From Collection to Furnace: A Critical Review of Aluminum Can Recycling Routes, Technologies, and Sustainability Challenges

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ABSTRACT

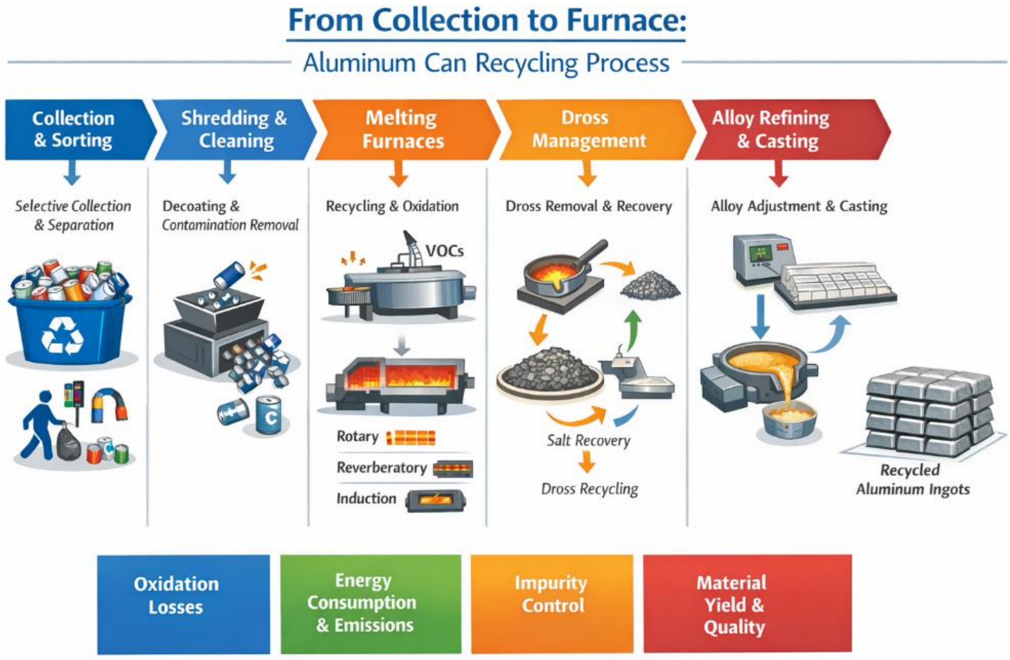
Aluminum beverage cans are among the most successful examples of metal recycling in a circular economy, with global collection rates exceeding 70% and surpassing 95% in some regions. However, the pathway from post-consumer collection to remelting is technically complex, involving cumulative material losses, energy penalties, and quality constraints often overlooked in simplified sustainability narratives. This critical review examines the entire recycling chain of used beverage cans (UBCs), including collection systems and reverse logistics, sorting and physical preparation, decoating technologies, melting furnace configurations, dross formation, alloy control, and environmental performance. Emphasis is placed on the metallurgical and thermodynamic mechanisms governing oxidation losses, coating removal efficiency, impurity accumulation, and metal yield during remelting in reverberatory, rotary, and induction furnaces. The influence of contamination, scrap variability, furnace atmosphere, and operational practices on energy consumption, emissions, and final alloy quality is systematically assessed, along with the limitations of life-cycle assessment (LCA) data and of industrial transparency. Although aluminum can recycling is often described as nearly lossless and infinitely recyclable, industrial evidence indicates measurable yield losses, alloy downgrading risks, and process-related emissions that challenge the idealized closed-loop paradigm. Emerging solutions—including advanced sensor-based sorting, controlled-atmosphere melting, digital process optimization, and improved dross valorization routes—are discussed as pathways to enhance material efficiency and reduce environmental impact. The review identifies key technological bottlenecks and research gaps necessary to improve the metallurgical robustness and sustainability performance of aluminum can recycling systems.

Keywords. Aluminum cans; Recycling; Scrap pretreatment; Decoating; Melting furnaces; Dross formation; Circular economy

Highlights

- Aluminum can recycling achieves high collection rates but remains subject to measurable metallurgical and thermodynamic losses.
- Decoating efficiency and oxidation during melting are primary determinants of metal yield and environmental performance.
- Furnace type and atmosphere strongly influence dross formation, energy intensity, and alloy quality.
- Industrial data reveal cumulative material losses that challenge the idealized “infinite closed-loop” assumption.
- Advanced sorting, controlled-atmosphere melting, and digital process integration represent key future improvements.

Graphical Abstract



INTRODUCTION

Recycled aluminum is crucial for decarbonization, replacing energy-intensive primary production. It uses less energy, so it's key for efficiency and low-carbon manufacturing (Kumai, 2023; Hagelüken & Goldmann, 2022; Weritz & Dudek, 2022). However, true recycling depends on collection, scrap quality, separation, and remelting, which cause losses not reflected in headline rates or narratives (Marinina et al., 2022; Kotabe, 2023).

Primary aluminum is produced from alumina via electrolytic reduction, mainly limited by electricity and upstream emissions. Secondary aluminum relies on feed variability, contamination, and thermochemical losses during scrap handling and melting (Padamata et al., 2021; Alawady, 2024). As secondary aluminum's global share grows, policies and markets promote recycled content (Li et al., 2020; Yang et al., 2024). Higher scrap use doesn't ensure closed-loop recycling; alloy mixing, impurity buildup, and yield losses may lead to downcycling unless sorting and process control improve (Van den Eynde et al., 2022; Hagelüken & Goldmann, 2022).

Used beverage cans (UBCs) are highly collected post-consumer aluminum, exemplifying effective “can-to-can” recycling with high rates and quick market return (Simmons, 2020). However, UBC recycling faces technical issues: coatings and organics require controlled decoating, bales may contain tramp materials, and melting leads to oxidation and metal loss. Achieving sheet-grade quality demands tighter control of residual elements than most scrap streams can provide, revealing the gap between ideal circularity and industrial reality (Padamata et al., 2021; Van den Eynde et al., 2022; Pereira & dos Santos, 2025). Reviews show that the “closed-loop” label can mask regional differences in collection systems, technology, and data transparency, complicating cross-country comparisons and sustainability claims (Pereira, 2025a; Pereira, 2025b).

This article takes a critical-review approach and does not equate the recycling rate with circularity. Instead, it traces the process from collection to furnace, pinpointing key factors such as material efficiency, alloy quality, and large-scale industrial interventions that influence outcomes. The review emphasizes (i) collection and reverse logistics, particularly scrap quality; (ii) sorting and physical preparation, including limits on alloy separation; (iii) decoating and emissions; (iv) remelting technologies, oxidation, and dross formation; and (v) the effects on alloy control, energy consumption, and sustainability metrics (Padamata et al., 2021; Yang et al., 2024; Pereira & dos Santos, 2025). It synthesizes evidence from these stages to identify bottlenecks—whether technological, systemic (market and policy), or methodological (reporting and LCA framing) (Marinina et al., 2022; Kotabe, 2023).

The remainder of the paper is organized as follows. Section 2 describes the review design, databases, screening criteria, and the handling of peer-reviewed and grey sources to balance coverage with evidentiary strength. This methodology provides the foundation for the subsequent stage-by-stage assessment of the UBC recycling pathway.

METHODOLOGY

This review balances coverage and rigor to identify contributions on material losses, energy performance, alloy control, and sustainability in aluminum can recycling. It follows PRISMA 2020 guidelines adapted for metallurgical and industrial-process literature.

The final database has 103 references, including peer-reviewed articles, conference proceedings, book chapters, and grey literature. Grey sources are justified due to aluminum recycling's industrial nature, which often presents data, analyses, and models outside standard journals.

Databases, search strings, and selection criteria

Literature searches were conducted in Scopus, Web of Science, ScienceDirect, and Google Scholar from January to March 2026, focusing on 2020-2025 to capture recent advances in sorting tech, furnace optimization, dross valorization, and LCA. Earlier works were included for context.

Search strings combined technical, environmental, and systemic terms, including:

“used beverage cans” OR “UBC recycling.”; “secondary aluminum production.”; “aluminum decoating” AND “VOCs.”; “dross formation” AND “aluminum melting.”; “alloy contamination” AND “recycled aluminum.”; “LCA aluminum recycling” OR “exergy aluminum recycling.”; “deposit return system” AND “aluminum.”

The database platform adjusted the Boolean operators. Screening was performed in three stages: title review, abstract screening, and full-text assessment.

Inclusion criteria:

- Direct relevance to aluminum scrap, UBC recycling, melting, alloy control, dross, or environmental assessment;
- Peer-reviewed journal articles, recognized conference proceedings, or authoritative book chapters;
- Quantitative or mechanistic analysis of technical performance;
- Studies addressing energy, emissions, or material-flow implications.

Exclusion criteria:

- Purely descriptive policy commentary without technical linkage;
- Studies unrelated to metallic aluminum recycling;
- Duplicated datasets across derivative publications.

Methodological references on LCA, exergy, and recycling modeling were retained to support cross-study comparisons (Meskers et al., 2024; Doutre & Kvithyld, 2024; Hildenbrand et al., 2020; Rossi et al., 2025; Luo et al., 2024).

Figure 1 shows that the initial database search returned many records. After removing duplicates and irrelevant titles, abstracts were screened for relevance to aluminum can recycling, secondary melting, alloy control, and environmental assessment. Full texts yielded 103 references covering process metallurgy, sorting, life cycle assessment, and the circular economy. Grey literature was included if it provided unique industrial or regulatory insights not found in peer-reviewed sources.

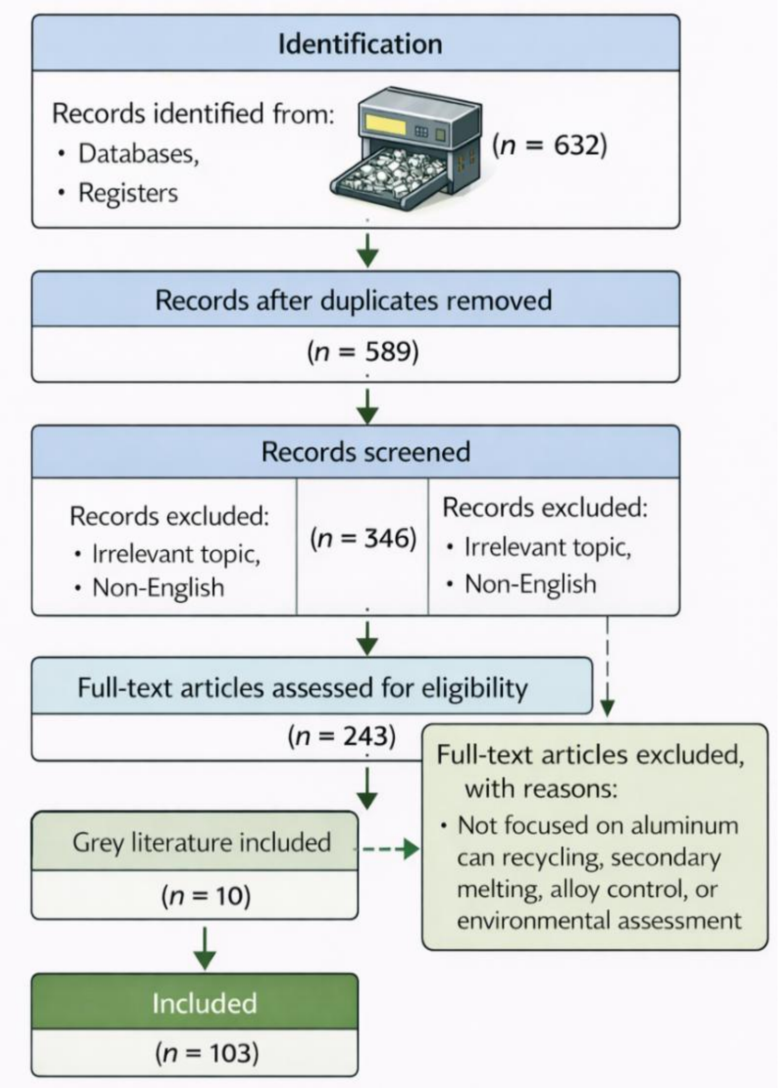


Figure 1. PRISMA-based flow diagram describing the identification, screening, eligibility, and inclusion stages of the literature review process. Adapted from Page et al. (2021).

Inclusion of grey literature

Aluminum recycling operates at the intersection of industrial practice, policy, and environmental accounting. Some relevant data—particularly those on furnace heat management, regulatory mechanisms, and lifecycle modeling assumptions—are reported in theses, technical reports, and institutional publications rather than in indexed journals.

