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ALUMINUM SCRAP RECYCLING FOR FOUNDRY ALLOYS: REVIEW OF TECHNOLOGICAL ADVANCES AND CIRCULAR ECONOMY CHALLENGES

RECICLAGEM DE SUCATA DE ALUMÍNIO PARA LIGAS DE FUNDIÇÃO: REVISÃO DOS AVANÇOS TECNOLÓGICOS E DESAFIOS DA ECONOMIA CIRCULAR

RECICLAJE DE CHATARRA DE ALUMINIO PARA ALEACIONES DE FUNDICIÓN: REVISIÓN DE LOS AVANCES TECNOLÓGICOS Y LOS DESAFÍOS DE LA ECONOMÍA CIRCULAR

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ABSTRACT

Aluminum recycling is pivotal for achieving carbon neutrality and advancing the circular economy, offering significant reductions in energy use and greenhouse gas emissions compared to primary production. This review synthesizes global advances from 2020 to 2025 in scrap collection, sorting, remelting, and alloy recovery, with a focus on technological progress, sustainability metrics, and policy integration. Secondary aluminum already supplies over one-third of global demand and could surpass 50 % by 2030 with stronger segregation systems and extended producer responsibility (EPR) schemes. Innovations such as high-shear degassing, solid-state chip recycling, and chloride-free refining have improved melt quality and reduced salt-slag waste. At the same time, life-cycle assessments indicate up to 95% lower emissions compared to virgin aluminum. Persistent barriers remain—namely alloy contamination, inconsistent scrap classification, and limited traceability in informal collection networks. Regional policy experiences demonstrate that harmonized standards, mandatory recycled-content targets, and digital traceability accelerate market adaptation, whereas developing economies still face fragmented logistics and weak governance. Future directions include integrating real-time life-cycle assessment, artificial intelligence-based scrap sorting, and international alloy standards, enabling over 80% recycled content. Overall, aluminum recycling emerges as a technologically mature, economically competitive, and environmentally decisive route for decarbonizing metallurgical production and supporting the global energy transition.

Keywords: Aluminum Recycling. Foundry Alloys. Dross Management. Industry 4.0. Circular Economy. Carbon Reduction. Sustainability.

RESUMO

A reciclagem de alumínio é fundamental para alcançar a neutralidade de carbono e promover a

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economia circular, oferecendo reduções significativas no consumo de energia e nas emissões de gases de efeito estufa em comparação com a produção primária. Esta revisão sintetiza os avanços globais de 2020 a 2025 na coleta, triagem, refusão e recuperação de ligas de sucata, com foco no progresso tecnológico, métricas de sustentabilidade e integração de políticas. O alumínio secundário já supre mais de um terço da demanda global e poderá ultrapassar 50% até 2030 com sistemas de segregação mais robustos e esquemas de responsabilidade estendida do produtor (REP). Inovações como a desgaseificação por cisalhamento de alta intensidade, a reciclagem de cavacos em estado sólido e o refino sem cloretos melhoraram a qualidade da fusão e reduziram o desperdício de escória salina. Ao mesmo tempo, as avaliações do ciclo de vida indicam emissões até 95% menores em comparação com o alumínio virgem. Barreiras persistentes permanecem — principalmente a contaminação por ligas, a classificação inconsistente da sucata e a rastreabilidade limitada em redes informais de coleta. Experiências em políticas regionais demonstram que padrões harmonizados, metas obrigatórias de conteúdo reciclado e rastreabilidade digital aceleram a adaptação do mercado, enquanto as economias em desenvolvimento ainda enfrentam logística fragmentada e governança frágil. Direções futuras incluem a integração da avaliação do ciclo de vida em tempo real, triagem de sucata baseada em inteligência artificial e padrões internacionais para ligas, possibilitando mais de 80% de conteúdo reciclado. Em suma, a reciclagem de alumínio emerge como uma rota tecnologicamente madura, economicamente competitiva e ambientalmente decisiva para a descarbonização da produção metalúrgica e o apoio à transição energética global.

Palavras-chave: Reciclagem de Alumínio. Ligas de Fundição. Gestão de Escória. Indústria 4.0. Economia Circular. Redução de Carbono. Sustentabilidade.

