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LANDFILL MINING FOR INTEGRATED RESOURCE RECOVERY: FIELD-SCALE WASTE CHARACTERIZATION WITH EMPHASIS ON ALUMINUM PERSISTENCE, CORROSION, AND RECOVERABILITY

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ABSTRACT

Aluminum is a critical industrial material with high recyclability, yet significant quantities are lost to municipal solid waste (MSW) landfills due to inefficient collection and sorting. This study evaluates landfill waste composition and examines aluminum persistence, corrosion behavior, and recoverability as part of an integrated resource recovery assessment through field-scale excavation and laboratory-scale simulations at the Marquette County Solid Waste Management Authority (MCSWMA) landfill. A total of 208 kg (dry weight) of excavated waste was sieved at 7 mm, yielding 67.4 wt.% fines and 32.58 wt.% coarse fraction. Manual sorting identified plastics (7.28 wt.%), wood (6.26 wt.%), and stones (11.03 wt.%) as major fractions alongside metals (2.34 wt.%), with aluminum at 0.43 wt.%. The combustible fraction (17.66 wt.%) presents potential for refuse-derived fuel production, while inert materials (~12.4 wt.%) are suitable for secondary aggregate reuse, together supporting a multi-stream recovery framework. Approximately 40% of recovered aluminum displayed surface corrosion, primarily affecting foils, while most beverage cans retained metallic integrity. Barrel-scale simulations and SEM-EDS analysis were consistent with the finding that uncoated foils are highly susceptible to corrosion through oxide formation and organic surface contamination, while coated cans largely persist in metallic form. All field data derive from a single sampling point and barrel experiments represent a simplified analog; conclusions are therefore site-indicative rather than site-wide. The findings indicate that while standalone aluminum recovery is economically insufficient at this concentration, integration within a multi-resource recovery framework — combining metals, combustibles, and inerts — presents a viable pathway toward circular economy objectives.

1. INTRODUCTION

Aluminum stands as a cornerstone material in modern industries, indispensable across sectors such as transport, construction, electrical applications, and packaging. Its unique properties, including lightweight strength and corrosion resistance, make it a preferred choice for numerous applications (Dey, 2025). However, the production of aluminum carries a significant environmental footprint, particularly from primary extraction and smelting. Primary aluminum production from bauxite ore accounts for approximately 2% of global greenhouse gas (GHG) emissions and consumes about 3% of the world's electricity demand, with a substantial portion of this energy derived from fossil fuels (Hasanbeigi et al., 2022). This reliance on energy-intensive primary production presents a fundamental challenge, and there is an urgent need for a paradigm shift in how aluminum is produced and managed.

Aluminum production follows two pathways: primary extraction from bauxite ore and secondary production through recycling (Padamata et al., 2021). Secondary production requires only about 5% of the energy of primary smelting, yielding roughly 95% energy savings and substantial emission reductions, while avoiding the land disturbance and process-water demands of primary refining (Jirang & Roven, 2010). Economically, recycled aluminum possesses considerable market value, generating revenue and reducing waste disposal costs for businesses and mu-

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nicipalities (Das et al., 2010). The price of aluminum scrap ranges between $0.10-$1.50 per pound, depending on quality and form (Monster, 2024). It is estimated that recycling all aluminum beverage cans in the United States (U.S.) could save the economy over $1 billion annually (missed revenue opportunity) (Association, 2023). The transformative potential of a circular economy approach for aluminum is therefore immense.

While aluminum is theoretically infinitely recyclable, current waste management practices, particularly for post-consumer products, result in a significant loss of valuable material to landfills (Stark et al., 2012). This inefficiency is driven by systemic issues such as contamination from organics and inadequate collection and sorting infrastructure.

In the United States, MSW generation reached approximately 292.4 million tons in 2018, with metals comprising 8.8% of the total waste stream (EPA, 2020). Aluminum containers and packaging alone accounted for approximately 1.9 million tons, of which more than 52% was landfilled, representing an estimated economic loss exceeding $800 million annually (this figure represents the estimated economic value of aluminum containers and packaging landfilled in the U.S. in 2018, based on Aluminum Association estimates of material value). Recycling rates for aluminum beverage cans have declined in recent years, from 50.4% in 2018 to approximately 45.2% today. While improving upstream recycling remains a priority, these statistics indicate that large quantities of aluminum are already buried in landfills, prompting interest in landfill mining as a potential secondary recovery pathway (EPA, 2020).

Landfill mining aims to excavate and process buried waste to recover valuable materials, reduce long-term environmental liabilities, and reclaim landfill capacity (Krook & Baas, 2013). Aluminum is widely regarded as a promising target for landfill mining because of its perceived corrosion resistance and high recycling value (Wagner & Raymond, 2015). However, the feasibility of aluminum recovery from landfilled waste remains poorly constrained. Aluminum persistence and recoverability are strongly influenced by site-specific factors such as waste composition, burial depth, moisture content, and, critically, the form and surface treatment of aluminum products. Moreover, landfill mining operations must contend with high proportions of fine material, material heterogeneity, and contamination, all of which directly affect screening efficiency, separation performance, and economic viability.

In landfill mining operations, aluminum does not exist in isolation but is embedded within a heterogeneous waste matrix composed primarily of plastics, combustibles (paper, textiles, wood), glass, and fine organic-rich material. The relative abundance and physical characteristics of these materials strongly influence excavation efficiency, screening performance, and the effectiveness of downstream separation processes. High proportions of fines and plastics can reduce recovery yields by increasing material handling costs and contaminating recyclable fractions. Consequently, evaluating aluminum recovery potential requires not only an assessment of aluminum persistence and corrosion, but also a site-specific understanding of overall waste composition and material fractionation behavior. Sections 3.4 and 3.5 present the comprehensive waste characterization that provides this essential contextual foundation.

Most existing studies on aluminum behavior in landfills rely on generalized MSW composition models (Calder & Stark, 2010; Stark et al., 2012). While these approaches provide valuable insights into corrosion mechanisms and material transformation processes, they offer limited guidance for landfill mining decision-making, where operators must assess whether excavation, screening, and material separation can yield sufficient quantities of recoverable aluminum to justify operational and economic costs (Jones et al., 2013; Krook et al., 2012; Tian et al., 2025). Laboratory studies often fail to capture the heterogeneity and aging effects present in landfills, while composition-based models do not adequately reflect material accessibility or recoverability (Tian et al., 2025). Previous work has established that aluminum corrosion in landfill environments is form-dependent, and that coated products exhibit greater persistence than uncoated foils (Calder & Stark, 2010; Stark et al., 2012). However, these findings have largely been derived from controlled laboratory conditions or inferred from composition models rather than from direct field excavation at known burial depths. Studies such as Lucas et al. (Lucas et al., 2019) have examined the refining of landfill-recovered aluminum scrap from European sites, and Almoiqli et al. (Almoiqli et al., 2023) have characterized the corrosion behavior of coated aluminum cans under simulated conditions; yet direct, field-derived evidence linking aluminum product form, corrosion state, and waste fractionation within a single site-specific investigation remains scarce, particularly for North American landfills operating under bottle-deposit and single-stream recycling regimes. As a result, there remains a lack of field-based, site-specific investigations that directly link aluminum corrosion behavior, material form, and waste fractionation to practical recovery feasibility under realistic landfill mining conditions. The novelty of the present work lies specifically in combining direct field excavation at a known burial depth with controlled barrel-scale simulation and SEM-EDS surface characterization within a single site-specific investigation — an approach not previously applied, in literature, to a North American landfill operating under bottle-deposit and single-stream recycling conditions.

