluate the net economic balance of standalone aluminum recovery. Furthermore, this analysis establishes critical breakeven thresholds for aluminum content and operational expenditures (OPEX), providing a rigorous framework to determine whether single-stream recovery is a feasible industrial strategy or if a transition toward multi-stream revenue models is required for financial sustainability.

5.1 Techno-economic assessment methodology

The net economic balance N for an aluminum recovery stream is calculated as:

$$R_{Al} = M_{waste} \times Y_{Al} \times \eta \times f_{cont} \times P_{Al}$$
$$C_{total} = M_{waste} \times C \text{ per tonne}$$
$$N = R_{Al} - C_{total}$$

R_{Al} - Revenue generated from selling recovered aluminum
Operational Cost (OPEX) - cost of excavation, transportation and separation and recovery of metal.
Capital Expenditure (CAPEX) - equipment and machinery investment

Base-case parameters are summarized in Table 3 Values are drawn from peer-reviewed literature (Hogland et al., 2011; Ratcliffe et al., 2012; van Vossen & Prent, 2013; Wagner & Raymond, 2015) and industry reports, with conservative assumptions favoring economic viability.

5.2 Base-case results

$$R_{Al} = 100{,}000 \times 0.008 \times 0.70 \times 0.50 \times 2{,}200 = \text{USD } 616{,}000$$
$$C_{total} = 100{,}000 \times 40 = \text{USD } 4{,}000{,}000$$
$$N = 616{,}000 - 4{,}000{,}000 = \text{USD} -3{,}384{,}000$$

Net loss: USD -3.38 million. This loss equates to USD -33.84 per tonne of waste processed.This implies that standalone aluminum recovery is not economically feasible.

TABLE 2: Comparative analysis of aluminum separation technologies.

Technology	Recovery Efficiency for Aluminum	Key Advantages	Key Limitations for landfill waste	Operation Cost
Air Separation	60-75% for bulk density separation	Low capital cost, simple operation, high throughput, effective for lightweight material removal	Ineffective on wet waste; limited to dry, pre-shredded material; misses small or embedded Al	Low
Magnetic Separation	Not for aluminum (95%+ for ferrous removal)	Highly efficient for ferrous metals, continuous operation, low maintenance, improves downstream Al quality	Only removes ferrous metals; requires additional processes for aluminum recovery; ineffective for non-magnetic materials	Low-Medium
Eddy Current Separation	70-85% for clean Al scrap; 50-70% for landfill-aged Al	Effective for aluminum, copper, brass; handles varied particle sizes; non-contact method	Efficiency decreases with oxidation, small particles (<5mm), moisture; high energy consumption; sensitive to material conductivity	Medium-High
Electrostatic Separation	75-90% for conductive metals	High purity achievable; separates based on electrical conductivity; effective for aluminum and copper separation	Requires completely dry, finely sized materials (<5mm); sensitive to surface contamination; high voltage requirements	Medium
Sink-Float Separation	80-90% based on density differences	Can separate multiple materials simultaneously; high purity achievable; effective for mixed metal streams	Environmental concerns with heavy liquids; requires drying; high operational costs; media management needed	High
Optical Sorting	85-95% for identifiable aluminum pieces	High accuracy; effectively remove aluminum from waste stream; non-contact process; real-time processing	Requires >10mm particle size; sensitive to surface contamination and coatings; high capital investment; requires clean material presentation	High
Laser-Induced Breakdown Spectroscopy (LIBS)	85–95% (when integrated with pre-separation technologies)	Real-time elemental identification; enables alloy-specific sorting; minimal sample preparation; detects trace contaminants; high-speed, in-line analysis	High equipment cost; requires calibration for heterogeneous landfill-derived materials; performance depends on consistent particle presentation	High

TABLE 3: Base-case model parameters for techno-economic assessment.

Parameter	Symbol	Base-Case Value	Rationale & Source
Project Scale	M_waste	100,000 ton	Represents a realistic, commercial-scale operation
Total OPEX & CAPEX	C_Total	USD 40 / Mt	Conservative synthesis of literature
Al Content	Y - Al	0.8 wt.% (0.008)	Mid-point of reported range (0.3–1.5%) in landfill
Separation Efficiency	η	70%	Realistic recovery rate for mechanical separation
Contamination Discount	f_cont	0.50	Reflects a 50% price reduction for low-grade, oxidized landfill scrap
Aluminum Price	P_Al	USD 2,200 / tonne	Approximate 5-year average LME price

5.3 Breakeven thresholds

To determine under what conditions the operation could break even (N≥0), we solved for the required value of each key parameter. Table 4 presents these thresholds.

Every single breakeven threshold lies far outside the realm of economic or technical feasibility. No combination of plausible parameter adjustments can render standalone aluminum recovery profitable.