Accordingly, selected grey sources were included when they met at least one of the following criteria:

(i) provided original quantitative modeling or experimental data;

(ii) addressed regulatory or economic mechanisms directly influencing recycling systems;

(iii) offered methodological advances relevant to LCA or process modeling.

These sources include furnace heat-transfer modeling (Andayesh, 2024), trade-policy impacts (Arora, 2023), industry LCA reports (Elzein et al., 2025), energy pathway comparisons (Metlen, 2022), recyclability studies (Önen, 2022), alternative scrap-processing routes (Pasqualini, 2024), compliance frameworks (Ren, 2025), and methodological reflections on circularity metrics (Sazdovski, 2025).

These materials strengthen the review by integrating technical, regulatory, and systemic dimensions that are often fragmented across publication types. Their use is limited to contextual or quantitative support and does not replace peer-reviewed evidence when available.

This methodological framework provides the basis for the stage-by-stage assessment presented in the following sections, starting with collection systems and reverse logistics.

1. Collection and reverse logistics of aluminum cans

Collection systems determine both the quantity and the quality of material entering the recycling chain. High recovery rates are often presented as proof of circular success. However, collection performance does not automatically translate into metallurgical efficiency. Reverse logistics defines scrap purity, alloy segregation potential, and ultimately metal yield in the furnace.

Collection Systems

Two main models govern aluminum can recovery: curbside collection and deposit-return systems (DRS). DRS usually has higher return rates and less contamination, especially with consistent incentives and centralized logistics (Simmons, 2020; Jarossová & Gubíniová, 2022). Economic studies show better recovery with national DRS (Broniewicz et al., 2023). Consumer research confirms higher participation when return systems are accessible and clear (Jarossová et al., 2023).

Performance varies regionally due to policy, socioeconomic factors, and informal-sector participation (Ile et al., 2025; Reshetnikova et al., 2025). Selective collection relies on manual sorting and networks, causing bale composition variability (Gavrilescu et al., 2023; Vicente & Karen, 2024). New deposit frameworks and hybrid models seek to balance costs and coverage (Paurom, 2020; Spataru-Negura, 2024).

Economic and regulatory pressures, such as trade policies and carbon border mechanisms, shift secondary aluminum geographically, affecting regional scrap availability (Arora, 2023). Packaging-sector dynamics influence collection volume and material mix (Awan, 2023). Volume-reduction methods like crushing improve transport but may impact processing (Aydın et al., 2025).

Despite high local collection rates, global aluminum scrap flows remain uneven. Forecasts show rising scrap but highlight gaps in sorting and infrastructure that limit closed-loop recycling (Van den Eynde et al., 2022). Collection systems differ in recovery rates, scrap quality, contamination, and logistics. A comparison is in Table 1.

Table 1. Comparative characteristics of aluminum can collection systems (curbside, deposit-return, and hybrid models), including recovery rate, contamination risk, logistics complexity, and economic drivers. Adapted from Simmons (2020); Broniewicz et al. (2023); Jarossová & Gubíniová (2022); Aydın et al. (2025); Gavrilescu et al. (2023).

Parameter	Curbside Selective Collection	Deposit-Return System (DRS)	Hybrid Systems
Recovery rate	Moderate to high (40–80%)	High to very high (70–95%+)	Variable
Contamination risk	Moderate to high	Low	Moderate
Consumer incentive	None or indirect	Direct financial incentive	Partial
Logistics complexity	Distributed	Centralized	Mixed
Scrap quality consistency	Variable	More consistent	Intermediate
Policy dependency	Moderate	High	High

As shown in Table 1, higher return rates do not eliminate quality variability. Systems optimized for quantity may still produce heterogeneous bales. This distinction is critical in downstream processing.

Figure 2 presents the integrated closed-loop pathway for aluminum can recycling, linking collection, separation, decoating, melting and refining, production, and remanufacturing into new cans and sheets. The circular arrangement emphasizes the conceptual objective of continuous material circulation.

Figure 2. Simplified reverse logistics pathway for used beverage cans, from consumer disposal to baled scrap at remelting facilities. Adapted from Simmons (2020) and Van den Eynde et al. (2022).

Collection is the entry point for used beverage cans (UBCs) into the recycling system. The efficiency and purity of this stage directly affect downstream process stability. Separation follows, using magnetic and sensor-based technologies to remove steel, non-metallic contaminants, and off-spec alloys.

Decoating removes organic coatings, inks, and internal polymer liners. This step is critical to minimize oxidation during melting and to control atmospheric emissions. Inadequate decoating increases dross formation and reduces metal yield.

Melting and refining form the metallurgical core of the cycle. Here, oxidation losses, flux interactions, and dross generation determine net metal recovery. Refining operations adjust composition and remove inclusions, but elemental impurities such as Fe are difficult to eliminate once dissolved.

Production converts refined aluminum into sheets and coils suitable for can manufacturing. Mechanical properties and alloy chemistry must meet strict specifications to enable closed-loop reuse.

The central recycling symbol suggests circularity, but melting losses, contamination, and alloy mixing mean full recirculation is conditional. The figure shows that each stage must be optimized to approach true closed-loop performance, not assuming it is inherent to aluminum recycling.ing.

Quality of collected material

Material quality at the collection stage directly affects melting yield and furnace stability. UBC bales typically contain coatings, residual liquids, organics, and entrained foreign materials. Steel components, plastics, and glass fragments are frequent contaminants (Steglich et al., 2020). Even low percentages of non-aluminum material can increase oxidation losses or disrupt thermal balance during charging.

Compaction improves transport density but alters bale permeability and heat transfer during decoating and melting. Experiments show bale density and thermal pretreatment affect dross formation and metal loss (Steglich et al., 2020). Studies confirm bale geometry and scrap morphology impact melting efficiency (Chamakos et al., 2023; Tzevelekou et al., 2024).

Alloy mixing starts at collection, with post-consumer streams rarely being pure. Without advanced sorting, mixed scrap dilutes sheet-grade alloys and hampers closed-loop recycling (Pedneault et al., 2023; Van den Eynde et al., 2022). This is a structural issue, not incidental, as increasing scrap volumes raise impurity risks unless sorting accuracy improves.

Metal yield during remelting of used beverage cans depends on scrap quality, physical preparation, and bale density, which in turn affect oxidation, furnace time, and melt efficiency (Figure 3). Managing contamination and compaction is crucial to reduce dross and maximize recovery, especially in high-throughput operations, where small yield differences can lead to large losses.

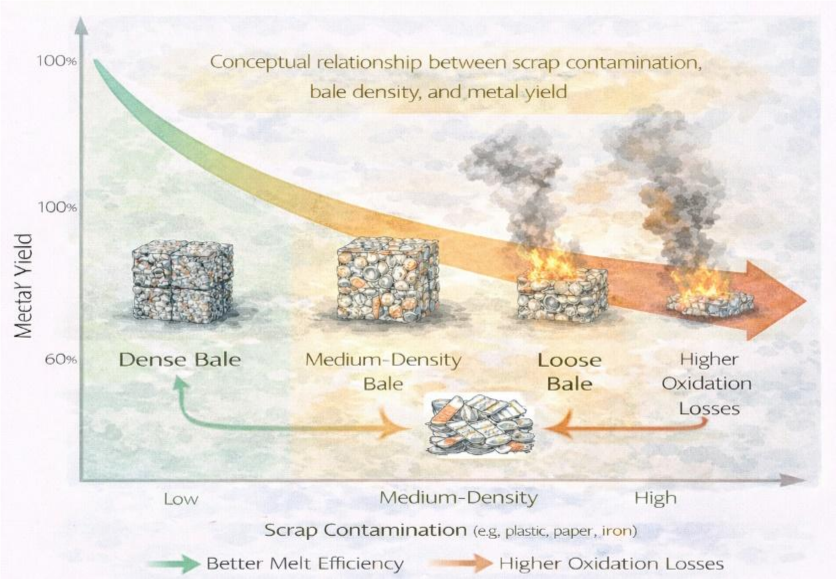


Figure 3. Conceptual relationship between scrap contamination, bale density, and metal yield during remelting of used beverage cans. Adapted from Steglich et al. (2020); Chamakos et al. (2023); Tzevelekou et al. (2024).

Figure 3 shows dense, low-contamination bales yield more metal due to better thermal contact, less surface exposure, and lower oxidation. As contamination rises (plastics, paper, iron) and bale density drops, melt efficiency and metal recovery decline, with increased oxidation and dross. Loose scrap increases surface reactivity and melting time, trapping more metal in oxides. This highlights the importance of sorting and compaction upstream for better metallurgical performance.

The next section examines how sorting and pre-treatment aim to mitigate constraints and their limits. The effectiveness of collection depends on how well subsequent sorting and pre-treatment manage material variability.t.

Sorting and physical pre-treatment

Sorting and physical preparation determine whether collected scrap becomes a controlled metallurgical input or a source of cumulative losses. Collection systems deliver variability. Sorting attempts to reduce it. The effectiveness of this stage largely defines alloy integrity, furnace stability, and oxidation behavior.

Magnetic separation and eddy current processing

The first separation step targets ferrous contamination. Magnetic separators remove steel closures, wires, and entrained fragments. This step is technically mature but not loss-free. In mixed municipal streams, incomplete removal of steel can still occur, especially when fragments are small or mechanically embedded (Hannula et al., 2020).

Eddy current separators then isolate the non-ferrous fraction. These systems rely on induced currents to eject aluminum from mixed waste streams. Their performance depends on particle size distribution and material morphology (Trancoso et al., 2020). Fine fractions and irregular shapes reduce separation efficiency.

Material flow analyses indicate that imperfect physical separation at this stage propagates downstream, increasing alloy mixing and impurity accumulation (Pedneault et al., 2023; Van den Eynde et al., 2022). Sorting efficiency is therefore not only a mechanical parameter but a structural determinant of recycling quality.

After size reduction, mechanical sorting enhances scrap quality pre-remelting (Figure 4). It removes ferrous metals and contaminants, reducing furnace contamination, alloy dilution, and improving melt efficiency. Magnetic and eddy current systems are essential for aluminum can sorting, providing a cost-effective way to prevent alloy cross-contamination.

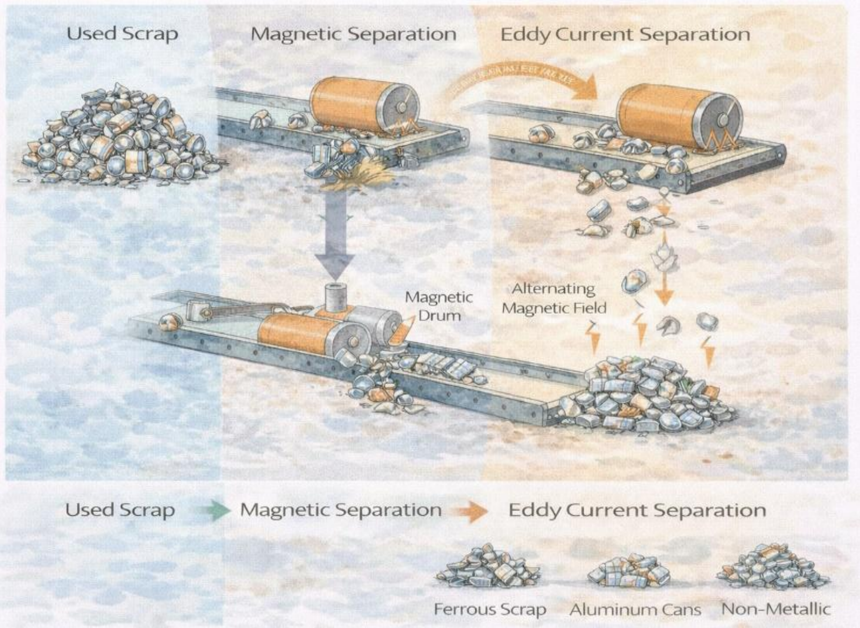


Figure 4. Simplified mechanical sorting sequence for used beverage cans, including magnetic separation and eddy current processing. Adapted from Hannula et al. (2020) and Trancoso et al. (2020).

The process begins with magnetic separation to remove ferrous metals like steel and iron. Non-ferrous materials are then separated using an eddy current separator, which induces forces in conductive aluminum to separate it from non-metallic residues. Though simple, these steps' efficiency impacts alloy quality and metal yield. Poor separation causes contamination, dross, increased refining, and downcycling.ing.

Alloy classification and sensor-based sorting

Mechanical separation isolates aluminum without distinguishing alloy families, crucial for preserving sheet-grade alloys in closed-loop uses. Advances in LIBS, optical recognition, and machine learning enhance alloy detection (Diaz-Romero et al., 2023; Efe et al., 2025). Acoustic and time-frequency methods improve signal clarity (Wang et al., 2025a), but are limited by throughput, cost, and surface contamination.