To address this gap, the present study evaluates the persistence, corrosion behavior, and recovery potential of aluminum within the MCSWMA landfill, an active MSW landfill in the Upper Peninsula of Michigan. The study integrates field-scale excavation conducted during landfill gas well drilling with laboratory-scale simulated landfill experiments to assess aluminum degradation under both real-world and controlled conditions. Aluminum abundance, product form, and corrosion state are characterized at burial depths of 70-100 ft, providing rare field-derived data relevant to landfill mining assessments. Given the single-point sampling strategy and simplified barrel simulation, the findings are interpreted as site-indicative evidence, with implications discussed in the context of broader landfill mining feasibility rather than as definitive site-wide characterizations.

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2. MATERIALS AND METHODS

2.1 Site Description

The MCSWMA is a state-permitted regional solid waste management site located in Sands Township, Michigan (Authority, 2024a). Established in 1988 as a response to the closure of numerous unlicensed and unlined landfills across Michigan's Upper Peninsula, the Authority operates under an Intergovernmental Agreement representing all 23 municipalities within Marquette County. The landfill officially commenced operations in late December 1989.

As of December 31, 2024, a cumulative total of 2,081,474 tons of non-hazardous MSW has been placed in the landfill. The facility currently manages both Type II (household) and Type III (construction and demolition) waste, receiving a total of 105,368.24 tons during the 2024 calendar year. The average daily tonnage for 2024 was approximately 414.84 tons, representing a significant increase from previous years due to large-scale demolition projects, including the former Marquette General Hospital and structures at the K.I. Sawyer Air Force Base. Waste placement follows a systematic process in which incoming materials are spread by bulldozers, compacted to reduce volume, and covered at the end of each operating day with a soil layer.

The landfill occupies a 210-acre site with approximately 47 years of projected capacity remaining. It incorporates engineered systems for daily waste placement, compaction, interim cover, leachate collection, and gas management. In 2024 alone, 13,047,000 gallons of leachate were collected and treated on-site.

MCSWMA also operates a materials recovery facility (MRF) and implements a range of diversion programs, including single-stream recycling, household hazardous waste collection, scrap tire processing, and composting. The facility received 7,038 tons of recyclables in 2024, with over 40% sourced from outside Marquette County (AUTHORITY, 2024b). Despite ongoing efforts to recover valuable resources through the MRF, a significant quantity of recyclable materials was landfilled prior to the MRF installation.

MCSWMA was selected as the study site following unsuccessful attempts to obtain waste from other landfills. Access to materials from alternative facilities was restricted due to stringent environmental and safety regulations, which limited the handling of MSW for research purposes. MCSWMA offered a feasible and controlled source of landfill material, allowing the study to conduct both field-scale excavation and laboratory-scale investigations.

2.2 Drilling

In December 2024, MCSWMA initiated drilling operations on the active landfill site to install gas extraction wells for the purpose of methane recovery. Drilling was conducted using a CZM EK125 heavy-duty cylinder-crowd rotary drilling rig (Figure 1a). During the drilling process, waste material samples were collected from depths ranging between 70 and 100 feet (Figure 1b). The exact sampling intervals were determined by the facility operator; the research team did not control the specific depth increments. A total of twenty 5-gallon buckets were used to collect waste samples from a single well (Figure 1c). Sampling was performed manually using shovels, with material placed directly into the buckets for subsequent waste characterization analysis.

2.2.1 Waste age and burial history

The MCSWMA landfill commenced operations in December 1989, meaning that buried waste has been in place for periods ranging from a few years (in recently active cells) to over 35 years at the time of sampling. Drilling for gas extraction wells targets older, more degraded zones where sufficient organic decomposition has occurred to generate extractable methane. The samples collected during this study are therefore expected to represent relatively mature landfill material. This inference is supported by direct physical evidence recovered during manual sorting: several items bearing dates from the 1990s were recovered from the excavated material, including newspapers, calendars, and product packaging with visible manufacturing or expiry dates from that decade. The presence of these 1990s-dated items suggests that the sampled material was deposited during the first decade of the landfill's operation, corresponding to approximately 25-35 years of burial at the time of sampling (2024). This is consistent



FIGURE 1: (a) CZM EK125 drilling rig employed for well drilling; (b) waste materials retrieved from depths of 70 to 100 feet during drilling operations; and (c) waste samples stored in twenty 5-gallon buckets for subsequent processing.

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with the extensive fines generation (67.4 wt.%) and advanced corrosion of susceptible materials observed in the samples, both of which are characteristic of aged landfill material. The depth interval of 70-100 ft is indicative of mature waste zones, and the presence of 1990s-dated materials in the recovered waste provides direct chronological evidence supporting this interpretation.

2.2.2 Sampling representativeness

All samples were collected from a single gas extraction well at a fixed spatial location within the landfill footprint. The twenty 5-gallon buckets were filled sequentially as drill cuttings emerged, providing a composite vertical sample across the 70-100 ft depth interval. A total of 266 kg (wet weight) of waste material was recovered across all buckets, representing the full composite sample analyzed in this study. While this approach does not allow for depth-stratified sampling, the sequential bucket-filling method provided a composite representation of material encountered within that interval. It is acknowledged that a single borehole in a 210-acre facility cannot be considered fully representative of the entire landfill inventory. Spatial variability in waste composition, compaction history, and hydrological conditions may produce local concentrations or depletions of aluminum that differ from the values reported here. This limitation is discussed further in Section 4.

2.3 Processing of waste samples

The twenty buckets were processed in batches. The waste sample from each bucket was first weighed and dried in a Blue-M laboratory oven at 70°C for 48 hours. After drying, the moisture content was determined by calculating the difference between the wet and dry mass expressed as a percentage. Each dried sample was manually screened using a 7 mm sieve mesh. Materials >7 mm were categorized as the coarse fraction, while materials <7 mm were categorized as the fine fraction. This mesh size was selected to separate soil particles from landfilled materials, thereby facilitating sorting and recovery (Zhang et al., 1998).



FIGURE 2: Hand-sorting of the coarse fraction (>7 mm) performed to quantify and classify the material composition of each waste sample.

Following manual sieving, the coarse fraction was hand-sorted (Figure 2), and the material composition was determined. Materials were grouped into the sub-fractions shown in Figure 3 (paper/cardboard, plastics, textiles, wood, ferrous metal, aluminum, stones, copper, ceramic, and glass). A small rubber fraction (0.19 wt.%) was also separated and is reported in Table 1. Individual sub-fractions were weighed and recorded. A schematic representation of the sample treatment process is presented in Figure 3. A total of 67.8 kg of coarse fraction material was manually sorted.

Recovered aluminum from the hand-sorting process was visually inspected to assess surface oxidation. Samples were categorized as corroded or non-corroded based on the following operational criteria: (i) presence or absence of a continuous metallic luster; (ii) evidence of pitting, surface discoloration, or powdery oxide deposits; and (iii) the estimated fraction of surface area affected. No quantitative criteria, such as minimum oxide layer thickness, minimum affected surface area percentage, or

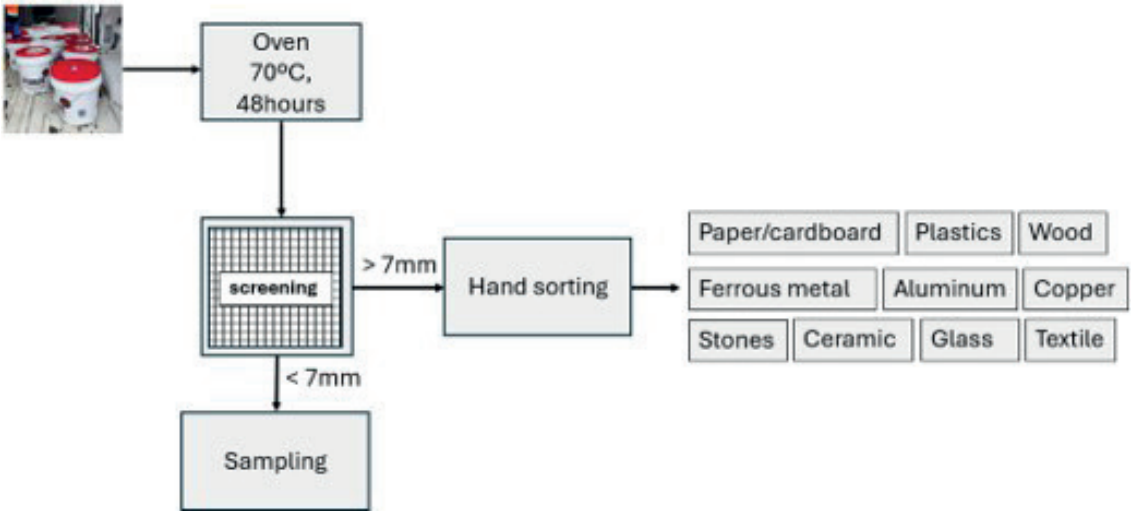


FIGURE 3: Process flow diagram for the processing of waste samples obtained from MCSWMA.