5.4 Comparison with successful multi-stream models

The uneconomic outcome of single-stream recovery contrasts sharply with profitable multi-stream operations. Table 5 compares the base-case model with the Ashfill project in Maine, USA, illustrating the advantages of recovering multiple materials (Wagner & Raymond, 2015). European pilot projects, including EURELCO and the Horizon 2020 NEW-MINE initiative, further confirm that standalone recovery is rarely viable. NEW-MINE demonstrated that profitability required an Integrated Value Recovery approach combining (1) material recycling, (2) waste-to-energy of high-calorific fractions, and (3) landfill reclamation and remediation. This holistic strategy captures additional value from avoided remediation costs and reusable land, emphasizing that the feasibility of Enhanced Landfill Mining often depends on supportive regulatory frameworks and policy incentives when raw material markets alone are insufficient (Blengini et al., 2019; Hernandez Parrodi et al., 2019).

5.5 Implication: Single-stream aluminum mining is economically irrational

The TEA demonstrates that standalone aluminum recovery from landfill is profoundly uneconomic, regardless of project scale. The required aluminum grade (3.6 wt.%) is more than quadruple the realistic maximum; the required aluminum price (USD 7,143/tonne) is without historical precedent; and the required OPEX (USD 6.16/tonne) is an order of magnitude below current best practice. These findings lead to an unequivocal conclusion: any economically viable landfill mining operation must adopt a multi-stream revenue model, recovering ferrous metals, copper, plastics, and potentially realizing land value or airspace recovery. A general form of such a model is:

$$R_{total} = R_{Al} + R_{Fe} + R_{Cu} + R_{plastics} + V_{Landspace}$$

where $V_{Landspace}$ represents the avoided cost of new landfill capacity or the value of reclaimed land. This multi-stream approach is the only pathway – demonstrated by the Ashfill case – toward positive economics.

6. BARRIERS TO LANDFILL MINING

Landfill mining (LFM) has been explored as a strategy for sustainable waste management and resource recovery and has been implemented in the U.S. and other countries for land redevelopment, airspace recovery, and environmental remediation (Jain et al., 2023). However, its broader adoption remains limited by interconnected environmental, economic, societal, technological, and regulatory barriers.

TABLE 4: Breakeven thresholds for standalone aluminum recovery (N ≥ 0).

Parameter Adjusted for Breakeven	Required Threshold Value	Comment on Practical Attainability
Minimum Aluminum Price (P_Al)	USD 7,143 / tonne	Over 3x the historical average; economically implausible
Minimum Aluminum Content (Y_Al)	3.6 wt.%	Far exceeds typical landfill composition (<1.5%)
Maximum Allowable OPEX (C_total)	USD 6.16 / tonne	technologically impossible
Minimum Scrap Quality (f_cont)	1.0	Unattainable for contaminated landfill scrap

TABLE 5: Contrast with the case study's successful model.

Parameter	Case study 1 (Raw MSW)	Case Study 2 (Ashfill)
Feedstock	Raw MSW (0.8% Al)	Incinerator Ash (7% metal)
OPEX	$40/Mt	$158/Mt (but higher revenue)
Revenue	Only Al	Ferrous + Non-ferrous + Stainless + Zorba
Outcome	Net Loss ($-3.38M)	Profitable ($7.42M)
Net gain/loss per tonne	$ -33.84	$16.96

Environmental risks arise from the disturbance of stabilized waste, which can release methane and volatile organic compounds and increase leachate generation, potentially contaminating soil and groundwater, particularly in older landfills without engineered containment systems (Jain et al., 2023). Although hazardous materials typically constitute less than 1% of landfill content, accidental release remains a concern, and reuse of untreated soil-like fractions may cause secondary contamination (Burlakovs et al., 2017; Gurusamy & Thangam, 2023).

Economic feasibility remains a major constraint, as high costs associated with excavation, separation, transportation, and residual waste management often exceed revenues from recovered materials. While metals provide some value, most waste fractions lack sufficient market demand, making project viability highly dependent on policy incentives, infrastructure availability, and commodity prices (Frändegård et al., 2015; Krook & Baas, 2013; Söderholm & Ekvall, 2020; Van Passel et al., 2013). Without subsidies or favorable regulatory conditions, most projects remain economically marginal, with unrecovered residues returned to landfills, increasing operational costs (Frändegård et al., 2015; Lawal, 2024).

Societal opposition further limits implementation due to concerns about health risks, odors, noise, air pollution, and traffic, compounded by the imbalance between localized short-term impacts and delayed benefits (Einhäupl et al., 2021; Johansson et al., 2017; Johansson & Pettersson, 2022).