Alloy mixing remains a systemic challenge. Even small compositional deviations can alter downstream properties or require corrective alloying additions (Mysliu et al., 2023). When alloy segregation is incomplete, closed-loop recycling shifts toward dilution strategies rather than true alloy recovery.

Table 2 compares major alloy-sorting technologies in terms of detection principle, industrial maturity, throughput, and limitations.

Table 2. Comparison of sensor-based alloy sorting technologies for aluminum scrap (LIBS, optical sorting, acoustic methods), including detection mechanism, throughput capacity, and technical limitations. Adapted from Diaz-Romero et al. (2023); Efe et al. (2025); Wang et al. (2025c).

Technology	Detection Principle	Industrial Maturity	Throughput	Main Limitations
LIBS	Laser-induced plasma spectroscopy	Advanced / Industrial	Medium	Surface contamination interference
Optical/XRF	Elemental optical response	Mature	High	Limited alloy discrimination
Acoustic/AI-assisted	Signal pattern recognition	Emerging	Medium	Calibration complexity
AI-integrated systems	Data-driven classification	Emerging	Variable	High capital cost

Advanced sorting improves alloy control but does not eliminate residual variability. Economic feasibility remains a limiting factor to widespread deployment.

Comminution, densification, and briquetting

Scrap morphology affects furnace behavior. Shredding and size reduction increase surface area, which can improve heat transfer but also intensify oxidation. Bale density and compaction directly influence melting kinetics and dross formation (Steglich et al., 2020).

Experiments and simulations show scrap geometry affects thermal penetration and melt efficiency (Chamakos et al., 2023). Higher density improves transport economics but requires pretreatment to avoid incomplete decoating or uneven heating. Volume reduction during collection can also change scrap structure before melting (Aydın et al., 2025).

Industrial overviews highlight the trade-off between densification and oxidation losses (Gogoi, 2025; Padamata et al., 2021). Increased surface exposure can elevate metal loss unless furnace atmosphere and charging strategy are optimized.

Figure 5 shows key industrial aluminum can decoating methods. Thermal can screening, the most common, involves heating shredded cans to remove organic coatings. Although simple and reliable, it can cause localized overheating and incomplete removal if not properly controlled.

Scrap compaction before remelting affects oxidation by reducing surface area, limiting oxygen access, and shortening oxidation time, making bale structure crucial for controlling metal losses.

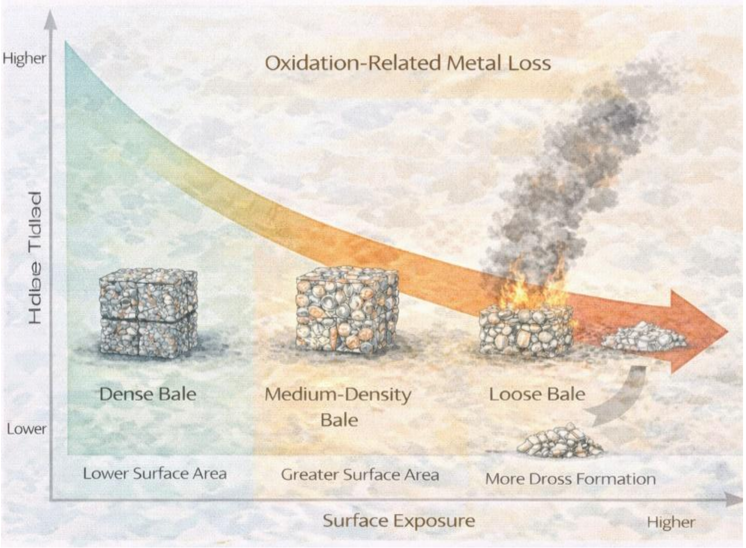


Figure 5. Conceptual relationship between scrap densification, surface exposure, and oxidation-related metal loss during remelting. Adapted from Steglich et al. (2020) and Chamakos et al. (2023).

Higher densification reduces surface area and oxygen–metal interaction during melting, while loosely compacted scrap increases surface exposure, oxidation, and dross formation. This leads to metal entrapment in oxide phases and yield loss. Therefore, upstream compaction strategies are crucial for logistics, metallurgical performance, and resource conservation.

While mechanical and sensor-based sorting reduce compositional variability, surface contaminants and coatings introduce additional thermochemical constraints that must be addressed before remelting, as discussed in the following section on Surface Treatments and Decoating.

Surface treatments and decoating

Surface condition defines furnace behavior. Coatings, residual organics, and surface oxides influence oxidation kinetics, emission profiles, and dross formation. Decoating is therefore not a peripheral step. It determines both metal yield and environmental performance.

Nature of coatings and metallurgical implications

Used beverage cans are coated internally and externally. Organic lacquers protect the metal from corrosion and prevent beverage interaction. Exterior layers include inks, varnishes, and protective films. These materials introduce carbonaceous compounds into the recycling stream (Padamata et al., 2021).

During heating, these coatings decompose and release volatile compounds. If removal is incomplete before melting, combustion inside the furnace can destabilize thermal control and increase oxidation losses (Tzevelekou et al., 2024). Residual char may adhere to scrap surfaces, affecting melt cleanliness (Melwyn et al., 2023).

Surface oxides build up during collection and storage. Aluminum's stable oxide layer thickens with exposure, but excessive oxidation traps more metal in dross. Organics combined with oxides complicate thermal behavior during charging.

During thermal pretreatment, organic coatings on used beverage cans undergo physical and chemical changes, affecting metal yield and emissions during melting. Polymer decomposes gradually through volatilization, residue formation, and interaction with aluminum. Understanding these processes helps optimize decoating temperature, time, and atmosphere. Figure 6 illustrates the main stages of coating decomposition.

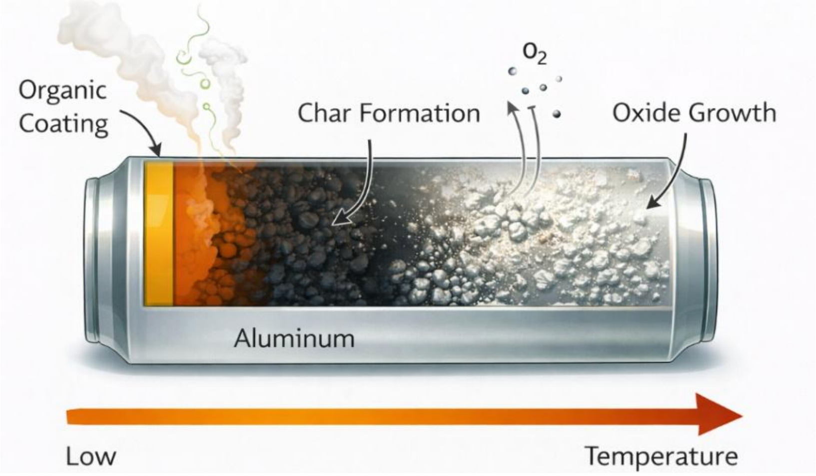


Figure 6. Schematic representation of coating decomposition during thermal pretreatment of used beverage cans, including volatilization, char formation, and oxide growth. Adapted from Padamata et al. (2021) and Tzevelekou et al. (2024).

At moderate temperatures, organic binders and polymers volatilize, releasing hydrocarbons and gases. Limited oxygen can cause incomplete combustion, forming a carbon-rich char layer on aluminum. This layer temporarily acts as a diffusion barrier but can cause localized overheating if not fully oxidized.

As the temperature rises, oxygen diffusion promotes the growth of alumina (Al_2O_3) on aluminum. If coating removal is incomplete, oxide formation intensifies, increasing dross and reducing metal recovery.

The figure shows the narrow window needed to maximize coating removal while minimizing oxidation. Controlling temperature and atmosphere during decoating is crucial for preserving metal yield and lowering environmental emissions in secondary aluminum production.

Decoating technologies

Thermal decoating furnaces operate by controlled heating below the melting point of aluminum. Organic layers are volatilized or pyrolyzed prior to remelting (Steglich et al., 2020). Process control requires a balance between temperature, residence time, and airflow.

Pyrolysis-based systems offer partial recovery of organic energy content. Under controlled atmospheres, volatile gases can be combusted in secondary chambers to provide process heat (Yang et al., 2025). However, energy recovery depends on coating composition and system integration.

Atmosphere management is critical. Excess oxygen promotes oxidation of exposed aluminum surfaces. Insufficient oxygen can result in incomplete combustion and higher VOC emissions (Tzevelekou et al., 2024). Industrial practice varies according to plant configuration and regulatory requirements.

Table 3 shows that decoupling technologies differ in their temperature regimes, atmosphere control, emission profiles, and energy integration.

Table 3. Comparison of thermal and pyrolytic decoating technologies for UBC scrap, including operating temperature, atmosphere type, emission characteristics, and energy recovery potential. Adapted from Steglich et al. (2020); Yang, J., et al. (2025); Tzevelekou et al. (2024).

Technology	Operating Temperature	Atmosphere	Emission Profile	Energy Recovery Potential
Thermal decoating kiln	400–550°C	Air	VOC generation	Limited
Controlled pyrolysis	350–500°C	Low-O_2 / inert	Reduced VOC	Moderate
Afterburner-integrated systems	Variable	Controlled combustion	VOC destruction	High
Hybrid systems	Variable	Controlled	Optimized	Moderate to high

Although technological options exist, performance depends heavily on operational discipline. Decoating efficiency directly affects downstream oxidation losses.

Atmospheric emissions and environmental control

Organic decomposition produces VOCs that can surpass regulatory limits without proper post-combustion treatment (Astarita et al., 2023). Thermal oxidizers and afterburners are commonly used to lower VOC emissions.

Under unfavorable combustion conditions, trace amounts of dioxins and furans may form, particularly in mixed waste streams containing chlorine-bearing residues (Tamburini et al., 2021). Although aluminum can coatings typically have low chlorine content, contamination from other materials introduces variability.

Life cycle assessments indicate that pretreatment emissions significantly contribute to the overall environmental footprint of recycled packaging (Rossi et al., 2025). Regional infrastructure and regulatory enforcement further shape environmental outcomes (Gavrilescu et al., 2023).

Thermal decoating generates gaseous by-products needing treatment before release. During decomposition, VOCs, hydrocarbons, particulates, and trace pollutants can form, risking pollution and non-compliance. Modern systems use combustion and gas-cleaning to oxidize organics and capture particulates. Figure 7 illustrates a typical emission-control setup.

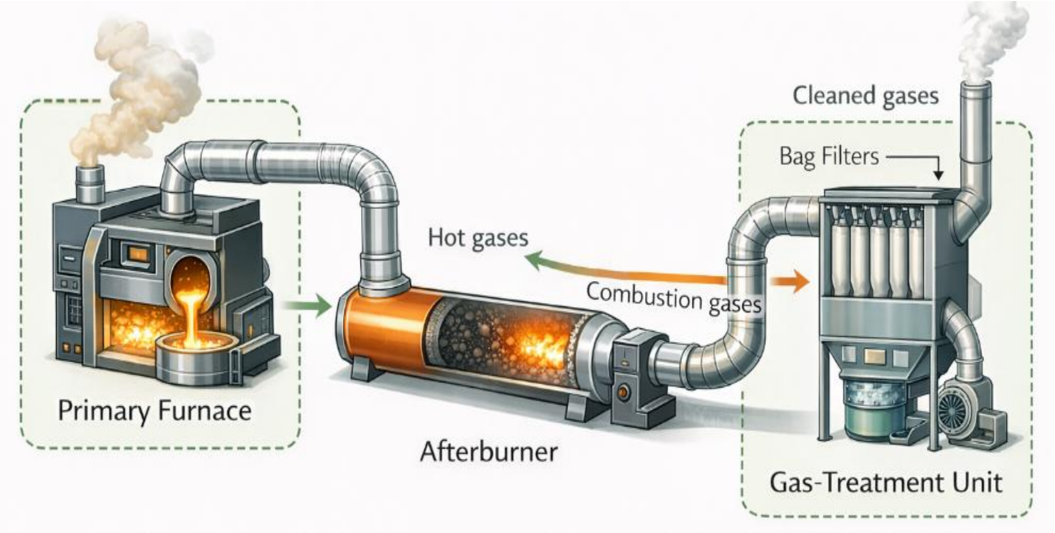


Figure 7. Simplified emission-control configuration for decoating systems, including primary furnace, afterburner, and gas-treatment unit. Adapted from Astarita et al. (2023) and Tamburini et al. (2021).