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image analysis, were defined prior to sorting. Gravimetric mass loss measurements, surface roughness analysis, or oxide layer thickness measurements were not performed. Inter-observer repeatability was not assessed. This visual classification approach introduces inherent subjectivity, and the reported corrosion fractions (approximately 40% at MCSWMA; approximately 50% of foils in the barrel experiment) should be interpreted as descriptive visual estimates without statistical uncertainty bounds. The visual approach was selected as a practical, operationally straightforward method appropriate for the study's primary objective: to assess whether recoverable metallic aluminum persists in landfill environments and to identify which product forms are most likely to remain recyclable.

2.4 Simulation of landfill conditions using barrel experiment

Aluminum can undergo oxidation in landfills, which diminishes its suitability for recycling (Calder & Stark, 2010; Stark et al., 2012). The stability of metallic aluminum in landfill environments is not well understood; this study therefore investigates its corrosion behavior under simulated conditions.

Two barrel-scale experiments, each with a capacity of 200 liters as shown in Figure 4c, were conducted to replicate the moisture content, limited oxygen availability, and waste composition typical of landfilled MSW. It should be noted that the barrels did not include the daily soil cover layer applied during standard landfill operations, a deliberate simplification whose implications for internal redox conditions are discussed below. The objective was to assess the extent of aluminum degradation over a six-month period and determine the potential for recovering recyclable metallic aluminum from aged landfill materials. MSW samples were obtained from the Houghton County Materials Management Facility in Michigan, USA. The selected waste consisted primarily of household materials representative of typical landfilled streams. Samples were initially collected in seven waste bags; however, the aluminum content of the as-collected waste was relatively low. To ensure sufficient interaction between aluminum and the simulated landfill environment, additional aluminum in the form of foil and beverage cans was incorporated: 0.60 kg to barrel 1 and 0.30 kg to barrel 2 as shown in Figure 4a and 4b. The combined mass of waste and water in barrel 1 was 28.4 kg and in barrel 2 was 14.9 kg, yielding effective aluminum loadings of approximately 2.1 wt.% and 2.0 wt.% respectively. These values are broadly representative of aluminum concentrations reported in fresh MSW in the United States and were approximately five times higher than the 0.43 wt.% measured in the field excavation (EPA, 2020). The implications of this concentration difference for the comparability of corrosion environments are addressed in Section 3.3.4. The difference in total waste masses between barrels resulted from the allocation of seven waste bags (four to barrel 1, three to barrel 2); individual bag weights were not measured prior to allocation. Accordingly, results from the two barrels are treated as a



FIGURE 4: Aluminum materials and experimental setup used in the barrel simulation study: (a) aluminum foil, (b) aluminum beverage cans, (c) two 55-gallon barrels used for landfill simulation, and (d) air-drying of barrel contents prior to aluminum recovery and inspection.

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TABLE 1: Material composition of waste samples recovered from MCSWMA, determined through manual sorting of the coarse fraction (>7 mm). All values are reported on a dry weight percentage (wt.%) basis.

Materials composition	Paper & cardboard	Plastics	Rubber	Textiles	Wood	Metals	Glass	Stones	Ceramic	Fines
Amount (wt.%)	1.42	7.28	0.19	2.70	6.26	2.34	1.00	11.03	0.36	67.42

combined qualitative trend rather than as independently controlled replicates. Waste samples, including the supplemental aluminum fractions, were loaded into each barrel and compacted manually using metal rod; compaction density was not measured. Water was added at 25% by mass (w/w) to replicate moisture conditions typical of municipal landfills. The barrels were then loosely sealed using fitted lids to allow limited pressure equalization, mimicking the semi-aerobic to anaerobic transition conditions found in landfills. No additional nutrients, inoculants, or leachate were introduced, so that the simulation reflected the natural decomposition environment as closely as practical. The barrel experiment was designed as a complementary, controlled analog to the field excavation, not as a substitute for comprehensive analysis of field samples. The field samples provided the primary evidence of long-term corrosion; the barrel experiment was intended to provide comparative information on differential corrosion susceptibility under simplified, observable conditions. A six-month barrel experiment cannot directly replicate the 35+ years of burial represented by the MCSWMA field samples. The absence of daily soil cover means that oxygen availability during the simulation likely exceeded that in a real landfill cell, potentially accelerating early-stage aerobic corrosion of aluminum foils while underrepresenting the anaerobic alkaline-corrosion regime that may dominate in deeper mature waste zones. The six-month duration was selected as a practical constraint for an initial qualitative assessment; it was not intended to replicate the full 35-year burial period but rather to observe early-stage corrosion processes under controlled conditions that could be compared with the advanced corrosion observed in the field samples. The inherent limitations, including differences in temperature (room temperature vs. landfill internal temperatures), pressure (atmospheric vs. overburden pressure), leachate flow (static vs. dynamic), and microbial community development—are acknowledged. The barrel results are therefore interpreted as qualitatively consistent with field observations rather than as quantitatively predictive of long-term corrosion rates.

The barrels were left undisturbed at room temperature for six months, with no mechanical agitation or leachate removal during this period. It is noted that the barrel experiment was initiated prior to the field excavation campaign and concluded after field samples were collected; the two components of the study are complementary, and this timing difference does not affect the interpretation of results. At the end of the experiment, the barrels were opened, materials were air-dried as shown in Figure 4d, and aluminum components were recovered, cleaned, and physically inspected for signs of oxidation and degradation using the same operational criteria applied to the field-sorted material.

3. RESULTS AND DISCUSSION

3.1 Composition of excavated waste

A total of 266 kg (wet weight) of recovered waste yielded 208 kg (dry weight) after oven drying, corresponding to a bulk moisture content of 22.2 ± 5.2%. Sieving at 7 mm produced a fines fraction (<7 mm) of 67.42 wt.% and a coarse fraction (>7 mm) of 32.58 wt.%.The dominance of fines reflects the typical characteristics of aged landfills, resulting from prolonged physicochemical degradation, microbial activity, mechanical compaction, and incorporation of daily cover soil. This fines-rich composition aligns with findings from previous landfill mining (LFM) investigations, including those by Kaartinen et al (Kaartinen et al., 2013) and Quaghebeur et al. (Quaghebeur et al., 2013), both of which reported that fine materials typically exceed 50% by weight in mature landfill sites. Additional fine fraction characterization studies have similarly documented the dominance of fines in aged MSW landfills, attributing this to advanced organic degradation and the progressive disintegration of inorganic matrices under prolonged burial conditions (López et al., 2018; Parrodi et al., 2018).

The coarse fraction (>7 mm) was manually sorted and classified into distinct material categories as detailed in Table 1. All values are expressed as a percentage of the total dried waste mass.

3.2 Recovered metals from the coarse fraction

Metals constituted 2.34 wt.% of the total dried waste mass, comprising both ferrous and non-ferrous fractions (Table 1). Following manual recovery of all metallic items, a bar magnet was used to separate ferrous metals from the non-ferrous fraction. The separation results indicated that ferrous metals formed the dominant category (1.88 wt.%), followed by aluminum, with copper being the least abundant (Figure 5). This is consistent with observations by Quaghebeur et al. (Quaghebeur et al., 2013).