Regulatory frameworks in both the U.S. and EU were designed for waste containment rather than resource recovery, creating uncertainty regarding permitting, liability, and cost allocation among stakeholders (Taelman et al., 2018; Velenturf & Purnell, 2017; Wilts et al., 2016). The absence of comprehensive regulations, combined with limited municipal capacity and the lack of standardized resource assessment frameworks such as United Nations Framework Classification for Resources (UNFC), further constrains large-scale implementation.

7. THE PARADIGM SHIFT TOWARD PRE-LANDFILL INTERVENTION

Pre-landfill recovery refers to the diversion and capture of recyclable materials before disposal in municipal solid waste landfills (Cimpan et al., 2015). Unlike landfill mining, which attempts recovery after materials have been burried, pre-landfill intervention targets materials within collection systems, source separation programs, and material recovery facilities (MRFs), where quality and economic value remain largely intact (Cimpan et al., 2015). For aluminum, upstream recovery preserves metallic aluminum (Al^0), which is essential for efficient recycling. Pre-landfill recovery therefore shifts the focus from attempting to recover burried materials to preventing degradation altogether.

7.1 Comparative Advantages of Pre-Landfill Intervention

Upstream recovery maintains aluminum purity and metallic continuity, enabling efficient remelting with minimal losses. In contrast, landfill exposure leads to oxidation, contamination, and fragmentation that reduce recyclability (Hull et al., 2005; Martin et al., 2013). Pre-landfill recovery eliminates major cost drivers associated with landfill mining, including excavation, waste handling, and intensive preprocessing (Zhou et al., 2015). Materials intercepted earlier in the waste stream require significantly less energy and processing (Raabe, 2023). Early recovery reduces landfill volume, prevents long-term corrosion reactions, and maximizes displacement of energy-intensive primary aluminum production. Because secondary aluminum production requires only a fraction of the energy of primary production, upstream diversion yields substantial emissions reductions (Anna et al., 2026).

7.2 Applicability of Existing Technologies Upstream

A critical insight emerging from landfill mining research is that most technologies proposed for post-disposal recovery are not inherently unsuitable; rather, they are applied too late in the material lifecycle (Krook & Baas, 2013). Technologies such as eddy current separation, air classification, optical sorting, magnetic separation, and density-based separation are already capable of efficiently recovering aluminum when feedstocks remain relatively clean and size-consistent (Cui & Forssberg, 2003; Vermeșan et al., 2019).

When deployed upstream in MRFs or dedicated recycling facilities, these technologies operate under far more favorable conditions. Waste streams are less compacted, moisture content is lower and contamination levels are much lower. Consequently, separation efficiencies increase while energy consumption and equipment wear decrease (Cimpan et al., 2015).

Adapting landfill-mining technologies for pre-landfill recovery therefore represents a technological reallocation rather than technological innovation. The challenge is not the absence of recovery technologies but the timing and system integration of their deployment within waste management infrastructure.

7.3 Policy and Infrastructure Pathways

Achieving large-scale pre-landfill aluminum recovery requires coordinated policy and infrastructure interventions that address systemic inefficiencies in collection and sorting systems (Hariyani et al., 2025). Evidence consistently shows that container deposit programs significantly increase recovery rates for aluminum beverage cans by providing direct economic incentives for consumer participation; modernizing deposit values to reflect inflation and expanding geographic coverage could substantially reduce aluminum leakage into landfills (Buffington, 2012; Gitlitz, 2005; Wen et al., 2025). Extended Producer Responsibility (EPR) frameworks further support recovery by shifting partial responsibility for end-of-life material management to producers, thereby incentivizing product designs that facilitate recyclability while funding improved collection infrastructure. For aluminum packaging, EPR mechanisms can stabilize recycling financing and reduce dependence on volatile commodity markets (Quinn; Thakur & Kalra, 2026).

Infrastructure modernization also plays a critical role. Upgrading Material Recovery Facility (MRF) systems with advanced sorting technologies, including improved eddy current separators and optical and artificial intelligence (AI) sorting systems, can significantly enhance aluminum capture rates, particularly within single-stream recycling systems where contamination currently limits recovery efficiency (Kannan et al., 2025; Staub, 2020). Expanding recycling access in multi-family housing, public spaces, and commercial environments addresses logistical barriers that contribute to aluminum disposal, while consistent labeling standards and public education initiatives are necessary to reduce contamination and improve participation (Kostakis et al., 2025; Trushna et al., 2024).

Collectively, these pathways shift waste management from reactive disposal toward proactive resource management.

7.4 The Circular Economy Connection

Pre-landfill intervention aligns directly with circular economy principles, which prioritize waste prevention, material retention, and resource efficiency over end-of-pipe recovery strategies (Ghisellini et al., 2016). While landfill mining represents a retroactive attempt to reintroduce materials into economic circulation, it inherently reflects earlier failures in product design, collection systems, and recycling infrastructure.