In the primary furnace, coatings undergo thermal decomposition, producing hot gases containing VOCs and fine particulates. These gases are directed to an afterburner, where high-temperature oxidation destroys residual hydrocarbons and reduces odor and organic emissions. Proper temperature control and residence time are critical to ensure effective oxidation.

Downstream of the afterburner, the gas-treatment unit—often incorporating bag filters or other particulate-control devices—removes particulates before discharge. Depending on regulatory requirements, additional treatment steps, such as scrubbers or activated carbon filters, may be included.

The configuration underscores that decoating is not only a metallurgical step but also an environmental control stage. Insufficient combustion efficiency or inadequate gas treatment can undermine the environmental benefits of recycling by increasing emissions. Effective integration of furnace operations and emission control is therefore essential to balance metal recovery with regulatory compliance and sustainability objectives.

Melting technologies for aluminum cans

Melting defines the real material yield of the recycling chain—losses accumulated during collection, sorting, and decoating become irreversible at this stage. Furnace configuration, atmosphere control, and slag management determine whether UBC recycling approaches theoretical efficiency or deviates from it.

Furnace types, melting efficiency, and thermal balance

Reverberatory furnaces remain widely used in secondary aluminum production. They offer high throughput and operational flexibility. Their open-bath configuration, however, increases exposure of molten aluminum to oxidizing atmospheres (Padamata et al., 2021; Tabereaux & Peterson, 2024). Heat transfer occurs primarily through radiation and convection, which can limit thermal efficiency if charge geometry is unfavorable.

Rotary furnaces improve mixing and heat transfer. Their rotating drum design enhances scrap immersion and reduces localized overheating (Chiloane-Nkomo et al., 2025). They are particularly suited for contaminated scrap streams but often require the addition of salt flux to protect the melt surface.

Induction furnaces provide controlled heating and reduced direct flame interaction. Their efficiency is higher in clean, homogeneous scrap streams (Melwyn et al., 2023). However, induction systems are sensitive to feed variability and may not tolerate high levels of contamination.

Hybrid configurations attempt to combine high throughput with improved thermal control (Andayesh, 2024). Exergy analyses show that furnace efficiency depends less on nominal power rating and more on charge preparation and operational discipline (Doutre & Kvithyld, 2024).

Table 4 presents the main furnace types used for UBC remelting, which differ in thermal efficiency, oxidation exposure, and scrap tolerance.

Table 4. Comparison of furnace technologies for aluminum can recycling, including heating principle, throughput, oxidation exposure, and typical efficiency range. Adapted from Padamata et al. (2021); Tabereaux & Peterson (2024); Chiloane-Nkomo et al. (2025); Doutre & Kvithyld (2024).

Furnace Type	Heating Principle	Throughput	Oxidation Exposure	Typical Efficiency
Reverberatory	Flame radiation	High	High	Moderate
Rotary	Rotational mixing	Medium–High	Moderate	Moderate–High
Induction	Electromagnetic heating	Medium	Low	High (clean scrap)
Hybrid	Combined systems	Variable	Controlled	High (optimized)

No type of furnace can eliminate oxidation losses. The selection depends on balancing productivity with metallurgical control.

Melting atmosphere, fluxes, and oxidation control

Atmosphere influences oxidation kinetics. Air-fired furnaces promote oxide formation on exposed metal surfaces. Controlled or inert atmospheres reduce direct oxidation but increase operational complexity (Milani & Timelli, 2023).

Salt fluxes are commonly used in rotary systems. These molten salts form a protective layer that limits direct contact between metal and oxygen (Steglich et al., 2020). Fluxes also facilitate the separation of non-metallic inclusions. However, salt use generates secondary residues that require treatment.

Surface turbulence, temperature gradients, and scrap morphology further influence oxide growth (Melwyn et al., 2023). Even under optimized conditions, oxidation cannot be fully suppressed. Process control can only reduce its rate.

During remelting of used beverage cans, oxidation causes metallic loss. Aluminum's high affinity for oxygen leads to rapid oxide formation when exposed to air. Native oxide acts as a diffusion barrier, but turbulence, scrap shape, and furnace atmosphere often disrupt this layer, speeding oxide growth and dross formation (Milani & Timelli, 2023; Steglich et al., 2020). Understanding oxide thickening and metal entrapment is vital for reducing yield loss in secondary aluminum. Figure 8 shows the main oxidation phenomena during remelting.

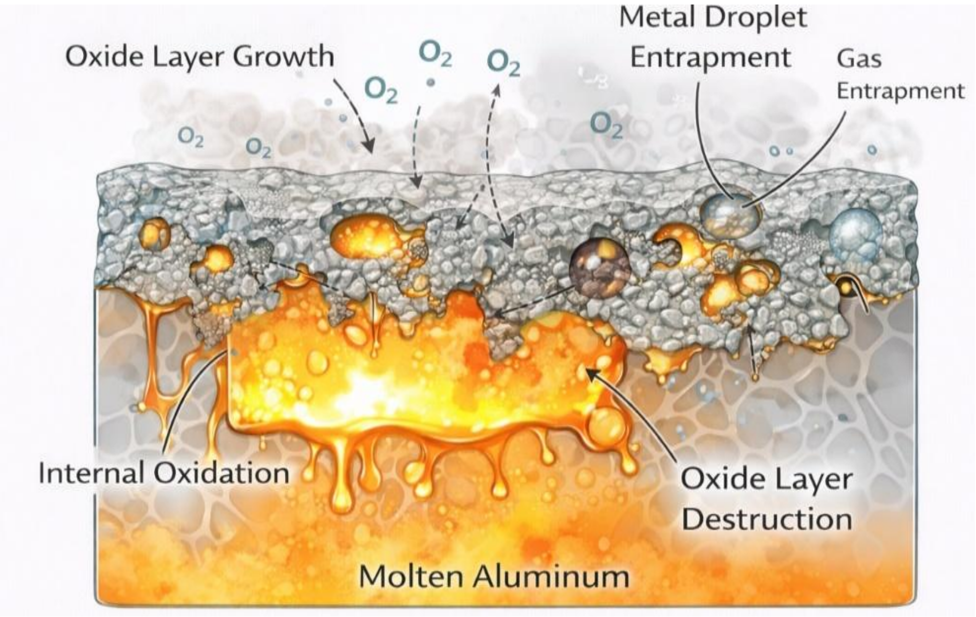


Figure 8. Schematic representation of aluminum oxidation during remelting, illustrating oxide layer growth and metal entrapment mechanisms. Adapted from Milani & Timelli (2023) and Steglich et al. (2020).

As shown in Figure 8, oxygen diffuses through discontinuities in the surface film, thereby promoting progressive oxide-layer growth. Mechanical agitation, scrap charging, and bath movement can fracture the oxide film, exposing fresh metal to further oxidation. This cyclic rupture–regrowth mechanism leads to thick, porous oxide layers.

Within this porous structure, molten aluminum droplets may become physically entrapped. Simultaneously, gas bubbles—originating from coating decomposition or hydrogen dissolution—can be retained within the oxide matrix. The combined entrapment of metal and gas increases dross volume while reducing effective metallic recovery.

These mechanisms show that oxidation is not merely a surface reaction but a dynamic interfacial process influenced by furnace atmosphere, temperature, and melt-handling practices. Improved atmosphere control and reduced turbulence are therefore essential strategies for limiting oxide formation and enhancing metal yield in closed-loop recycling systems.

Dross formation, quantification, and recovery

Dross is a mixture of aluminum oxide, entrapped metal, and non-metallic residues. Its formation is unavoidable during melting. Quantification studies show that yield losses depend on scrap cleanliness, furnace type, and atmosphere control (Steglich et al., 2020; Modalavalasa & Ayyagari, 2024).

Microscopic and thermodynamic analyses show that oxide films fold and trap liquid metal, forming a semi-solid matrix (Shi et al., 2022). The fraction of trapped metal can be substantial. Recovery technologies attempt to extract this metallic aluminum mechanically or thermally (Yuan et al., 2023; Wu et al., 2025).

Salt slag processing adds complexity. Metal recovery must be balanced with environmental management of residual salts (Wang et al., 2025b). Advanced separation and valorization methods aim to reduce reliance on landfills (Ji et al., 2025; Harmaji et al., 2024). Material-flow assessments confirm that incomplete dross recovery represents a structural loss in secondary production (Hannula et al., 2020).

Dross formation, an inevitable part of aluminum remelting, causes significant metal loss in secondary production. It consists of metallic aluminum droplets, oxides, spinel phases, entrapped salts, and minor alloying elements. Recoverable aluminum varies with furnace type, atmosphere control, and melt handling (Shi et al., 2022; Yuan et al., 2023). Effective recovery methods are crucial for economic efficiency, waste reduction, and environmental impact. Figure 9 shows the aluminum dross composition and the common recovery methods and processes.

Figure 9. Conceptual composition of aluminum dross and recovery pathways, including mechanical separation and salt slag processing. Adapted from Shi et al. (2022); Yuan et al. (2023); Wang et al. (2025b).

Primary dross often contains trapped metallic aluminum that can be partly recovered via mechanical separation or remelting in rotary furnaces. This step maximizes metallic yield before treating non-metallic residue.

Salt slag contains aluminum oxides, nitrides, chlorides, and other compounds. Processing involves crushing, leaching, and chemical treatment to recover salts and produce secondary products like alumina-rich materials. By-products can be used in cement or other industries.

Recovery efficiency depends on initial dross composition and process control. Excessive oxidation during remelting raises oxide levels and decreases recoverable metal. Poor salt slag management can create environmental issues. Thus, reducing dross formation during melting is more effective than relying solely on recovery techniques.

Alloy control and metal quality

Metal yield alone does not define recycling performance. Chemical composition determines if recycled aluminum enters high-value uses or must be downgraded. Alloy control is the final barrier between theoretical and industrial circularity.

Impurities, limits, and downcycling risk

Iron and silicon are the most critical residual elements in recycled aluminum. Their accumulation alters phase formation and mechanical properties. Excess iron promotes the formation of brittle intermetallic phases, reducing ductility and fatigue resistance (Zhu et al., 2021). Silicon variation modifies solidification behavior and casting performance.

Studies confirm that impurity buildup becomes progressively harder to correct as recycled content increases (Tu & Hertwich, 2022). Even when concentrations remain within specification, microstructural distribution can still influence final performance (Vicent Fanconi et al., 2023). Control strategies rely on dilution, refining additions, or scrap segregation.

Industrial assessments show that imperfect upstream sorting can cause alloy dilution or costly corrective alloying (Van den Eynde et al., 2022). Sensor classification reduces but doesn't eliminate this risk (Mysliu et al., 2023). Material-flow modeling indicates closed-loop recycling faces thermodynamic and compositional limits (Freitas et al., 2023).

Table 5 presents critical impurity limits for common aluminum alloy families, highlighting the narrow compositional windows required for sheet and structural applications.

Table 5. Typical impurity limits (Fe, Si, Mg, Zn) in selected aluminum alloy families and associated performance risks when exceeded. Adapted from Zhu et al. (2021); Vicent Fanconi et al. (2023); Van den Eynde et al. (2022).

Alloy Family	Fe Limit (%)	Si Limit (%)	Mg/Zn Sensitivity	Risk When Exceeded
3xxx (sheet)	~0.7	Controlled	Moderate	Loss of ductility
5xxx	~0.4–0.5	Low	High Mg sensitivity	Corrosion resistance loss
6xxx	~0.35	Controlled	Balanced Mg/Si	Reduced strength
7xxx	<0.3	Very low	Zn critical	Brittleness/fatigue risk

The table shows that tolerance margins are constrained. Incremental contamination can shift material from high-value sheet applications into casting grades. Downcycling is therefore not a market anomaly but a metallurgical consequence.

Upcycling and high-performance applications

Advanced refining and controlled alloying enable recycled aluminum to enter higher-performance categories. Research on recycled-content 6xxx and 7xxx alloys shows that mechanical performance can approach primary-material standards when composition and processing are tightly controlled (Du et al., 2024; Zhou et al., 2021).

Aerospace and structural alloys need strict control of residual elements and inclusions (Hou et al., 2025; Zhan et al., 2023). Microstructural refinement and thermomechanical treatments can mitigate impurity effects (Tangsuksan et al., 2025; Wang et al., 2025a). Additive manufacturing emphasizes the importance of compositional consistency (Milligan et al., 2024).

However, such upcycling strategies often require higher energy inputs, additional alloying additions, or stricter scrap selection (Al-Helal et al., 2021). The economic feasibility of large-scale upcycling remains uncertain.