The recovered ferrous metals included nails, food cans, and various household items. Visual inspection revealed extensive surface corrosion, with most items exhibiting uniform rust layers and pitting (Figure 6). Although corroded ferrous metals retain their magnetic properties and can be recycled through remelting, severe rusting can lower their market value due to increased slag generation, reduced yield, and the additional fluxing required during smelting. This surface corrosion trend is consistent with observations from long-term buried metals in aged landfill environments, where prolonged exposure to moisture accelerates oxidation (Hao, 2020).

Copper was recovered in trace amounts, accounting for 0.03 wt.% of the total dried waste mass. The recovered materials consisted primarily of thin electrical wires, small fragments embedded in plastic insulation, and a copper

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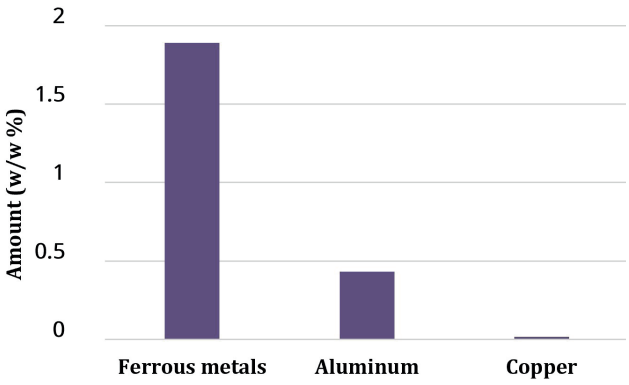


FIGURE 5: Mass distribution of ferrous metals, aluminum, and copper in the coarse fraction (>7 mm) following manual sorting and subsequent magnetic separation. All values are expressed as a percentage of the total dried waste mass.

rod. None of the recovered copper exhibited visible corrosion, reflecting the metal's inherent resistance to oxidation under landfill conditions. While copper has a high intrinsic market value, its recovery from MSW landfills is often limited by its low concentration and occurrence in heterogeneous forms. Insulated wires and embedded fragments typically require mechanical liberation via shredding, followed by physical separation processes. The extremely low concentration observed in this study further limits the standalone economic viability of copper recovery.

Aluminum was recovered at 0.43 wt.% of the total dried waste mass. The aluminum fraction was composed primarily of beverage cans, foils, and structural aluminum fragments (Figure 6d-f). Approximately 40% of the recovered aluminum exhibited corrosion, while the remaining 60% retained a metallic surface suitable for direct recovery and recycling. All recovered aluminum foil was corroded, suggesting that foil is more prone to degradation than other aluminum forms. The low concentration of metallic aluminum in the excavated material significantly limits the economic attractiveness of landfill mining for aluminum recovery at this site, especially given the cost-intensive nature of excavation, screening, and material separation.

3.3 Simulation of landfill conditions: aluminum corrosion behavior

After the waste from the barrels was air-dried, aluminum components were recovered and physically inspected to classify them as corroded or metallic. The results reveal a clear distinction in the corrosion susceptibility of different aluminum forms. Aluminum cans largely remained metallic, showing only minor surface contamination, whereas aluminum foils exhibited visible corrosion, including pitting and surface degradation (Figure 7). 50% of aluminum foils placed in the barrels exhibited signs of corrosion and pitting; the remaining 50% showed no visible surface corrosion. These findings are consistent with the interpretation that the form and surface treatment of aluminum influence its stability under landfill-simulated conditions. The barrel experiment results are qualitatively consistent with MCSWMA field observations: foils were more extensively corroded than cans in both settings.

3.3.1 Corrosion mechanisms in landfill environments

The corrosion mechanisms discussed below are drawn from the established literature on aluminum behavior in landfill environments and are presented as a framework for interpreting the empirical observations from our SEM-EDS analysis.

Stark et al. documented aluminum waste reaction indicators in MSW landfills, identifying hydrogen generation and temperature anomalies associated with aluminum corrosion under alkaline conditions (Stark et al., 2012). Calder and Stark further characterized aluminum reactions

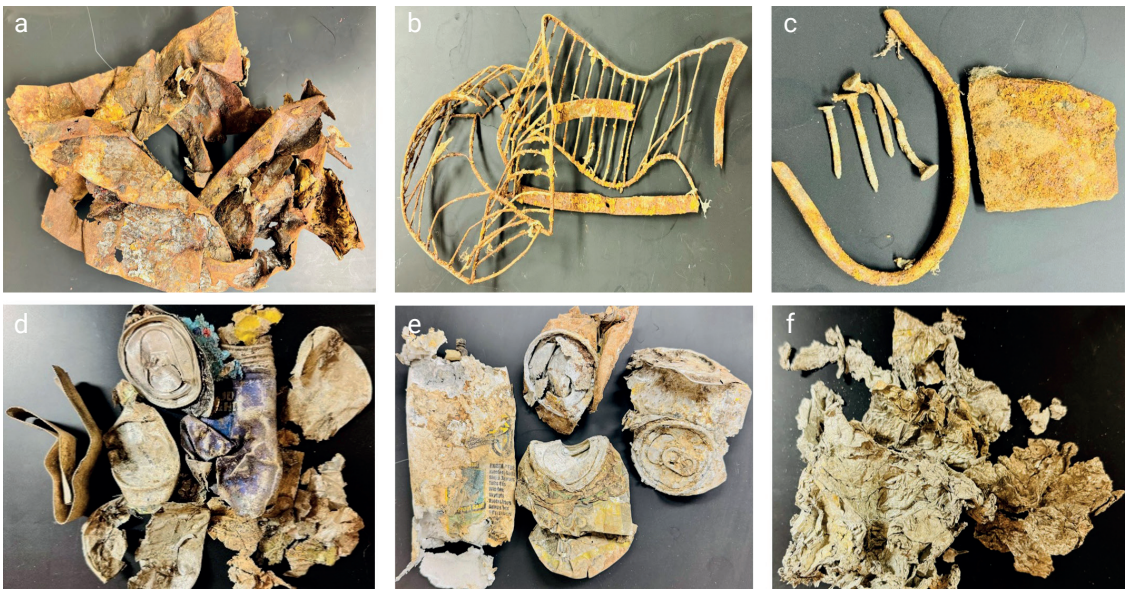


FIGURE 6: Aluminum materials and experimental setup used in the barrel simulation study: (a) aluminum foil, (b) aluminum beverage cans, (c) two 55-gallon barrels used for landfill simulation, and (d) air-drying of barrel contents prior to aluminum recovery and inspection.

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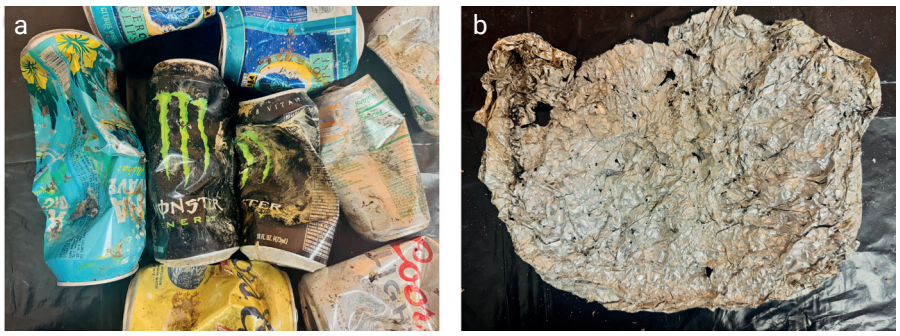


FIGURE 7: Samples of ferrous metals recovered from the coarse fraction exhibiting extensive surface rust: (a) metal sheets, (b) household item, and (c) nails, rod, and metal fragment. Aluminum recovered from the coarse fraction: (d) metallic aluminum, (e) corroded aluminum beverage cans, (f) corroded aluminum foil.

in landfills, noting that the presence of chlorides and elevated pH can accelerate corrosion (Calder & Stark, 2010). Almoiqli et al. (Almoiqli et al., 2023) examined the corrosion behavior of coated aluminum cans under simulated conditions and found that protective coatings significantly enhance corrosion resistance—a finding consistent with our field observations that beverage cans largely retained metallic integrity while uncoated foils were extensively corroded (Almoiqli et al., 2023).