Circular economy frameworks emphasize maintaining materials at their highest possible value for as long as possible (Blomsma & Tennant, 2020). Recovering aluminum before disposal preserves both material quality and embodied energy, enabling true closed-loop recycling. Unlike the circular economy goal of maintaining material integrity, landfilling aluminum may lead to the irreversible loss of metallic properties due to corrosion, effectively removing it from the recyclable material loop. From a system's perspective, landfill mining should therefore be viewed not as a primary circular strategy but as a corrective measure for historical inefficiencies. Pre-landfill recovery, by comparison, operationalizes circular economy objectives by preventing resource loss at the outset. Transitioning toward upstream intervention transforms aluminum waste management from a remediation challenge into a resource optimization strategy, strengthening domestic material security while reducing environmental burdens associated with primary production.

8. CONCLUSIONS

Recovering aluminum from landfills via landfill mining is technically, economically, and environmentally challenging. Landfilled aluminum suffers from severe contamination, oxidation, and corrosion, with up to 30% potentially unrecoverable (Lucas et al., 2019). Excavation and sorting costs often exceed the market value of the recovered material, while waste heterogeneity creates significant operational limitations. Economic and environmental assessments are inconsistent, reflecting differing assumptions and highlighting the need for standardized methodologies in the field (Frändegård et al., 2015; Krook & Baas, 2013).

Pre-landfill intervention offers a far more effective pathway. Recovering aluminum upstream preserves material quality, maximizes yields, reduces waste volumes, and avoids the resource-intensive processes associated with landfill mining. Strengthening U.S. recycling systems through expanded container deposit laws, extended producer responsibility programs, modernization of Material Recovery Facilities with advanced optical and AI-based sorting technologies, and enhanced public engagement promoting design-for-recycling and consumer education could divert an additional 815,000 tons of aluminum beverage cans annually, increasing the national used beverage can (UBC) recycling rate to approximately 85% (Institute, 2025).

Integrating aluminum recovery upstream within a circular economy framework mitigates the technical, financial, and environmental burdens of post-disposal recovery. The imperative is clear: the industry must shift from reactive landfill mining to proactive diversion to enhance resource efficiency, conserve landfill space, and strengthen domestic material security.

ACKNOWLEDGEMENTS

The author would like to thank the U.S. Department of Energy for funding this research under Grant DE-FE0032236.

DECLARATION OF THE USE OF AI

ChatGPT was employed to support language refinement, grammar correction, and clarity improvement. All intellectual contributions, data analysis, interpretations, and conclusions are the author's own responsibility. The use of AI did not involve generating or altering scientific results or research findings.

REFERENCES

Agency, U. S. E. P. (2018a). Aluminum: Material-Specific Data

Agency, U. S. E. P. (2018b). Guide to the Facts and Figures Report about Materials, Waste and Recycling

Agency, U. S. E. P. (2018c). Studies, Summary Tables, and Data Related to the Advancing Sustainable Materials Management Report

Agency, U. S. E. P. (2020). Sustainable Materials Management (SMM) - Materials and Waste Management in the United States Key Facts and Figures

Ahmad, S., Steen, J., Zajac, T., Azadi, M., & Ali, S. H. (2025). Carbon emissions in metal manufacturing productivity: A global analysis of aluminium smelting. Energy Research & Social Science, 129, 104343.

Al-Alimi, S., Yusuf, N. K., Ghaleb, A. M., Lajis, M. A., Shamsudin, S., Zhou, W., Altharan, Y. M., Abdulwahab, H. S., Saif, Y., & Didane, D. H. (2024a). Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing. Results in engineering, 102566.

Al-Alimi, S., Yusuf, N. K., Ghaleb, A. M., Lajis, M. A., Shamsudin, S., Zhou, W., Altharan, Y. M., Abdulwahab, H. S., Saif, Y., & Didane, D. H. (2024b). Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing. Results in engineering, 23, 102566.

Ali Hasanbeigi, P. D. (November 21, 2017). Aluminum Industry: 10 Emerging Technologies for Energy-efficiency and GHG Emissions Reduction. Global Efficiency Interligence. Retrieved June 19, 2025 from

Alicia Vallejo-Olivares, H. P., Mertol Gökelma, Hans J. Roven, Trond Furu, Anne Kvithyld, Gabriella Tranell. (October 7th,2020). Light Metals 2021: Compaction of aluminium foil and its effect on oxidation and recycling yield (L. Perander, Ed.). Springer Nature. https://doi.org/http://dx.doi.org/10.1007/978-3-030-65396-5_96