The destination of recycled aluminum depends on scrap quality, alloy control, and impurities. While cans are a model for closed-loop recycling requiring strict sorting (Van den Eynde et al., 2022), recycled metal can re-enter sheet production, become high-performance alloys, or downcycled into casting grades (Du et al., 2024; Hou et al., 2025). These routes influence whether recycling preserves material value or dilutes alloy quality. Figure 10 shows these pathways.

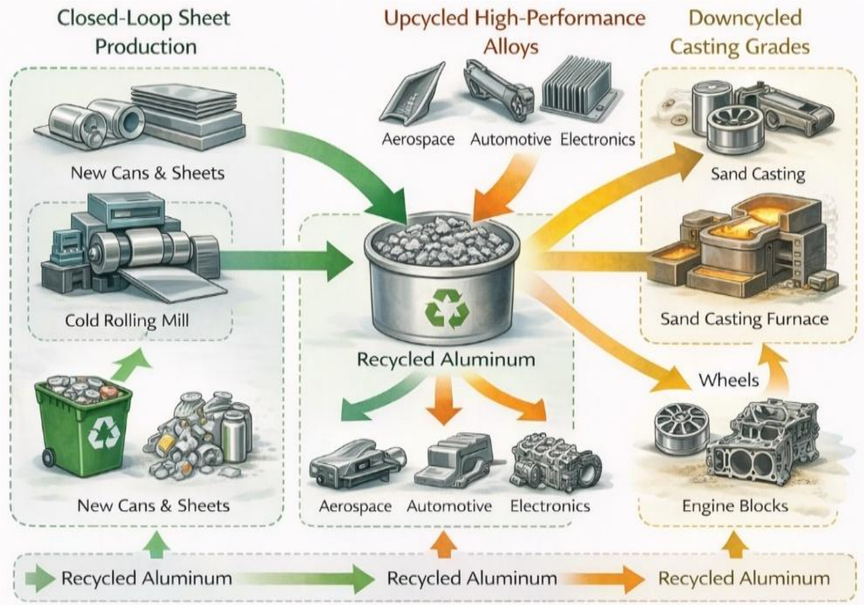


Figure 10. Conceptual pathways of recycled aluminum: closed-loop sheet production, upcycled high-performance alloys, and downcycled casting grades. Adapted from Du et al. (2024); Hou et al. (2025); Van den Eynde et al. (2022).

Closed-loop sheet production represents the highest level of material retention, in which used beverage cans are remelted and rolled into new can stock. This route requires strict limits on Fe, Si, and other residual elements, as well as careful melt treatment. When these conditions are met, recycled aluminum can maintain properties comparable to primary-based sheet.

Upcycling pathways aim to produce high-performance alloys for automotive, aerospace, or electronic applications. Achieving this outcome typically requires compositional adjustments, impurity dilution, or advanced refining strategies. Although technically feasible, these routes demand greater process control and often higher energy input.

By contrast, downcycling into casting grades is more tolerant of impurity accumulation. Scrap with mixed compositions or elevated residual content is often redirected to sand-casting or die-casting applications, such as engine blocks or wheels. While this preserves metallic value, it may reduce the likelihood of future closed-loop recovery due to compositional drift.

The balance of pathways highlights a key challenge in aluminum recycling: preserving alloy integrity amid complex scrap streams. It relates to the circularity debates and emphasizes quality-based recycling metrics over mass-recovery indicators.

Application-specific routes and performance considerations

Recycled aluminum serves diverse applications. Casting alloys tolerate higher impurity levels but have reduced mechanical margins (Holzschuh et al., 2023). Conductive strips and rolled products require tighter control of composition and surface quality (Badarulzaman et al., 2020; Yakubov et al., 2024).

Composite development offers another pathway by incorporating recycled aluminum into reinforced systems (Kazeem et al., 2020; Bao et al., 2023). Emerging fabrication routes examine performance retention under cyclic loading and structural stress (Memon et al., 2025; Hirsch et al., 2023).

Microstructural integrity remains critical. Residual stresses and phase distribution govern fatigue and fracture behavior (Khoshroyan & Darvazi, 2020; Lu et al., 2020). Grain structure evolution during remelting and solidification influences strength and ductility (Pan et al., 2023). These factors limit the extent to which recycled aluminum can replace primary material in high-integrity components.

Alloy control is the structural bottleneck in aluminum can recycling. Impurity accumulation is cumulative. Corrective alloying increases costs and embodied energy. Perfect closed-loop recycling requires near-perfect sorting and compositional monitoring, conditions rarely achieved at an industrial scale.

Upcycling is technically feasible but not inherently sustainable. It may shift energy demand from primary electrolysis to secondary refining. By contrast, downcycling preserves material flow but sacrifices value. The balance between these outcomes determines the true circular performance of aluminum recycling systems.

To evaluate whether recycled aluminum genuinely reduces environmental burdens while accounting for these metallurgical constraints, the next section examines energy use, emissions, and life cycle assessment results across the recycling chain.

Environmental and energy assessment

Environmental performance is the central argument for aluminum recycling. Yet reported advantages vary widely across studies. Energy intensity, emission factors, and system boundaries also differ. A critical assessment requires integrating thermodynamic analysis with life cycle modeling.

Energy consumption, exergy, and process–LCA integration

Secondary aluminum production consumes far less energy than primary electrolysis. Reported values for recycled aluminum typically range from 5–10% of the energy demand of primary production, depending on furnace type and scrap preparation (Hannula et al., 2020). However, this ratio masks variability associated with oxidation losses, decoating energy demand, and dross recovery.

Thermal balance modeling indicates furnace efficiency depends on charge cleanliness and heat recovery (Andayesh, 2024). Exergy assessments reveal losses from fuel combustion, irreversible oxidation, and slag formation (Meskers et al., 2024; Luo et al., 2024).

Recent LCA studies attempt to integrate process-level thermodynamic data with environmental indicators (Rossi et al., 2025), but this integration remains limited. Many studies rely on averaged industrial data rather than plant-specific measurements.

Table 6 presents a comparison of reported energy intensities, illustrating the variability between primary and secondary aluminum production.

Table 6. Reported energy consumption ranges (kWh/t Al) for primary electrolysis and secondary remelting of aluminum scrap, highlighting variability due to process configuration. Adapted from Hannula et al. (2020); Andayesh (2024); Meskers et al. (2024).

Production Route	Energy Consumption (kWh/t Al)	Relative Intensity
Primary (electrolysis)	13,000–15,000	100% baseline
Secondary (recycling)	600–1,500	5–10% of primary

Although secondary production remains less energy-intensive, actual performance depends on scrap quality and operational control.

Emissions and environmental trade-offs

Greenhouse gas emissions from recycled aluminum are substantially lower than those from primary production when fossil-fuel-based electricity dominates the grid (Yang et al., 2024). However, the carbon intensity of secondary production is sensitive to the regional electricity mix and furnace fuel choice (Zhang, Y., et al., 2023).

Beyond CO_2, melting operations emit NO_x, particulate matter, and combustion by-products from decoating (Astarita et al., 2023). Improper control can worsen local air-quality impacts (Tamburini et al., 2021). Emission-control systems mitigate these impacts but increase energy demand.

Comparisons within the packaging sector reveal additional trade-offs. Substituting aluminum with alternative materials shifts environmental burdens rather than eliminating them (Tian et al., 2025). Regional policy frameworks also shape environmental performance (Gavrilescu et al., 2023). Industrial assessments confirm that system boundaries determine whether recycled aluminum outperforms alternative packaging options (El Mehtedi et al., 2023).

Energy use accounts for the majority of GHG emissions in aluminum production. Although secondary recycling needs less energy than primary smelting, its carbon footprint depends on the electricity mix for remelting (Yang et al., 2024; Zhang et al., 2023). Therefore, comparing primary and secondary aluminum requires considering regional grid intensity, not uniform emission factors. Figure 11 compares emission intensities across different electricity grid scenarios.

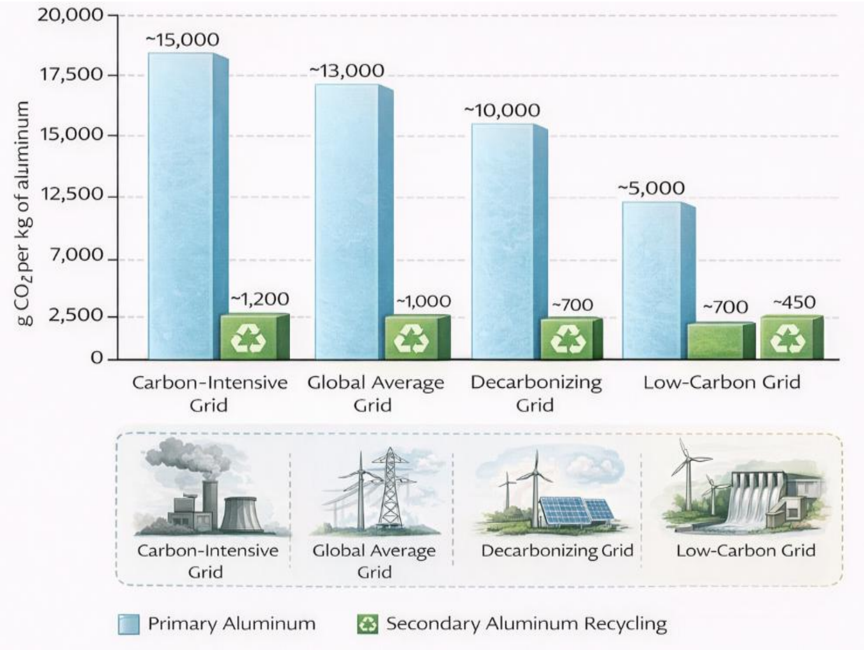


Figure 11. Comparative greenhouse gas emission intensity of primary aluminum production versus secondary recycling under different electricity grid scenarios. Adapted from Yang et al. (2024) and Zhang, Y., et al. (2023).

As illustrated, primary aluminum production has substantially higher GHG emissions across all grid configurations, reflecting the energy-intensive nature of alumina refining and electrolytic reduction. Even under decarbonizing or low-carbon electricity scenarios, primary production remains significantly more carbon-intensive than recycling.

Secondary aluminum consistently shows markedly lower emission intensities; however, the magnitude of its environmental advantage varies with grid carbon intensity. In carbon-intensive electricity systems, recycling emissions rise but remain well below those of primary production. In contrast, under low-carbon grids, secondary aluminum approaches very low emission levels, reinforcing its role in climate mitigation strategies.

These results highlight two critical implications. First, maximizing scrap recycling delivers immediate emission reductions compared with primary production. Second, decarbonizing electricity systems further amplifies the climate benefits of aluminum recycling. Consequently, climate performance assessments must integrate both process efficiency and regional energy context rather than rely on generalized global averages.

LCA, MFA, and methodological limitations

Life cycle assessment (LCA) and material flow analysis (MFA) are widely used to quantify the benefits of recycling. However, methodological differences limit comparability. Allocation rules, scrap-crediting methods, and system boundaries vary across studies (Pedneault et al., 2023).

Some LCAs assume perfect closed-loop recycling, ignoring alloy dilution and quality degradation (Tu & Hertwich, 2022). Others incorporate material-flow constraints but lack consistent data transparency (Rossi et al., 2025; Mika et al., 2025). Variability in emission factors and regional parameters complicates cross-study comparisons (Rosenberg et al., 2023).

Circularity metrics often prioritize mass flow while neglecting alloy integrity (Fridrich et al., 2024). Recent critiques emphasize integrating material quality into LCA frameworks (Elzein et al., 2025; Sazdovski, 2025). Energy pathway comparisons also show that crediting assumptions significantly alter results (Metlen, 2022).

LCA results for aluminum recycling are highly sensitive to methodological choices like boundary definitions (closed-loop vs. open-loop) and allocation methods, significantly affecting environmental benefit estimates (Pedneault et al., 2023; Tu & Hertwich, 2022; Fridrich et al., 2024). Differences in emission savings often result from accounting assumptions rather than technology. Figure 12 illustrates how boundary and allocation choices affect environmental performance.