The corrosion of aluminum in MSW landfills involves a complex interplay of electrochemical, chemical, and biological processes occurring across a wide range of evolving environmental conditions. In the early post-disposal phase, when oxygen is still available, aluminum undergoes electrochemical oxidation, forming a passive aluminum oxide (Al_2O_3) or aluminum hydroxide film that provides initial protection. Under neutral to mildly acidic conditions, this passive film is stable, consistent with the general perception of aluminum as corrosion-resistant.

However, as a landfill matures and transitions toward anaerobic conditions, the corrosion environment changes substantially. Chloride ions, sourced from food waste, organic leachate, and degradation products of chlorine-containing polymers, can locally disrupt the passive oxide film, initiating pitting corrosion. More significantly, locally elevated pH arising from alkaline waste constituents or buffering reactions can trigger alkaline corrosion of aluminum. At pH values above approximately 8-9, the passive film dissolves and aluminum reacts directly with water (Calder & Stark, 2010; Stark et al., 2012):

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

This reaction, well-documented in MSW landfill contexts (Calder & Stark, 2010; Stark et al., 2012), produces aluminum hydroxide ($Al(OH)_3$) and hydrogen gas, the latter of which has been associated with anomalous gas production and subsidence in some landfill systems (Stark et al., 2012). Aluminum hydroxide corrosion products may undergo dehydration-driven phase transformations, including conversion of gibbsite to boehmite and subsequent formation of less hydrated aluminum oxide phases at elevated local temperature (van Gog, 2021). These phases represent an irreversible chemical transformation, removing aluminum from the recyclable fraction.

3.3.2 SEM-EDS Analysis and Interpretation

SEM coupled with EDS was employed to examine the surface morphology and elemental composition of aluminum foil samples before and after the six-month barrel experiment. Metallic foil samples from the pre-experiment material and corroded foil samples from the post-experiment recovery were selected for direct comparison. The explicit objective of SEM/EDS characterization was to verify and quantify the visual corrosion classification by providing elemental evidence of oxide formation (elevated oxygen) and organic surface contamination (elevated carbon) on visually corroded samples, and to demonstrate the spatial heterogeneity of corrosion via elemental mapping. Metallic foil samples (pre-experiment) exhibited relatively smooth, homogeneous surface morphology with minimal irregularities (Figure 8a, 8b). EDS analysis (Spectrum 1) revealed a composition dominated by aluminum (95.44 wt.%), with minor carbon (3.72 wt.%) and oxygen (0.84 wt.%) (Table 2), indicating negligible surface oxidation.

In contrast, corroded foil samples (post-experiment) showed significant surface irregularities and heterogeneous contrast in the SEM micrographs, consistent with localized corrosion and pitting (Figure 8c, 8d). EDS analysis (Spectrum 8) indicated substantial changes in surface chemistry, with aluminum content reduced to 39.65 wt.%, accompanied by elevated oxygen (29.65 wt.%) and carbon (28.52 wt.%) (Table 3), as well as trace calcium (2.19 wt.%). The elevated oxygen content is consistent with extensive aluminum oxide or hydroxide formation. The high carbon content — far exceeding the pre-experiment baseline of 3.72 wt.% most likely reflects adsorption or physical entrapment of organic residues from the surrounding waste matrix rather than a sample preparation artifact; the magnitude of the difference substantially exceeds what would be expected from carbon coating applied for SEM conductivity purposes, suggesting that the elevated carbon is predominantly of organic origin. Trace calcium likely reflects contamination from alkaline leachate or cement-containing debris in the waste stream.

It is important to note that EDS analysis provides indirect evidence for oxide formation through elevated oxygen content but cannot distinguish between specific corrosion product phases. This limitation is acknowledged, and

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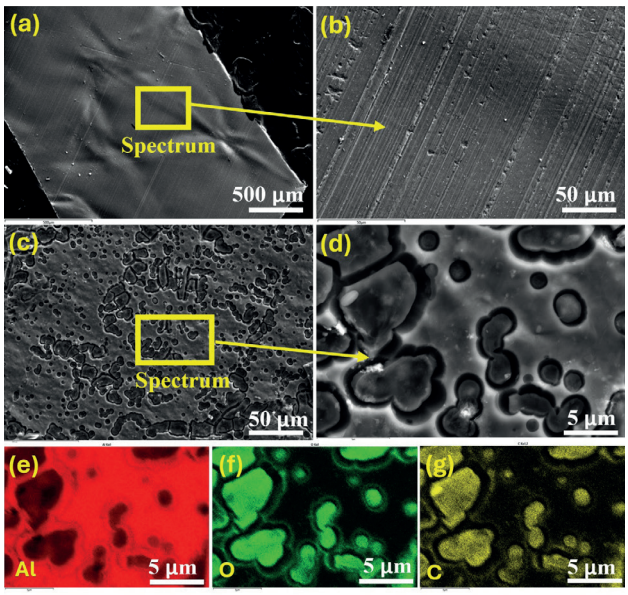


FIGURE 8: SEM images and corresponding EDS elemental mappings of metallic and corroded aluminum foils. (a, b) Metallic aluminum foil showing a smooth, continuous surface at low (scale bar = 500 µm) and high (scale bar = 50 µm) magnification. (c, d) Corroded aluminum foil displaying a rough, pitted surface at low (scale bar = 50 µm) and high (scale bar = 5 µm) magnification. (e–g) EDS elemental maps of corroded regions highlighting the distribution of (e) aluminum, (f) oxygen, and (g) carbon.

XRD or Raman spectroscopy are recommended for future phase-specific characterization.

In this study, the term "metallic" is used operationally to describe aluminum that retains a continuous metallic surface and recoverable metallic core suitable for conventional remelting, rather than implying a completely oxide-free surface. Even visually metallic aluminum surfaces may carry a thin native oxide film; however, such films are routinely dissolved during conventional secondary smelting and do not preclude recyclability.

Elemental mapping (Figure 8e, 8f, 8g) further revealed the spatial distribution of corrosion on the foil. Aluminum was concentrated in discrete, brighter regions corresponding to residual metallic or oxide-rich phases. Oxygen mapping revealed widespread distribution over corroded areas, confirming extensive oxide formation, while carbon mapping highlighted organic-rich deposits covering portions of the foil surface. These results support the point-analysis EDS data and illustrate the heterogeneous, localized nature of corrosion processes in uncoated aluminum foil under landfill-simulated conditions.

Collectively, these findings indicate that aluminum foil undergoes significant chemical transformation and surface contamination in landfill environments, reducing its suitability for recycling. In contrast, coated aluminum forms such as beverage cans retain metallic integrity and represent more promising targets for post-landfill recovery. Although beverage cans are constructed from different aluminum alloys—the body predominantly 3004 alloy (Al-97.8%, Mn-1.2%, Mg-1.0%) and the lid primarily 5182 alloy (Al-95.2%, Mn-0.35%, Mg-4.5%) (Padmanabhan et al., 2011) their recyclability is not fundamentally hindered by these compositional differences.

TABLE 2: EDS quantitative elemental composition (wt.%) of metallic aluminum foil prior to experimental exposure (Spectrum 1). Aluminum is the dominant element, with minor carbon and oxygen.