Anna, N., Camil, T., Constantin, I., Doina, R., & Violeta, M. L. (2026). Recycled Versus Primary Aluminum in European Automotive Industry: Trends, Challenges, and Opportunities. Recycling, 11(1), 19.
Archambo, M., & Kawatra, S. (2021). Red mud: fundamentals and new avenues for utilization. Mineral processing and extractive metallurgy review, 42(7), 427–450.
Ashkenazi, D. (2019). How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives. Technological Forecasting and Social Change, 143, 101–113.
Association, T. A. (2024, 12/05/2024). Amid Recycling Rate Decline, Aluminum Beverage Can Remains Most Recycled Drinks Package. https://www.aluminum.org/news/amid-recycling-rate-decline-aluminum-beverage-can-remains-most-recycled-drinks-package
Blengini, G., Mathieux, F., Mancini, L., Nyberg, M., & Viegas, H. (2019). Recovery of critical and other raw materials from mining waste and landfills. State of Play on Existing Practices, 1–125.
Blomsma, F., & Tennant, M. (2020). Circular economy: Preserving materials or products? Introducing the Resource States framework. Resources, Conservation and Recycling, 156, 104698.
Brooks, L., Gaustad, G., Gesing, A., Mortvedt, T., & Freire, F. (2019). Ferrous and non-ferrous recycling: challenges and potential technology solutions. Waste management, 85, 519–528.
Buffington, J. (2012). The beverage can in the United States: achieving a 100% recycled aluminum can through supply chain innovation. Jom, 64(8), 923–932.
Burlakovs, J., Kriipsalu, M., Klavins, M., Bhatnagar, A., Vincevica-Gaile, Z., Stenis, J., Jani, Y., Mykhaylenko, V., Denafas, G., & Turkadze, T. (2017). Paradigms on landfill mining: From dump site scavenging to ecosystem services revitalization. Resources, Conservation and Recycling, 123, 73–84.
Cadavid, J. Q. (2025). The UBC dilemma: Why the US is falling behind in recycling aluminium beverage can [Research].
Calder, G. V., & Stark, T. D. (2010). Aluminum reactions and problems in municipal solid waste landfills. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 14(4), 258–265.
Capuzzi, S., & Timelli, G. (2018). Preparation and melting of scrap in aluminum recycling: A review. Metals, 8(4), 249.
Center-USGS, N. M. I. (2022). Aluminum Statistics and Information. https://www.usgs.gov/centers/national-minerals-information-center/aluminum-statistics-and-information
Chen, K., Bao, S., Li, J., Li, J., Shi, M., Shi, X., & Ma, J. (2025). Research Progress on Inert Anode Materials for Aluminum Electrolysis. TMS Annual Meeting & Exhibition,
Chen, W.-Q., & Graedel, T. E. (2012). Dynamic analysis of aluminum stocks and flows in the United States: 1900–2009. Ecological Economics, 81, 92–102.
Choate, W. T., & Green, J. A. (2003). US energy requirements for aluminum production: historical perspective, theoretical limits and new opportunities. US Department of Energy, Energy Efficiency and Renewable Energy.
Cimpan, C., Maul, A., Jansen, M., Pretz, T., & Wenzel, H. (2015). Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the-art, cases, practice and implications for materials recycling. Journal of Environmental Management, 156, 181–199.
Cremers, D. A., & Radziemski, L. J. (2006). History and fundamentals of LIBS. Laser Induced Breakdown Spectroscopy: Fundamentals and Applications, 1, 1–39.
Cui, J., & Forssberg, E. (2003). Mechanical recycling of waste electric and electronic equipment: a review. Journal of hazardous materials, 99(3), 243–263.
Dascalescu, L., Zeghloul, T., & Iuga, A. (2016). Electrostatic separation of metals and plastics from waste electrical and electronic equipment. In WEEE recycling (pp. 75–106). Elsevier.
David, E., & Kopac, J. (2013). Aluminum recovery as a product with high added value using aluminum hazardous waste. Journal of hazardous materials, 261, 316–324.
directory, S. (2025). Why is aluminum recycling so effective?
Einhäupl, P., Van Acker, K., Peremans, H., & Van Passel, S. (2021). The conceptualization of societal impacts of landfill mining–A system dynamics approach. Journal of Cleaner Production, 296, 126351.
Energy, U. S. D. o. (2023). Critical Minerals & Materials Program
EPA, U. S. (2023). Facts and Figures about Materials, Waste and Recycling
Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. International journal of environmental research and public health, 16(6), 1060.
Fortier, S. M., Nassar, N. T., Lederer, G. W., Brainard, J., Gambogi, J., & McCullough, E. A. (2018). Draft critical mineral list—Summary of methodology and background information—US Geological Survey technical input document in response to Secretarial Order No. 3359 (2331-1258).
Frändegård, P., Krook, J., & Svensson, N. (2015). Integrating remediation and resource recovery: On the economic conditions of landfill mining. Waste Management, 42, 137–147.
Gaines, L. L. (1981). Energy and materials use in the production and recycling of consumer-goods packaging.
Gesing, A., & Wolanski, R. (2001). Recycling light metals from end-of-life vehicle. Jom, 53(11), 21–23.
Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32.
Gitlitz, J. (2005). Drink and deposit. Waste Management World.
Gitlitz, J. S. (2002). Trashed Cans: The Global Environmental Impacts of Aluminum Can Wasting in America. Container Recycling Institute.
Goh, K. C., Kurniawan, T. A., Othman, M. H. D., Jumaniyozov, K., Aziz, F., Anouzla, A., Ali, I., Khan, M. I., Alsultan, G. A., & Zhang, D. (2025). Promoting landfill mining for sustainable resource recovery, circular economy, and climate mitigation: a review. Frontiers in Environmental Science, 13, 1643195.
Green, J. A. (2007). Aluminum recycling and processing for energy conservation and sustainability. ASM International.
Guide, A. (2025). An aluminium beverage can. Aluminum Guide. Retrieved 08/05/2025 from
Gundupalli, S. P., Hait, S., & Thakur, A. (2017). A review on automated sorting of source-separated municipal solid waste for recycling. Waste Management, 60, 56–74.
Gurell, J., Bengtson, A., Falkenström, M., & Hansson, B. (2012). Laser induced breakdown spectroscopy for fast elemental analysis and sorting of metallic scrap pieces using certified reference materials. Spectrochimica Acta Part B: Atomic Spectroscopy, 74, 46–50.
Gurusamy, S., & Thangam, R. S. P. (2023). Potential health risk assessment of contaminants in soil-like material recovered from landfill mining. Environmental Monitoring and Assessment, 195(2), 330.
Hariyani, D., Hariyani, P., Mishra, S., & Sharma, M. K. (2025). A literature review on waste management treatment and control techniques. Sustainable Futures, 9, 100728.
Hernandez Parrodi, J. C., Lucas, H., Gigantino, M., Sauve, G., Esguerra, J. L., Einhaupl, P., Vollprecht, D., Pomberger, R., Friedrich, B., & Van Acker, K. (2019). Integration of resource recovery into current waste management through (enhanced) landfill mining. Detritus, 8, 141–156.
Hogland, W., Hogland, M., & Marques, M. (2011). Material recovery, energy utilization and economics of landfill mining in the EU (directive) perspective. Proceedings of "Sustainable Solid Waste Management In Eastern Europe-Prospects For The Future.
Huang, Z., Zhu, J., Wu, X., Qiu, R., Xu, Z., & Ruan, J. (2021). Eddy current separation can be used in separation of non-ferrous particles from crushed waste printed circuit boards. Journal of Cleaner Production, 312, 127755.
Hull, R. M., Krogmann, U., & Strom, P. F. (2005). Composition and characteristics of excavated materials from a New Jersey landfill. Journal of environmental engineering, 131(3), 478–490.
Igwegbe, C. A., López-Maldonado, E. A., Landázuri, A. C., Ovuoraye, P. E., Ogbu, A. I., Vela-García, N., & Białowiec, A. (2024). Sustainable municipal landfill leachate management: Current practices, challenges, and future directions. Desalination and Water Treatment, 100709.
Institute, C. R. (2025). Improving Efficiency and Sustainability in Aluminum Beverage Can Recycling, January 2025
Institute, T. A. A. a. C. M. (2024). The Aluminum Can Advantage:
Sustainability Key Performance
Indicators
Jain, M., Kumar, A., & Kumar, A. (2023). Landfill mining: A review on material recovery and its utilization challenges. Process Safety and Environmental Protection, 169, 948–958.
Johansson, N., Krook, J., & Eklund, M. (2017). The institutional capacity for a resource transition—A critical review of Swedish governmental commissions on landfill mining. Environmental Science & Policy, 70, 46–53.