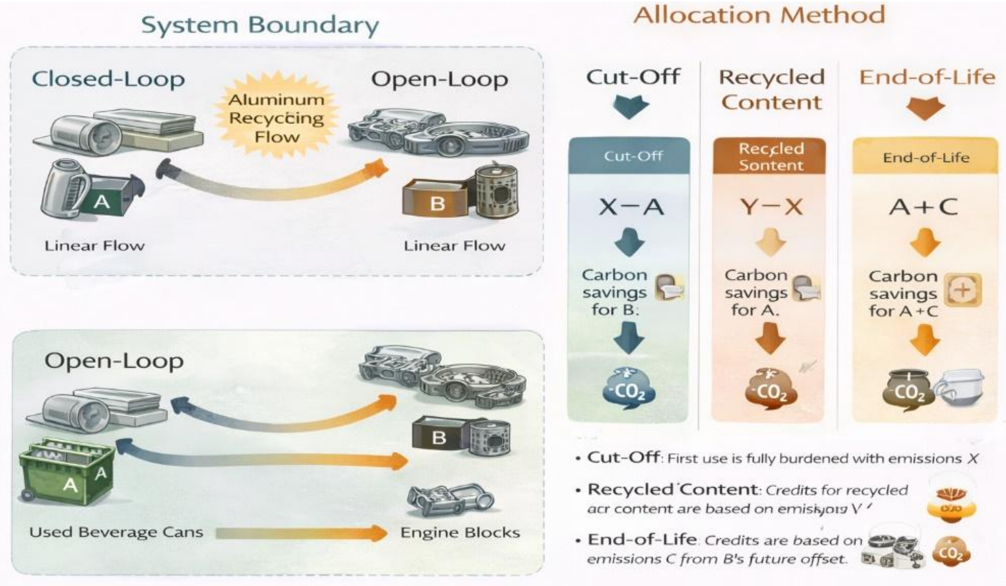


Figure 12. Influence of system boundary definition and allocation method on calculated environmental benefits of aluminum recycling. Adapted from Pedneault et al. (2023); Tu & Hertwich (2022); Fridrich et al. (2024).

As shown, a closed-loop boundary assumes that recycled aluminum directly substitutes for primary material within the same product system (e.g., can-to-can). Under this assumption, environmental credits are typically maximized because material value and quality are preserved. In contrast, open-loop modeling accounts for quality shifts and product substitution across different applications, often reducing the attributed environmental benefit.

Allocation approaches alter results. The cut-off method assigns all impact to the first life cycle, leaving recycled material “burden-free.” The recycled-content method divides impacts based on secondary input share. The end-of-life method credits recycling to the current system. Each reflects a different view of responsibility and circularity.

These methodological differences complicate direct comparisons among studies and may lead to over- or underestimation of recycling benefits. Transparent reporting of system boundaries and allocation rules is therefore essential. Without such clarity, environmental claims about aluminum recycling risk being misinterpreted, undermining policy and industrial decision-making.

While environmental performance underpins policy support for aluminum recycling, economic viability ultimately determines industrial adoption and investment. These factors are examined in the following section on Economic Aspects.

Economic aspects

Technical feasibility does not ensure economic viability. Aluminum can recycling operates under narrow margins influenced by scrap price volatility, energy cost, and logistics efficiency. Investment decisions reflect both market dynamics and policy frameworks.

Capital and operational costs

Secondary aluminum plants generally require lower capital expenditure (CAPEX) than primary smelters. They avoid electrolytic reduction infrastructure and large-scale power contracts (Li et al., 2020). However, melting furnaces, emission-control systems, decoating units, and dross treatment facilities still represent significant investments.

Operational expenditure (OPEX) is driven by scrap procurement, energy consumption, fluxes, labor, and environmental compliance. Scrap cost is the main factor in total production costs (Goncharova & Golodnova, 2023). Energy intensity, though lower than in primary production, remains sensitive to furnace type and yield losses.

Environmental compliance imposes both direct and indirect costs. Emission-control systems, salt slag treatment, and waste management increase operational complexity (Ji et al., 2025). These costs are often underestimated in simplified economic comparisons.

The table shows the cost structure of secondary aluminum production, reflecting the interaction among scrap input, energy use, and environmental management.

Table 7. Simplified cost structure of aluminum can recycling operations, including major CAPEX components and dominant OPEX drivers. Adapted from Li et al. (2020); Goncharova & Golodnova (2023); Ji et al. (2025).

Cost Component	CAPEX Impact	OPEX Impact	Sensitivity
Furnace system	High	Moderate	Medium
Decoating & emission control	High	Moderate	Medium
Scrap procurement	Low	Very High	High
Energy	Low	High	High
Dross treatment	Moderate	Moderate	Medium

Scrap procurement typically accounts for the largest share of OPEX. Variability in scrap quality further amplifies cost uncertainty.

Sensitivity to scrap price and market conditions

Secondary aluminum production depends on scrap prices. When scrap prices near or surpass the cost advantage over primary aluminum, margins shrink (Broniewicz et al., 2023). Price volatility varies due to global trade policies and regional demand (Arora, 2023).

Market analyses show that carbon pricing and regulations can affect competitiveness. In areas with low-carbon electricity, primary production may narrow the emissions gap, influencing policy incentives (Zhang, M., et al., 2025). Stricter controls can also raise costs in secondary production.

Scrap quality also affects economic performance. Lower-quality scrap increases oxidation losses and alloy-correction costs, resulting in direct economic penalties.

Secondary aluminum production depends on raw material costs and process efficiency. Scrap, a major OPEX component, can exceed energy and labor costs (Broniewicz et al., 2023; Arora, 2023). Metal yield, influenced by oxidation, dross, and handling, directly affects cost per kilogram of saleable aluminum. Small changes in these can greatly impact profitability. Figure 13 shows the combined sensitivity of production costs to scrap price and metal yield.

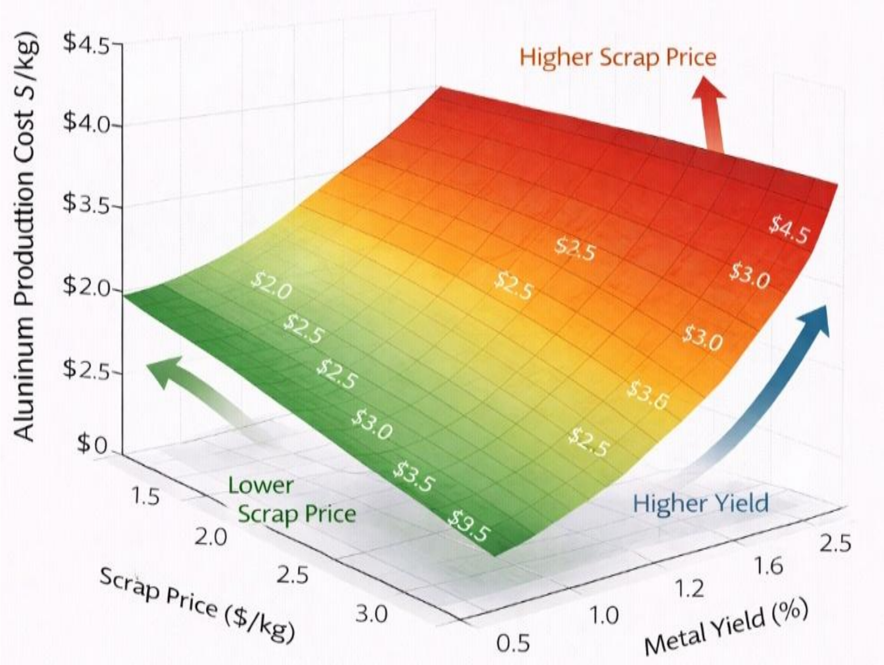


Figure 13. Conceptual sensitivity of secondary aluminum production cost to scrap price and metal yield. Adapted from Broniewicz et al. (2023) and Arora (2023).

Production costs soar with higher scrap prices, especially with low metal yield, making unrecovered aluminum in dross costly. Improving yield through better atmosphere control, charging, and dross management helps offset high scrap costs.

These variables reveal a vulnerability of secondary production: profitability is limited by market fluctuations in scrap prices and internal process efficiency. Plants with lower yields are more affected by changes in raw material costs.

This sensitivity highlights the need to integrate metallurgical optimization with strategic procurement. Long-term scrap contracts, improved sorting, and tech investments to reduce oxidation losses are key to stabilizing secondary aluminum margins.

Minimum viable scale and logistics impact

Scale influences economic viability. Small facilities may struggle to amortize investments in emissions-control and de-coating equipment. Larger plants benefit from economies of scale but require stable scrap-supply networks (Li et al., 2020).

Logistics adds complexity. Transport distance affects both cost and environmental impact. Regional concentration of scrap generation can create competitive advantages, whereas a fragmented supply increases handling costs (Goncharova & Golodnova, 2023).

Cross-border scrap flows pose regulatory risks. Trade restrictions and carbon border mechanisms can affect feedstock availability and price stability (Arora, 2023). Therefore, economic resilience depends not only on process efficiency but also on supply-chain robustness.

Secondary aluminum production is economically attractive under favorable scrap and energy conditions. However, profitability is fragile. Yield losses from oxidation and inadequate sorting undermine both environmental and economic benefits. Investment in advanced sorting or decoating must be justified by measurable improvements in metal recovery.

Economic assessments often assume a stable scrap supply and constant quality. In practice, variability introduces risk. Financial performance is therefore tied to upstream control as much as to furnace efficiency.

Economic viability shapes industrial deployment, but the long-term justification for aluminum can recycling rests on broader circular-economy and sustainability frameworks, examined in the following section.

Circular economy and sustainability perspectives

Aluminum cans are frequently presented as a model of circular economy. High collection rates and material recoverability support this narrative. Yet circularity depends on more than mass recovery. Alloy integrity, energy intensity, and system boundaries define real sustainability performance.

Closed-loop versus open-loop recycling

Closed-loop recycling means used beverage cans return to sheet-grade production without quality loss, requiring strict alloy segregation and controlled impurities (Hagelüken & Goldmann, 2022). When composition drifts, material is diverted to casting or lower-value uses.

Material-flow analyses demonstrate that even high-recovery systems experience alloy dilution over time (Marinina et al., 2022). Open-loop recycling preserves mass flow but alters material function. This distinction is often overlooked in policy discourse (Kotabe, 2023).

Thermodynamic and resource-efficiency perspectives highlight the limits of infinite recyclability (Sherwood, 2020). Each melting cycle introduces oxidation losses and impurity accumulation. Perfect circularity is therefore a boundary condition rather than an industrial norm.

The claim that aluminum is “infinitely recyclable” is common in sustainability discussions. However, closed-loop recycling requires strict alloy and impurity control (Hagelüken & Goldmann, 2022; Marinina et al., 2022; Sherwood, 2020). Well-sorted scrap and maintained alloy chemistry make can-to-can recycling feasible. Mixed or contaminated scrap causes compositional drift and lower-grade use. Figure 14 compares closed- and open-loop aluminum recycling, showing where quality may degrade.

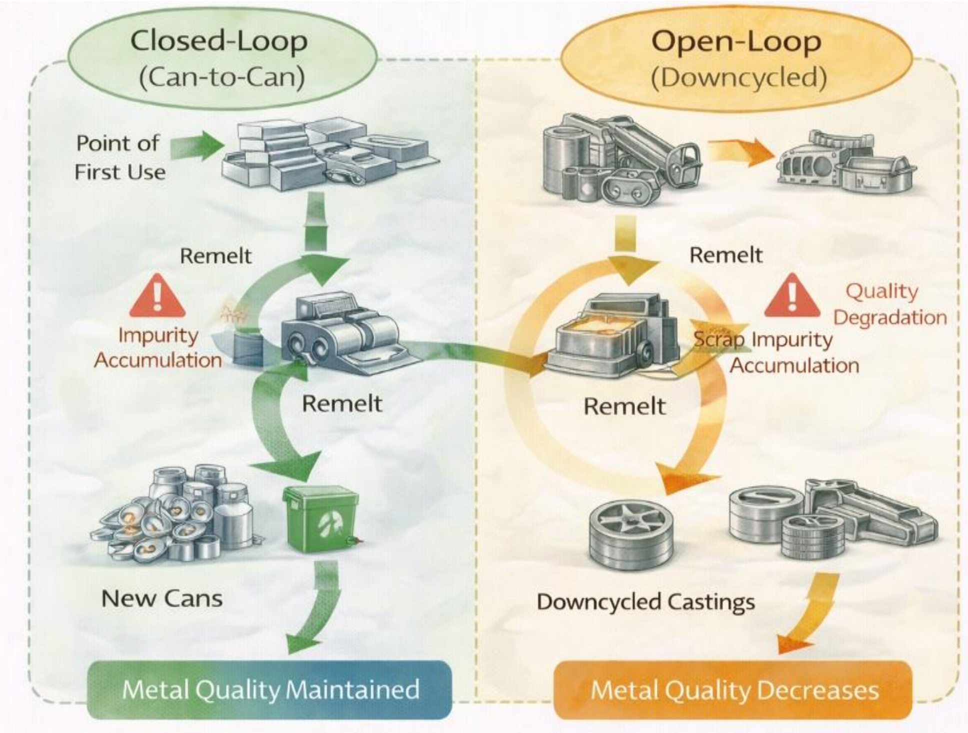


Figure 14. Conceptual comparison of closed-loop (can-to-can) and open-loop (downcycled) aluminum recycling pathways, including quality degradation points. Adapted from Hagelüken & Goldmann (2022); Marinina et al. (2022); Sherwood (2020).