Elements	C	O	Al
Wt.%	3.72	0.84	95.44

TABLE 3: EDS quantitative elemental composition (wt.%) of corroded aluminum foil after experimental exposure (Spectrum 8). Reduced aluminum content with elevated oxygen and carbon, and trace calcium.

Elements	C	O	Al	Ca
Wt.%	28.52	29.65	39.65	2.19

3.3.3 Differential corrosion: coated vs. uncoated aluminum

The organic coatings applied to the interior and exterior surfaces of aluminum beverage cans, typically epoxy-based lacquers of a few micrometers in thickness, act as a physical barrier between the aluminum substrate and the corrosive landfill environment. This substantially reduces contact with moisture, chloride ions, and organic acids. Corrosion of coated cans under landfill conditions is therefore largely confined to mechanically damaged areas or cut edges, while the bulk of the can body remains metallic.

Uncoated aluminum foil, by contrast, exposes the entire metallic surface area directly to the corrosive environment. With a typical thickness of only 6-25 µm, even shallow pitting or uniform surface corrosion can penetrate the foil entirely. This is consistent with the observation that all recovered foil from the MCSWMA excavation was corroded, whereas beverage cans largely retained metallic integrity.

3.3.4 Approximate mass loss estimation

An approximate mass balance from the barrel experiment helps contextualize the practical significance of foil corrosion. Of the 0.90 kg of aluminum added across both barrels, foil and beverage cans were added in roughly equal proportions by mass. 50% of the foil fraction exhibited visible corrosion, while the can fraction remained largely metallic, implying that approximately 25% of the total added aluminum mass showed corrosion within six months under conditions that likely overestimate early-stage aerobic oxidation. In a real landfill environment, where alkaline corrosion and chloride attack intensify over decades, the proportion of foil aluminum lost to corrosion would be expected to be substantially higher. This reinforces the field observation that the approximately 40% overall corrosion rate in the MCSWMA samples likely underestimates total aluminum lost since initial disposal, as partially degraded foil may have contributed corrosion products to the fine fraction and thus escaped detection during coarse fraction hand-sorting.

3.4 Potential for waste-to-energy recovery

Although not the primary focus of this study, characterizing the combustible fraction is necessary context for the multi-resource recovery framing developed in Section

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5.1, since aluminum recovery alone was found to be economically insufficient to justify excavation at this site. The combustible fraction accounted for over 17 wt.% of the total dry mass, comprising plastics (7.28 wt.%), wood (6.26 wt.%), textiles (2.70 wt.%), and paper and cardboard (1.42 wt.%). These materials possess significant calorific value and present an opportunity for thermal energy generation or refuse-derived fuel (RDF) production. Quaghebeur et al. (Quaghebeur et al., 2013) highlighted the importance of these fractions in RDF production, particularly in scenarios where material recycling is infeasible due to degradation or contamination.

The estimated average energy content of 12-14 MJ/kg for this combined combustible fraction was derived by weighting literature-based calorific values for each sub-fraction by their relative mass proportions within the combustible total (17.66 wt.% of total dry mass). Plastics, predominantly polyolefins and polystyrene, typically exhibit calorific values of 30-40 MJ/kg on a dry basis (Brems et al., 2012; Janáková et al., 2024). Wood and partially degraded textiles yield 10-20 MJ/kg depending on moisture content and degree of degradation (Telmo et al., 2010). Paper and cardboard, at the degradation stage expected in 35-year-old landfill waste, yield approximately 8-12 MJ/kg. Weighing these values by sub-fraction mass proportion (plastics 41.2%; wood 35.4%; textiles 15.3%; paper 8.0%) yields a weighted average of approximately 22 MJ/kg on a fully dry basis. Applying a conservative correction factor for residual moisture and partial cellulosic degradation yields the reported estimate of 12-14 MJ/kg, consistent with calorific data reported for aged MSW combustible fractions in prior LFM studies (Quaghebeur et al., 2013). Effective pre-treatment—mechanical drying and particle size reduction—would be required to approach the upper end of this range.

Plastics possess the highest calorific value among the combustible components, making them suitable for RDF. Nevertheless, their thermal treatment presents environmental concerns due to the potential release of toxic gases from chlorine- or fluorine-containing polymers. Mechanical recycling is preferable where feasible but is often hindered by contamination and polymer degradation after extended burial (Brems et al., 2012; Janáková et al., 2024). Wood and textiles retain meaningful energy content and are more suitable for direct thermal recovery (Telmo et al., 2010).

3.5 Inert fractions and reuse potential

As with the combustible fraction, the inert fraction is characterized here because it directly informs the parallel-stream revenue and cost considerations discussed in Section 5.3-5.4, which are necessary to contextualize the standalone economics of aluminum recovery. Inert components — principally stones (11.03 wt.%), glass (1.00 wt.%), and ceramics (0.36 wt.%) — collectively represent 12.39 wt.% of the total dry waste mass, or approximately 38.0 wt.% of the coarse fraction. These materials are generally not economically viable for conventional recycling due to contamination and mixed composition. However, they can be reused as secondary aggregates for road sub-base, construction fill, or as daily cover material during landfill operations, subject to environmental characterization and regulatory compliance (Masi et al., 2014; Parrodi et al., 2018). The elevated stone and inert content at MCSWMA is consistent with the facility's documented history of receiving demolition waste from large-scale deconstruction projects, including the former Marquette General Hospital and K.I. Sawyer Air Force Base structures, which likely elevated stone and ceramic fractions relative to a typical household MSW stream. Fine fractions from LFM have similarly been characterized as potential secondary aggregates and cover materials when environmental quality criteria are satisfied (Parrodi et al., 2018).

4. STUDY LIMITATIONS

The findings of this study should be interpreted in light of several important methodological limitations.

4.1 Single sampling point and spatial representativeness

All 208 kg (dry weight) of field material was obtained from a single gas extraction well within a 210-acre facility that has received over 2 million tons of waste since 1989. MSW landfills are highly heterogeneous environments: waste composition, compaction density, moisture content, and burial history vary considerably across the facility and with depth. The aluminum content (0.43 wt.%), corrosion state (approximately 40% corroded), and overall waste composition reported here are representative of the specific location and depth interval sampled, but cannot be extrapolated with confidence to the landfill as a whole. Multi-point sampling across the facility, ideally with depth stratification, would be necessary to construct a more reliable facility-wide inventory of recoverable aluminum. This study is therefore best regarded as a preliminary site-specific characterization rather than a comprehensive facility-wide assessment.

4.2 Absence of depth stratification

The sampling depth (70-100 ft) was determined by the facility's gas well installation program, and the research team did not control the exact sampling intervals within this range. Because corrosion intensity is expected to increase with burial depth due to lower redox potential, higher moisture content, and greater overburden pressure, the reported corrosion rates may not be representative of shallower zones within the same facility.

4.3 Barrel experiment simplifications

The barrel experiments represent a simplified analog of landfill conditions. The absence of daily soil cover, the elevated aluminum loading relative to field concentrations (~5 × higher), the short experimental duration (six months) relative to actual burial periods (35+ years), and the unequal design of the two barrels collectively constrain the quantitative interpretation of corrosion rates. The experiment is best interpreted as providing qualitative, comparative evidence of differential corrosion susceptibility between aluminum forms rather than as a predictive model of long-term in-situ degradation.

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4.4 Visual classification of corrosion state

The classification of aluminum as corroded or non-corroded was based on visual inspection. No quantitative criteria (such as minimum oxide layer thickness or minimum affected surface area) were defined prior to sorting, and between-observer variability was not assessed. This introduces subjectivity into the reported corrosion fractions (approximately 40% at MCSWMA; approximately 50% of foils in the barrel experiment), and the absence of error bounds should be noted when comparing these values with other studies. Future investigations should consider standardized quantitative criteria, such as gravimetric mass loss after acid cleaning or image analysis of surface oxide coverage.