Johansson, O., & Pettersson, M. (2022). Environmental law issues in connection with landfill mining. Detritus, 18, 77–84.
Jones, P. T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., & Hoekstra, N. (2013). Enhanced Landfill Mining in view of multiple resource recovery: a critical review. Journal of Cleaner Production, 55, 45–55.
Kannan, E., Yuvarani, B., Sanjaykumar, S., Tamilvanan, T., Vasanth, J., & Manikandan, S. (2025). A High Efficient and Cost Effective Waste Sorting Solution using Advanced Sensors and AI. 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM),
Kelly, S., & Apelian, D. (2016). Automotive aluminum recycling at end of life: a grave-to-gate analysis. Worcester Polytechnic Institute.
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221–232.
Kostakis, I., Halkos, G., & Sardianou, E. (2025). Sustainability in municipal waste recycling: An empirical investigation of economic and institutional determinants. Global Economics Research, 100018.
Krook, J., & Baas, L. (2013). Getting serious about mining the technosphere: a review of recent landfill mining and urban mining research. Journal of Cleaner Production, 55, 1–9.
Krook, J., Svensson, N., & Eklund, M. (2012). Landfill mining: A critical review of two decades of research. Waste Management, 32(3), 513–520.
Kulas, D., Amponsah-Berko, D., Eisele, T., & Handler, R. Landfill Mining for Aluminum and Copper Recovery: An Economic and Environmental Feasibility Study. 2025 AIChE Annual Meeting,
Lawal, S. O. (2024). The economics of recycling: A review compiled with tax and subsidiary, implication for government, decision-makers, enterprises, community, and analysis cost/benefit and market. ASEAN Journal of Economic and Economic Education, 3(2), 165–188.
Lee, H., Coulon, F., & Wagland, S. (2023). The influence of humic acid on metal (loid) s leaching in landfill leachate for enhancing landfill mining. Science of the Total Environment, 896, 165250.
Li, Y., Yue, Q., He, J., Zhao, F., & Wang, H. (2020). When will the arrival of China's secondary aluminum era? Resources Policy, 65, 101573.
Lindstrom, S. (2024). Transitioning to a Circular Economy: Evaluating National Waste Management Policies. Future-Environmental Policy and Sustainable Development, 1(2).
Lucas, H. I., López, C. G., Parrodi, J. C. H., Vollprecht, D., Raulf, K., Pomberger, R., Pretz, T., & Friedrich, B. (2019). Quality assessment of nonferrous metals recovered by means of landfill mining: A case study in Belgium. Detritus, 8(December), 79–90.
Martin, J. W., Stark, T. D., Thalhamer, T., Gerbasi-Graf, G. T., & Gortner, R. E. (2013). Detection of aluminum waste reactions and waste fires. Journal of Hazardous, Toxic, and Radioactive Waste, 17(3), 164–174.
Miteva, A., & Hodjaoglu, G. Applications of Recycled Aluminum in the Modern Food Industry. Resources, Conservation and Recycling, 114, 18–31.
Morawski, C. (2010). Single stream uncovered. Resource Recycling, 21–25.
Munshi, B. ELYSIS™ Inert-Anode Aluminium Smelting: Electrochemistry, Scale-Up, and the India Adoption Pathway.
Mutz, S., Chatziavgoustis, T., & Pretz, T. (2005). Sorting of aluminum and its alloys within the European automobile recycling. Proceedings of 5th International Exhibition & Conference on Environmental Technology, Athens Greece, 3-6 February, C81,
Padamata, S. K., Yasinskiy, A., & Polyakov, P. (2021). A review of secondary aluminum production and its byproducts. Jom, 73(9), 2603–2614.
Parrodi, J. C. H., Höllen, D., & Pomberger, R. (2018). Potential and main technological challenges for material and energy recovery from fine fractions of landfill mining: A critical review. Detritus, 3(september 2018), 19–29.
Pecorini, I., & Iannelli, R. (2020). Characterization of excavated waste of different ages in view of multiple resource recovery in landfill mining. Sustainability, 12(5), 1780.
Pereira, A. C. (2025). From can to sheet: A critical review of aluminum can recycling processes, technologies, and sustainability dimensions (2020–2025). Revista FT, 10(2), 1026–1019.
Pourbaix, M. (1974). Atlas of Electrochemical Equilibria in Aqueoes Solution (N. A. o. C. Engineers, Ed. 2 ed.). National Association of Corrosion Engineers.