In closed-loop recycling, used beverage cans are collected, sorted, remelted, and reprocessed into new cans. Minor impurity buildup is managed through compositional adjustments and high-quality sorting, maintaining alloy integrity. This method preserves material value and ensures high recycling efficiency environmentally and economically.

The open-loop pathway shows how impurity buildup—mainly Fe, Si, Cu, and residual elements—limits recycling in sheet applications. Once thresholds are surpassed, recycled aluminum is often used for casting alloys, which tolerate more compositional variation. This shift indicates quality degradation, not total material loss.

The comparison highlights a key limitation of circularity metrics that rely only on mass flow. Both pathways are technically recycling, but only the closed-loop route preserves original performance. Policies and strategies should focus on quality-preserving recycling to prevent downcycling and alloy value loss.

Policy integration and governance

Circular performance is shaped by policies like deposit-return systems, EPR, and recycling targets, which influence scrap flows and investments (Weritz & Dudek, 2022). Regulatory design impacts collection efficiency and material quality.

Comparative studies show that regional governance models yield different recovery outcomes (Ile et al., 2025; Reshetnikova et al., 2025). Financial incentives can increase return rates but may not address alloy segregation. Policy integration with industrial capabilities remains uneven.

Environmental accounting frameworks also shape reported sustainability benefits (Hildenbrand et al., 2020). Without harmonized metrics, cross-country comparisons may exaggerate performance differences.

As shown in Table 8, policy instruments influence both collection volume and material quality.

Table 8. Policy instruments influencing aluminum can recycling performance, including deposit-return systems, EPR schemes, and recycling targets, and their impact on quality and yield. Adapted from Weritz & Dudek (2022); Ile et al. (2025); Reshetnikova et al. (2025).

Instrument	Primary Objective	Impact on Collection	Impact on Quality
Deposit-Return System	Increase recovery rate	High	Positive
Extended Producer Responsibility	Cost internalization	Moderate–High	Indirect
Recycling targets	Compliance	Moderate	Limited
Carbon pricing	Emission reduction	Indirect	None direct

Policy effectiveness depends on the alignment between regulatory ambition and technological capacity.

Circularity indicators and conceptual limits

Circularity indicators often measure recycled content or recovery rates. These metrics prioritize mass balance and rarely account for alloy degradation or oxidation losses (Souza Alvim et al., 2025).

Quality-adjusted indicators have been proposed to better reflect functional retention (Kotabe, 2023). Resource-efficiency metrics indicate that thermodynamic constraints should be incorporated into circularity assessments (Sherwood, 2020). However, standardized implementation remains limited.

The concept of “100% recyclable” aluminum is technically correct at the elemental level. Industrially, it is conditional. Losses occur in each cycle. Alloy quality constraints and contamination limit the true material's longevity (Hagelüken & Goldmann, 2022). The phrase, therefore, reflects potential rather than a guaranteed outcome.

Circularity in aluminum systems often uses mass-based indicators like recycling rate, recycled content, or recovery rate. While these metrics show material flow, they don't reflect changes in alloy quality or performance (Kotabe, 2023; Souza Alvim et al., 2025; Sherwood, 2020). Systems with high mass recovery can still face downcycling and value loss. Figure 15 shows the gap between traditional metrics and quality-adjusted recycling performance.

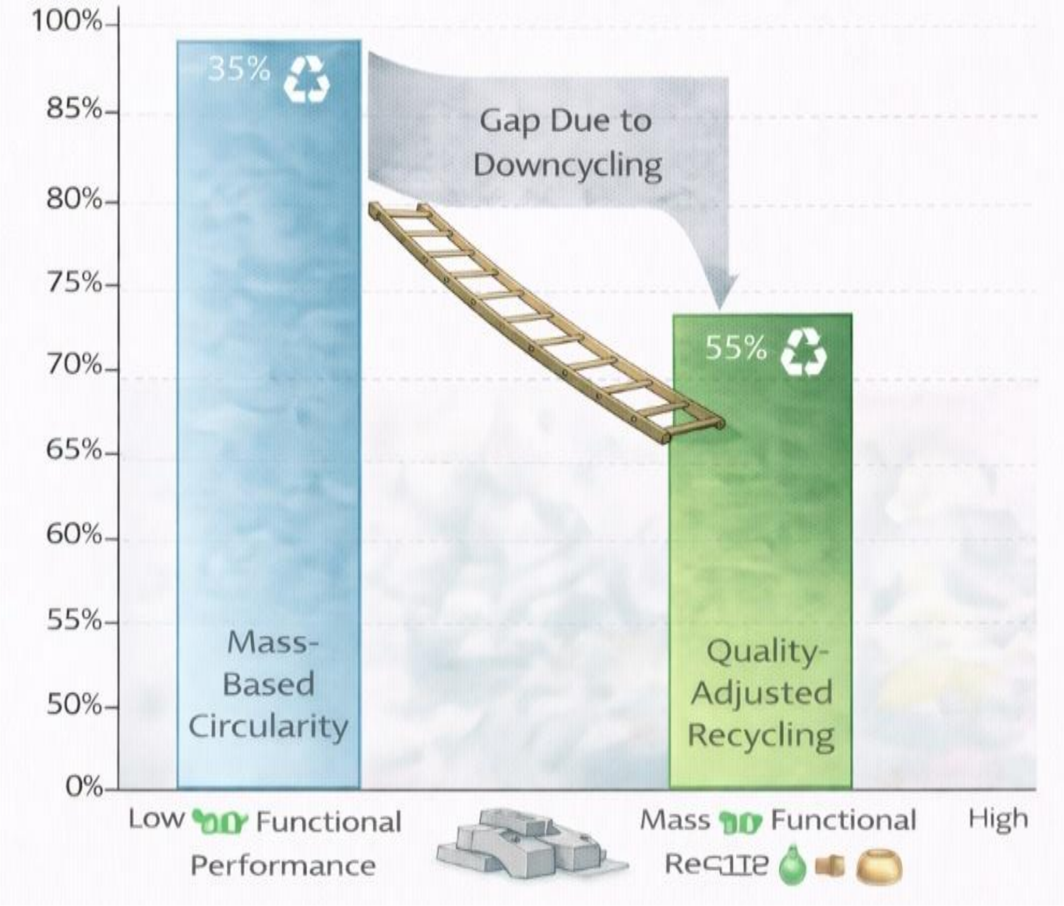


Figure 15. Gap between mass-based circularity metrics and quality-adjusted recycling performance in aluminum systems. Adapted from Kotabe (2023); Souza Alvim et al. (2025); Sherwood (2020).

Mass-based circularity indicates high recycling when most aluminum re-enters production. However, if alloy composition drifts beyond limits, recycled material can't fully replace its original use. It stays in circulation but at reduced functionality.

Quality-adjusted recycling metrics account for performance shifts by considering alloy integrity, substitution potential, and functional equivalence. The gap between indicators shows downcycling, where mass is retained but technical value drops.

This distinction affects policy and industry reports. Relying on mass-based indicators may overstate circular performance. Using quality-sensitive metrics offers a more accurate view of whether aluminum recycling preserves value or just delays degradation.

While current systems exhibit structural constraints, ongoing research and technological innovation aim to enhance sorting precision, melting efficiency, and environmental performance, which are explored in the following section on Emerging Technologies and Future Trends.

Emerging technologies and future trends

Current recycling systems face issues such as alloy mixing, oxidation losses, and limited data transparency. New technologies aim to solve these problems, but their success depends on scalability, costs, and actual yield improvements.

Advanced sorting and digitalization

Sensor-based sorting continues to evolve. LIBS systems provide rapid alloy identification at the particle level (Diaz-Romero et al., 2023). Machine-learning algorithms improve signal interpretation and classification accuracy (Efe et al., 2025). Time-resolved acoustic and spectroscopic techniques enhance detection in heterogeneous scrap streams (Wang et al., 2025c).

Digital integration links sorting data with production control. Real-time compositional mapping enables adaptive alloy correction before melting. Industry 4.0 frameworks support predictive maintenance and process optimization.

However, throughput limitations and capital cost remain barriers. High-resolution sorting may reduce impurity accumulation but increases system complexity. Economic feasibility is therefore linked to scrap value and product specification.

Recent digital advances are transforming aluminum recycling with sensor-based scrap characterization, machine learning, and adaptive furnace control. These innovations enable tighter alloy specifications, reduce oxidation losses, and boost energy efficiency. Industry 4.0 links sorting and melting, using data from scrap sorting to inform furnace setpoints, alloy additions, and process adjustments in a closed feedback loop.

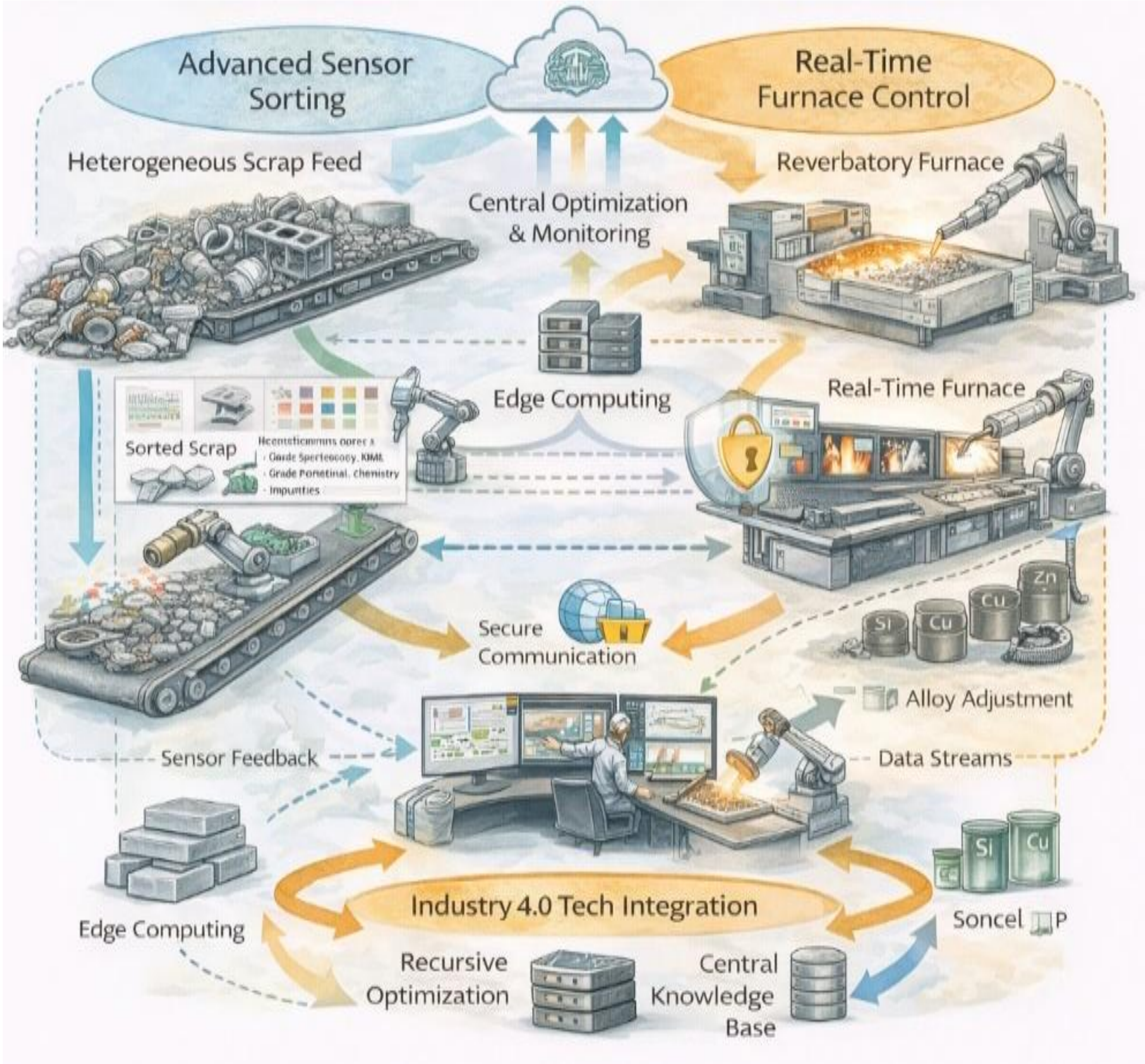


Figure 16. Conceptual integration of advanced sensor sorting, machine learning, and real-time furnace control within an Industry 4.0 aluminum recycling framework. Adapted from Diaz-Romero et al. (2023); Efe et al. (2025); Wang et al. (2025c).