4.5 Fine fraction aluminum

Aluminum analysis in this study was restricted to the coarse fraction (>7 mm). Corroded aluminum foil is friable, and its oxide and hydroxide degradation products may migrate into the fine fraction (<7 mm) over prolonged burial. The reported fines fraction (67.4 wt.%) reflects both material that was fine in-situ and material generated by mechanical fragmentation during drilling, transport, drying, and sieving; the proportion attributable to each cannot be distinguished with the present data, which confounds interpretation of any aluminum content subsequently measured in this fraction. This limitation affects the two possible purposes of fine-fraction analysis differently: for tracking the geochemical fate of degraded aluminum, the analysis remains justified regardless of the fragmentation confound; for assessing practical industrial recovery potential, however, the value of such analysis is limited, given the already-low aluminum concentration and advanced degradation state observed in the coarse fraction.

The reported aluminum concentration of 0.43 wt.% should therefore be regarded as a minimum estimate of total aluminum present at the time of initial disposal. A complete mass balance of aluminum across all size fractions would require chemical analysis (e.g., acid digestion and ICP-OES) of the fine fraction, which is recommended for future investigations.

5. IMPLICATIONS FOR RESOURCE RECOVERY

The results from MCSWMA provide practical guidance for landfill mining as a strategy for aluminum and integrated resource recovery. While the overall aluminum content at this site is low, the study offers important insights into how aluminum persists, degrades, and can be selectively targeted during LFM operations.

5.1 Aluminum recovery potential and economic considerations

Field-scale excavation at MCSWMA revealed that aluminum recovery from aged landfill deposits may be heterogeneous and form-dependent. At MCSWMA, aluminum accounted for 0.43 wt.% of the total dried waste mass, with approximately 60% remaining in a metallic state suitable for recycling. The recoverable fraction was dominated by coated aluminum products, particularly beverage cans, whereas uncoated aluminum foils were consistently corroded. This distinction is essential for LFM planning: recovery efforts should target specific product categories rather than bulk metal extraction.

A rough economic estimate illustrates the challenge of standalone aluminum recovery at this concentration. At an aluminum scrap value of approximately $1.10-$2.20 per kg (Monster, 2024), which is consistent with current US secondary market conditions-the recoverable metallic aluminum fraction (~0.26 wt.% of total waste mass, representing ~60% of the 0.43 wt.% total) yields approximately 2.6 kg of recoverable metal per ton of excavated waste. At $1.50/kg, this corresponds to roughly $3.90 per ton in aluminum revenue. Against typical LFM processing costs, which in European and North American case studies have ranged from approximately $40-$158 per ton (operational and capital cost) depending on scale, technology, and site conditions (Krook et al., 2012; Wagner & Raymond, 2015), aluminum recovery alone does not generate a positive economic return at this concentration (Amponsah-Berko et al., 2026). Threshold aluminum concentrations for standalone economic viability have been estimated in the broader LFM literature at approximately 1-2 wt.% in the processed coarse fraction (Krook et al., 2012; Wagner & Raymond, 2015), significantly above the 0.43 wt.% observed at MCSWMA. Aluminum recovery must therefore be integrated within a multi-resource recovery framework to improve economic feasibility at this site. As highlighted by Wagland et al., landfill mining should be considered as an integrated resource recovery strategy, where multiple material streams are recovered simultaneously to improve overall environmental and economic performance compared with single-material recovery approaches (Wagland et al., 2019). Michigan's container deposit system (the "bottle bill"), which places a $0.10 deposit on beverage containers including aluminum cans, is a significant upstream factor limiting aluminum concentration at this site (Porter, 2004). High redemption rates divert a large proportion of aluminum cans from the waste stream prior to disposal, leaving a residual inventory skewed toward foil, non-deposit packaging, and industrial scraps—forms that are less corrosion-resistant and lower in unit recovery value. This suggests that LFM assessments must account for the upstream policy context when estimating recoverable aluminum inventories.

5.2 Efficiency and surface contamination

The practical recovery of aluminum from LFM coarse fractions involves eddy current separation (ECS) as the principal non-ferrous recovery technology. ECS efficiency is sensitive to particle size, shape, and critically the electrical conductivity of the particle surface. The extensive organic surface contamination observed in the EDS analysis of post-experiment samples (carbon content of 28.52 wt.% in corroded foils) suggests that even nominally metallic particles may carry organic-rich surface deposits that reduce eddy current induction efficiency. A pre-treatment washing step, or mild abrasive surface cleaning, applied to the coarse non-ferrous fraction prior to ECS could improve

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both recovery yield and concentrate purity, particularly for coated beverage cans that retain a conductive metallic core beneath surface deposits. This is an important process engineering consideration for LFM operations targeting aluminum recovery and warrants further investigation at pilot scale.

5.3 Proposed industrial-scale process chain

Based on the findings of this study and supporting LFM literature (Kaartinen et al., 2013; López et al., 2018; Wagner & Raymond, 2015), the following conceptual process chain is proposed for aluminum recovery at a site analogous to MCSWMA. This flowsheet is presented as a conceptual framework rather than an experimentally validated process design, and its individual unit operations require site-specific validation at pilot scale:

- Stage 1: Excavation and primary screening. Waste is excavated by mechanical equipment and transported to a processing area. Primary screening at 40-50 mm removes oversized inerts and reduces processing volume.
- Stage 2: Fines removal. Secondary screening at 7-10 mm removes the dominant fine fraction (<7 mm), which constituted 67.4 wt.% of excavated mass at MCSWMA and contains little recoverable metallic aluminum. Early fines removal is critical for reducing downstream processing costs. The fine fraction may be directed to geotechnical reuse as daily cover material or sub-base aggregate following environmental characterization.
- Stage 3: Ferrous metal recovery. The coarse fraction enters a sorting line equipped with an overhead magnetic separator, recovering nails, food cans, and structural steel. Ferrous recovery is reliable even through extensive corrosion, as high magnetic susceptibility is retained.
- Stage 4: Non-ferrous metal recovery. The de-ferrous coarse fraction passes an eddy current separator, which ejects electrically conductive non-ferrous metals (principally aluminum and copper). As noted above, pre-treatment to reduce organic surface contamination may improve ECS performance for landfill-aged aluminum.
- Stage 5: Sorting and cleaning. The non-ferrous concentrate is sorted to separate aluminum from copper and other materials. Sensor-based sorting (near-infrared, color camera, or laser-induced breakdown spectroscopy) enables high-purity separation at scale; manual sorting, as employed in this study, is viable for smaller operations.
- Stage 6: Secondary smelting. Recovered aluminum is baled or briquetted for transport to secondary smelters. The alloy composition of recovered beverage cans is compatible with standard secondary smelting operations (Padmanabhan et al., 2011). Contemporary approaches to processing aluminum-containing secondary resources demonstrate that mixed-composition secondary aluminum can be refined into commercially viable alloys (Kuz'min et al., 2026), supporting the broader applicability of secondary smelting for LFM-recovered material.
- Parallel streams. The combustible fraction is directed to RDF production or thermal energy recovery. Inert materials (stones, glass, ceramics) are directed to aggregate reuse. Revenue from these parallel streams is essential for overall project economic viability.

5.4 Integration with circular economy objectives

The MCSWMA case study illustrates that aluminum recovery, while insufficient to independently justify LFM at this site, contributes meaningfully to a multi-resource recovery portfolio. Each kilogram of landfill-recovered aluminum diverted to secondary production avoids approximately 95% of the energy and GHG emissions associated with primary aluminum smelting from bauxite ore (Jirang & Roven, 2010), representing a substantial avoided environmental burden (Amponsah-Berko et al., 2026). This is consistent with circular economy principles that prioritize the retention of materials at high value within the economic system for as long as possible.