Quaghebeur, M., Laenen, B., Geysen, D., Nielsen, P., Pontikes, Y., Van Gerven, T., & Spooren, J. (2013). Characterization of landfilled materials: screening of the enhanced landfill mining potential. Journal of Cleaner Production, 55, 72–83.
Quinn, E. Circular economy and the potential for extended producer responsibility policies.
Raabe, D. (2023). The materials science behind sustainable metals and alloys. Chemical reviews, 123(5), 2436–2608.
Rabinovich, D. (2013). The allure of aluminium. Nature Chemistry, 5(1), 76–76.
Ratcliffe, A., Prent, O., & van Vossen, W. (2012). Feasibility of material recovery from landfills (MFL) in the European Union. The ISWA World Waste Congress,
Recovery, U. S. E. P. A. O. o. R. C. a. (2014). Municipal Solid Waste Generation,Recycling, and Disposal in the United States: Facts and Figures. A methodology Document
Saevarsdottir, G., & Kvande, H. (2025). Development of the Carbon Footprint of Primary Aluminum Production. TMS Annual Meeting & Exhibition,
Sariatli, F. (2017). Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. Visegrad Journal on Bioeconomy and Sustainable Development, 6(1), 31–34.
Shapiro, M., & Galperin, V. (2005). Air classification of solid particles: a review. Chemical Engineering and Processing: Process Intensification, 44(2), 279–285.
Shen, A., & Zhang, J. (2024). Technologies for CO2 emission reduction and low-carbon development in primary aluminum industry in China: A review. Renewable and Sustainable Energy Reviews, 189, 113965.
Silveira, A., Cella, M., Tanabe, E., & Bertuol, D. (2018). Application of tribo-electrostatic separation in the recycling of plastic wastes. Process Safety and Environmental Protection, 114, 219–228.
Smith, Y. R., Nagel, J. R., & Rajamani, R. K. (2019). Eddy current separation for recovery of non-ferrous metallic particles: A comprehensive review. Minerals Engineering, 133, 149–159.
Söderholm, P., & Ekvall, T. (2020). Metal markets and recycling policies: impacts and challenges. Mineral Economics, 33(1), 257–272.
Stark, T. D., Martin, J. W., Gerbasi, G. T., Thalhamer, T., & Gortner, R. E. (2012). Aluminum waste reaction indicators in a municipal solid waste landfill. Journal of geotechnical and geoenvironmental engineering, 138(3), 252–261.
Staub, C. (2020). Equipment upgrades drive greater UBC recovery
Tabereaux, A. T., & Peterson, R. D. (2024). Aluminum production. In Treatise on process metallurgy (pp. 625–676). Elsevier.
Taelman, S. E., Tonini, D., Wandl, A., & Dewulf, J. (2018). A holistic sustainability framework for waste management in European cities: Concept development. Sustainability, 10(7), 2184.
Thakur, V., & Kalra, S. (2026). Approaches to Extended Producer Responsibility: Fostering Sustainable Consumption and Circular Economy. In Green Horizons: Advancing Climate Solutions Through Green Finance, Circular Economy, and ESG (pp. 291–316). Springer.
Trushna, T., Krishnan, K., Soni, R., Singh, S., Kalyanasundaram, M., Annerstedt, K. S., Pathak, A., Purohit, M., Lundbog, C. S., & Sabde, Y. (2024). Interventions to promote household waste segregation: A systematic review. Heliyon, 10(2).
Van Passel, S., Dubois, M., Eyckmans, J., De Gheldere, S., Ang, F., Jones, P. T., & Van Acker, K. (2013). The economics of enhanced landfill mining: private and societal performance drivers. Journal of Cleaner Production, 55, 92–102.
van Vossen, W., & Prent, O. (2013). Feasibility study sustainable material and energy recovery from landfills in Europe. ISTANBUL3WCONGRESS 2013, 347.
Veit, H. M., Diehl, T. R., Salami, A. P., Rodrigues, J. d. S., Bernardes, A. M., & Tenório, J. A. S. (2005). Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste management, 25(1), 67–74.
Velenturf, A. P., & Purnell, P. (2017). Resource recovery from waste: Restoring the balance between resource scarcity and waste overload. Sustainability, 9(9), 1603.
Vermeşan, H., Tiuc, A.-E., & Purcar, M. (2019). Advanced recovery techniques for waste materials from IT and telecommunication equipment printed circuit boards. Sustainability, 12(1), 74.
Vollprecht, D., Machiels, L., & Jones, P. T. (2021). The EU training network for resource recovery through enhanced landfill mining—A review. Processes, 9(2), 394.