Figure 16 shows sensors like LIBS, XRF, and hyperspectral systems classifying scrap with machine learning. Data feeds a central platform linking composition prediction with furnace setpoints, alloy addition, and energy input. Real-time monitoring allows dynamic melt chemistry corrections, reducing dilution and dross. Feedback among scrap yard, edge computing, and furnace shifts from reactive to predictive quality control. This digital integration is essential for closed-loop recycling in complex alloy markets.

Emerging processing routes

Alternative remelting approaches seek to reduce oxidation and energy demand. Solid-state recycling techniques consolidate aluminum without full melting (El Mehtedi et al., 2023). These routes reduce liquid-phase oxidation but require homogeneous feedstock.

Shear-assisted processing enhances melt homogenization and may reduce inclusion formation (Padamata et al., 2021). Molten-salt and protective-atmosphere furnaces aim to limit surface oxidation (Wang et al., 2025a). Process innovations targeting chip and machining-scrap recovery show potential for high-yield recycling (Milligan et al., 2024).

Thermal optimization strategies emphasize heat recovery and improved combustion control (Gogoi, 2025; Dey, 2025). While these approaches promise efficiency gains, industrial adoption depends on compatibility with existing infrastructure.

Table 9 presents how emerging technologies differ in technical maturity, oxidation control potential, and scalability.

Table 9. Comparison of emerging aluminum recycling technologies, including solid-state consolidation, shear processing, molten-salt protection, and advanced furnace control. Adapted from El Mehtedi et al. (2023); Milligan et al. (2024); Wang et al. (2025a).

Technology	Maturity Level	Oxidation Reduction Potential	Scalability	Main Constraint
Solid-state consolidation	Pilot	High	Limited	Feed homogeneity
Shear-assisted processing	Pilot	Moderate	Medium	Equipment complexity
Molten-salt protection	Industrial	High	Medium	Salt residue
AI-integrated control	Emerging	Indirect	High	Investment cost

Many technologies show laboratory or pilot success. Industrial-scale validation remains limited.

New application frontiers

Recycled aluminum is increasingly used in additive manufacturing (AM), conductive strip production, and advanced composites. AM applications require strict control of powder composition and microstructural consistency (Yakubov et al., 2024). Feedstock stability remains a limiting factor.

Food-contact applications require surface cleanliness and compositional compliance (Miteva & Hodjaoglu, 2024). Regulatory standards set limits on impurity levels. Composite reinforcement strategies incorporate recycled aluminum into hybrid systems (Memon et al., 2025).

These emerging applications expand potential value but also increase quality requirements. Scrap variability, therefore, becomes a greater challenge rather than a lesser one.

Recycled aluminum is increasingly used in high-value, advanced sectors beyond traditional casting and sheet applications (Figure 17). Advances in melt cleanliness, alloy design, and powder production are broadening potential uses. Secondary aluminum isn't limited to lower-quality products if compositional control and processing are precise, especially in applications with strict chemical and microstructural requirements.

Figure 17. Emerging application pathways for recycled aluminum, including additive manufacturing, conductive products, and advanced composites. Adapted from Yakubov et al. (2024); Miteva & Hodjaoglu (2024); Memon et al. (2025).

Figure 17 shows three innovation routes. In additive manufacturing, recycled aluminum powders are reprocessed for 3D printing lightweight structures and custom parts. For conductive uses, secondary aluminum can be used in foils, powders, and interconnects for electronics and energy, if impurities are controlled. In advanced composites, recycled aluminum serves as a matrix or filler in hybrid and surface-engineered systems. These routes show that quality-controlled recycling supports diversification but needs stricter alloy management and traceability than traditional remelting.

Emerging technologies target known bottlenecks: impurity accumulation, oxidation losses, and data gaps. Advanced sorting and digital control may reduce variability. Alternative processing routes may mitigate oxidation. Yet scalability and cost remain decisive factors.

Innovation does not eliminate thermodynamic constraints. Each recycling cycle still incurs losses. The question is not whether losses can be eliminated, but whether they can be reduced enough to sustain high-quality closed-loop flows.

Technological progress alone does not resolve systemic inefficiencies. Critical bottlenecks arise at specific interfaces: coating chemistry is rarely quantified at scale, scrap traceability diminishes after baling and aggregation, and remelting yields used in LCA models are often based on standardized assumptions rather than plant-level data. As a result, reported circularity and environmental benefits may overestimate actual material retention. Addressing these discrepancies requires integrating process metallurgy, data transparency, and methodological rigor—issues examined in the following section on Critical Synthesis and Research Gaps.

Critical synthesis and research gaps

The preceding sections show that aluminum can recycling is technically robust but structurally constrained. Material losses, alloy drift, and methodological inconsistencies limit the claim of near-perfect circularity. This section consolidates the main bottlenecks and identifies priority research directions.

Technical bottlenecks across the chain

Oxidation and dross formation remain the most persistent sources of metal loss. Even under optimized furnace conditions, oxide growth traps liquid aluminum and reduces effective yield (Steglich et al., 2020; Padamata et al., 2021). Dross recovery technologies improve metal extraction but do not eliminate losses (Harmaji et al., 2024; Wu et al., 2025).

Upstream sorting determines alloy integrity. Incomplete segregation introduces impurity accumulation that cannot be fully corrected at the melting stage (Pedneault et al., 2023; Van den Eynde et al., 2022). Advanced sorting technologies reduce variability but require economic justification and system integration.

Decoating efficiency also influences oxidation and emissions. Inadequate pretreatment shifts combustion to the melting furnace, increasing yield loss and environmental burden (Yang, J., et al., 2025). Process control across stages remains fragmented.

Figure 18 shows structural bottlenecks affecting whether high collection rates lead to high material retention. Oxidation and dross formation during remelting cause the most immediate yield loss, influenced by controllable variables like furnace atmosphere, scrap charging rate, bale density, and decoating efficiency. Key performance indicators include metal yield (%), dross rate (kg/t scrap), and aluminum loss from oxidation.

Figure 18. System-level bottleneck map for aluminum can recycling, highlighting yield losses (oxidation/dross), alloy contamination, decoating inefficiencies, and data limitations. Adapted from Padamata et al. (2021); Steglich et al. (2020); Van den Eynde et al. (2022).

Alloy contamination primarily stems from insufficient sorting resolution and uncontrolled scrap mixing. The critical control variables are sensor accuracy, alloy classification thresholds, and segregation strategy at the yard level. Relevant KPIs include residual Fe and Cu content in the melt (wt.%), dilution rate with primary aluminum, and rejection frequency for sheet-grade production.

Decoating inefficiencies increases both energy demand and emission intensity. Temperature uniformity, residence time, and oxygen availability are measurable parameters that directly affect VOC destruction efficiency and oxide growth. Useful indicators include specific energy consumption (kWh/t), VOC destruction efficiency (%), and post-decoating organic residue content.

Finally, limited coating composition data and incomplete scrap traceability reduce predictive process control. Without reliable input data, remelting yields used in mass balance or LCA models may reflect assumptions rather than plant-level performance. Traceability index (% of scrap batches with compositional metadata) and variance in remelting yield are practical metrics to evaluate data transparency.

Taken together, these bottlenecks demonstrate that high collection rates alone do not guarantee quality-adjusted circularity. Performance depends on measurable operational variables and data integrity across the chain, reinforcing the need for integrated sorting accuracy, metallurgical control, and transparent reporting standards.

Optimism in the literature

Many studies emphasize the energy advantage of secondary aluminum without accounting for alloy degradation or cumulative oxidation (Tu & Hertwich, 2022). Reported recycling rates often reflect mass recovery rather than quality retention.

Life cycle assessments often assume a stable scrap composition and high furnace yield (Rossi et al., 2025). Industrial variability is rarely captured. Material-flow analyses show that impurity accumulation limits the scale of closed-loop recycling (Van den Eynde et al., 2022).

Circular-economy narratives sometimes conflate theoretical recyclability with operational performance (Hagelüken & Goldmann, 2022). The distinction between elemental recyclability and alloy-grade preservation remains underaddressed.

Data gaps and industrial transparency

A recurring limitation is the lack of publicly available plant-level data. Yield figures, oxidation rates, and dross recovery efficiencies are often aggregated or anonymized (Hannula et al., 2020). This reduces comparability across studies.

Environmental assessments rarely report furnace-specific losses or quality-adjusted material flows (Pereira & dos Santos, 2025). Without consistent data, LCA and MFA models rely on assumptions that may not reflect operational conditions.

Standardization of reporting protocols is limited. Differences in system boundary selection and allocation rules further complicate interpretation (Rossi et al., 2025).

Research priorities

Future research should focus on four areas:

Oxidation and Dross Minimization:

Improved understanding of oxide growth kinetics and metal entrapment mechanisms at the industrial scale (Steglich et al., 2020; Wu et al., 2025).

Quality-Adjusted Circular Metrics:

Integration of alloy integrity into LCA and circularity indicators (Tu & Hertwich, 2022; Pereira & dos Santos, 2025).

Sorting–Furnace Integration:

Integrating advanced sensor data with adaptive melting control to reduce impurity-driven losses (Pedneault et al., 2023).

Transparent Industrial Data:

Development of standardized yield-reporting frameworks and harmonized system boundaries (Hannula et al., 2020; Rossi et al., 2025).

These priorities reflect the need to align technological improvements with measurable performance metrics.

Aluminum recycling remains one of the most mature circular systems. Yet maturity does not imply perfection. Oxidation losses, alloy drift, and methodological inconsistencies limit the full realization of a closed loop. The literature often emphasizes comparative advantages over primary production, but it less frequently quantifies internal inefficiencies.

Progress requires integration across collection, sorting, de-coating, melting, and environmental accounting. Improvements must be systemic rather than isolated. Circularity claims should incorporate quality retention and cumulative yield loss.

These synthesized findings provide the basis for the concluding reflections on the realistic potential and limits of aluminum can recycling presented in the final section.

CONCLUSIONS

Aluminum recycling is among the most advanced examples of large-scale material recovery. Secondary production consistently requires far less energy than primary electrolysis and reduces greenhouse gas emissions across most electricity scenarios. High collection rates, especially under deposit-return systems, support strong material circulation. However, the technical analysis presented in this review shows that circularity is conditional rather than automatic.

Metal losses from oxidation and dross formation during melting aren't fully recoverable, even with optimized conditions. Scrap variability impacts alloy quality, despite advanced sorting technologies that reduce impurities. Decoating efficiency affects yield and emissions. Overall, recycling depends on coordinated control throughout the process.

Industrial implications are clear. Improvements in yield, sorting precision, and atmospheric control can deliver both environmental and economic gains. Small increases in metal recovery translate into significant cost savings at scale. Conversely, poor scrap quality or inadequate process integration reduces profitability and sustainability performance. Investment decisions should therefore prioritize system integration over isolated technological upgrades.

For policymakers, mass-based recycling rates are insufficient indicators of circular performance. Quality retention, oxidation losses, and the regional energy mix must be incorporated into evaluation frameworks. Deposit-return systems and extended producer responsibility can improve collection efficiency, but alloy segregation and technological capacity determine whether true closed-loop recycling is achieved. Harmonized reporting standards and transparent industrial data are necessary to align regulatory ambition with metallurgical reality.

From a sustainability perspective, aluminum cans remain a strong candidate for circular material systems. Yet the term “100% recyclable” must be understood within thermodynamic and operational limits. Each recycling cycle introduces incremental losses and compositional constraints. The challenge is not to eliminate these limits but to reduce them through integrated process control, standardized environmental accounting, and targeted innovation.

In summary, aluminum recycling offers substantial environmental and economic advantages over primary production. Its long-term credibility as a circular model depends on continued reductions in oxidation losses, improved alloy control, and greater methodological transparency in environmental assessment.

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Conflicts of Interest

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability

No new experimental data were generated in this study. All data supporting the findings of this review are derived from the published literature cited in the reference list. Any additional information can be provided by the corresponding author upon reasonable request.

Author Contributions

Antonio Clareti Pereira: Conceptualization; methodology; literature screening and analysis; critical synthesis; writing – original draft; writing – review and editing; visualization; supervision.

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