The predominance of fines (67.4 wt.%) at MCSWMA also has direct implications for LFM system design. Because aluminum was almost exclusively recovered from the coarse fraction, aggressive fine screening at early stages reduces processing volume, lowers separation costs, and improves the efficiency of aluminum recovery, supporting the implementation of staged excavation, screening, and targeted sorting.

Importantly, the site-specific findings reinforce the primacy of pre-landfill aluminum capture as the most efficient intervention point. Michigan's bottle-deposit system shows that upstream collection policies shape the composition and recoverability of the residual landfill resource decades into the future. Landfill mining recovers what evades pre-landfill systems; improving those upstream systems is the more efficient long-term strategy. Nonetheless, the persistent metallic aluminum identified in this study, particularly in the form of coated beverage cans that have survived 35+ years of burial, represents a residual secondary resource of growing strategic relevance as demand for low-carbon secondary aluminum increases.

6. CONCLUSIONS

This study provides a site-specific evaluation of aluminum persistence, corrosion behavior, and recoverability within the MCSWMA landfill, contributing to the understanding of aluminum recovery potential in LFM applications. The combined field excavation and laboratory simulation approach indicates that while aluminum can persist in landfills in a recoverable metallic form, its extractive potential is strongly dependent on product type, surface treatment, and local waste management practices.

At MCSWMA, aluminum was present at low concentrations (0.43 wt.%), and a significant portion, particularly aluminum foils, had undergone corrosion and chemical transformation, reducing recycling value. In contrast, coated aluminum beverage cans largely retained metallic integrity, suggesting that certain aluminum products remain viable targets for post-landfill recovery. SEM-EDS analyses indi-

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cated that corrosion processes are associated with oxide formation and organic contamination, which directly affect recyclability and processing efficiency.

These findings advance LFM research by revealing that aluminum recovery should not be treated as a uniform metal recovery problem. Effective LFM for aluminum requires selective targeting of persistent aluminum forms, early-stage screening to remove fines, and integration with broader material and energy recovery strategies. For landfills similar to MCSWMA, aluminum recovery alone is unlikely to justify excavation; however, aluminum can meaningfully contribute to the overall resource recovery portfolio when combined with ferrous metal recovery, RDF production, and reuse of inert materials, as outlined in the proposed industrial process chain.

The study's findings are subject to limitations arising from single-point sampling, barrel experiment simplifications, and visual corrosion classification, which are explicitly discussed. Future work should incorporate multi-point field sampling with depth stratification, fine fraction chemical analysis for a complete aluminum mass balance, and XRD characterization of corrosion products. Overall, this work positions LFM as a complementary pathway for aluminum recovery that is most effective when informed by site-specific material characterization and corrosion behavior, while reinforcing the importance of pre-landfill aluminum capture in support of circular economy objectives.

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REFERENCES

Almoiqli, M., Alharbi, K. N., Alnuwaiser, M. A., Yajizi, G., Alshoshan, S., Baduways, W., Albeladi, M. I., Alsanea, R. S., & Aljohani, T. A. (2023). Corrosion behavior of Aluminium-Coated cans. Materials, 16(3), 1041.

Amponsah-Berko, D., Kwofie, R., Eisele, T., & Robins, J. (2026). Mining Aluminum from Landfills: Challenges, Technologies, and the Case forPre-Landfill Intervention. Detritus, 34, 13-29.

Association, T. A. (2023). Aluminum: The Element of Sustainability

Authority, M. C. S. W. M. (2024a). Annual report

AUTHORITY, M. C. S. W. M. (2024b). Annual report. M. C. S. W. M. Authority.

Brems, A., Baeyens, J., & Dewil, R. (2012). Recycling and recovery of post-consumer plastic solid waste in a European context. Thermal Science, 16(3), 669-685.

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.

Das, S. K., Green, J., & Kaufman, J. (2010). Aluminum recycling: Economic and environmental benefits. Light Metal Age, 68(1), 42.

Dey, D. (2025). Aluminium for the Future: Recycling, Green Manufacturing, and Emerging Technologies.

EPA, U. (2020). Advancing sustainable materials management: facts and figures report. Environmental Protection Agency.

Hao, Z. (2020). Understanding and predicting temperatures in municipal solid waste landfills. North Carolina State University.

Hasanbeigi, A., Springer, C., & Shi, D. (2022). Aluminum Climate Impact: An International Benchmarking of Energy and CO2 Intensities. Global Efficiency Intelligence. In.

Janáková, I., Čech, M., Grabovská, Š., Šigut, O., Sala, P., & Kijo-Kleczkowska, A. (2024). Pyrolysis of Specific Non-Recyclable Waste Materials: Energy Recovery and Detailed Product Characteristics. Materials, 17(8), 1752.

Jirang, C., & Roven, H. J. (2010). Recycling of automotive aluminum. Transactions of Nonferrous Metals Society of China, 20(11), 2057-2063.

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.

Kaartinen, T., Sormunen, K., & Rintala, J. (2013). Case study on sampling, processing and characterization of landfilled municipal solid waste in the view of landfill mining. Journal of Cleaner Production, 55, 56-66.

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.

Kuz'min, M. P., Kuz'mina, A. S., & Kuz'mina, M. Y. (2026). Recycling silicon waste into hypereutectic aluminum-silicon alloys. The International Journal of Advanced Manufacturing Technology, 1-10.

López, C. G., Küppers, B., Clausen, A., & Pretz, T. (2018). Landfill mining: a case study regarding sampling, processing and characterization of excavated waste from an Austrian landfill. Detritus, 2(June), 29-45.

Lucas, M. S. H., Li, M. S. C., López, M. S. C. G., Hernández, M. S. J. C., Parrodi, M., Pretz, I. T., Wotruba, I. H., & Mercatorstraat, G. (2019). Primary evaluation of the use and refining of Al scrap recovered from a landfill in Belgium. EMC, Dusseldorf, Germany, 51-61.

Masi, S., Caniani, D., Grieco, E., Lioi, D. S., & Mancini, I. M. (2014). Assessment of the possible reuse of MSW coming from landfill mining of old open dumpsites. Waste management, 34(3), 702-710.

Monster, S. (2024). Aluminum Scrap Prices Paid by Scrap Yards in Michigan, United States

Padamata, S. K., Yasinskiy, A., & Polyakov, P. (2021). A review of secondary aluminum production and its byproducts. Jom, 73(9), 2603-2614.

Padmanabhan, R., Oliveira, M., & Menezes, L. (2011). Lightweight metal alloy tailor welded blanks. In Tailor Welded Blanks for Advanced Manufacturing (pp. 97-117). Elsevier.

Parrodi, J. C. H., Höllen, D., & Pomberger, R. (2018). Characterization of fine fractions from landfill mining: A review of previous investigations. Composites, 6(4), 46-62.

Porter, R. C. (2004). Efficient targeting of waste policies in the product chain. the Economics of Waste, 117.

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.

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.

Telmo, C., Lousada, J., & Moreira, N. (2010). Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood. Bioresource technology, 101(11), 3808-3815.

Tian, A., Tang, H., Chen, W., Pan, X., Wu, F., & Tang, Q. (2025). A Multi-Field Coupling Model for Municipal Solid Waste Degradation in Landfills: Integrating Microbial, Chemical, Thermal, and Hydraulic Processes. Sustainability, 17(21), 9691.

van Gog, H. (2021). First-principles study of dehydration interfaces between diaspore and corundum, gibbsite and boehmite, and boehmite and γ-Al2O3: Energetic stability, interface charge effects, and dehydration defects. Applied Surface Science, 541, 148501.

Wagland, S. T., Coulon, F., & Canopoli, L. (2019). Developing the case for enhanced landfill mining in the UK.

Wagner, T. P., & Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. Waste management, 45, 448-457.

Zhang, S., Forssberg, E., Arvidson, B., & Moss, W. (1998). Aluminum recovery from electronic scrap by High-Force® eddy-current separators. Resources, Conservation and Recycling, 23(4), 225-241.

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