Wagner, T. P., & Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. Waste management, 45, 448–457.
Wang, J., Shi, A., Yue, D., Wang, C., Liu, Y., & Shi, Y. (2024). Resources Recovery from Landfill Leachate: Current Status, Challenges, and Prospects. A Review of Landfill Leachate: Characterization Leachate Environment Impacts and Sustainable Treatment Methods, 215–238.
Wen, J., Yu, W., Yuan, H., Chen, H., Xiong, T., & Yang, F. (2024). A new strategy for extracting aluminum and iron from red mud via vacuum thermal reduction, alkali-leaching and magnetic separation. Journal of Cleaner Production, 485, 144409.
Wen, P., Li, X., Shi, G., Wang, Z., & Ma, Z. (2025). Age and hydrogeological conditions of landfill site control groundwater pollution in landfill site. Waste management, 208, 115171.
Wilts, H., Von Gries, N., & Bahn-Walkowiak, B. (2016). From waste management to resource efficiency—The need for policy mixes. Sustainability, 8(7), 622.
Xia, Y., He, P., Shao, L., & Zhang, H. (2017). Metal distribution characteristic of MSWI bottom ash in view of metal recovery. Journal of Environmental Sciences, 52, 178–189.
Zhou, C., Gong, Z., Hu, J., Cao, A., & Liang, H. (2015). A cost-benefit analysis of landfill mining and material recycling in China. Waste Management, 35, 191–198.