RESUMEN

El reciclaje del aluminio es fundamental para lograr la neutralidad de carbono y promover la economía circular, ofreciendo reducciones significativas en el consumo de energía y las emisiones de gases de efecto invernadero en comparación con la producción primaria. Esta revisión sintetiza los avances globales de 2020 a 2025 en la recolección, clasificación, refusión y recuperación de aleaciones de chatarra, con especial atención al progreso tecnológico, las métricas de sostenibilidad y la integración de políticas. El aluminio secundario ya abastece más de un tercio de la demanda mundial y podría superar el 50 % para 2030 con sistemas de segregación más sólidos y esquemas de responsabilidad extendida del productor (REP). Innovaciones como la desgasificación por alto cizallamiento, el reciclaje de chips de estado sólido y el refinado sin cloruro han mejorado la calidad de la masa fundida y reducido los residuos de escoria salina. Al mismo tiempo, las evaluaciones del ciclo de vida indican una reducción de emisiones de hasta un 95 % en comparación con el aluminio virgen. Persisten barreras persistentes, como la contaminación de las aleaciones, la clasificación inconsistente de la chatarra y la trazabilidad limitada en las redes informales de recolección. Las experiencias en políticas regionales demuestran que las normas armonizadas, los objetivos obligatorios de contenido reciclado y la trazabilidad digital aceleran la adaptación del mercado, mientras que las economías en desarrollo aún enfrentan una logística fragmentada y una gobernanza deficiente. Las futuras tendencias incluyen la integración de la evaluación del ciclo de vida en tiempo real, la clasificación de chatarra basada en inteligencia artificial y las normas internacionales de aleaciones, lo que permite un contenido reciclado superior al 80 %. En general, el reciclaje de aluminio se perfila como una vía tecnológicamente madura, económicamente competitiva y ambientalmente decisiva para descarbonizar la producción metalúrgica y apoyar la transición energética global.

Palabras clave: Reciclaje de Aluminio. Aleaciones de Fundición. Gestión de Escorias. Industria 4.0. Economía Circular. Reducción de Carbono. Sostenibilidad.

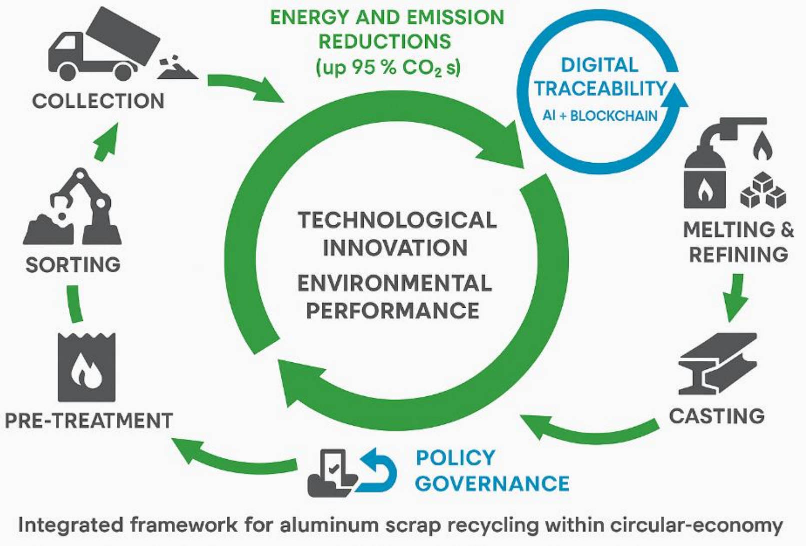
INTRODUCTION

Aluminum is vital in industries such as transportation, packaging, construction, and consumer goods. Its recycling has become essential for strategies aiming at decarbonization, supply assurance, and cost efficiency, as secondary aluminum production consumes significantly less energy and emits substantially less CO_2 than primary production (Padamata *et al*., 2021). In developed markets, circularity goals now extend beyond beverage cans to include cast and wrought alloys, driven by increasing demands for recycled content and traceability. These developments are influencing alloy design, refining techniques, and quality control methods (European Aluminum, 2022; International Aluminum Institute [IAI], 2025; ISO, 2016).

In Brazil, the high recycling rate of aluminum cans, combined with the leadership of national industry associations, emphasizes the potential for an inclusive circular economy. However, international competition and regulatory shifts pose threats to product quality and scrap traceability (ABAL, 2025; Ministério do Meio Ambiente, 2021). Globally, the aluminum industry faces the paradox of lower specific emissions despite growing production, making recycling efficiency and melt quality essential for sustainability (Reuters, 2024; IAI, 2024).

The overall conceptual framework of this review is summarized in Figure 1, which integrates the main technological stages of aluminum scrap recycling—collection, pre-treatment, melting, refining, and alloy recovery—within a circular-economy perspective. The diagram illustrates how technological efficiency, energy reduction, and policy mechanisms converge toward sustainable aluminum production and decarbonization targets

Figure 1. Graphical abstract summarizing the aluminum scrap recycling process and its integration with the circular economy and carbon-reduction principles.



Source: Author’s own elaboration (2025)

From a metallurgical and operational perspective, intensive scrap use presents several technical challenges: (i) pre-treatment and decoating of post-consumer and post-industrial scrap to reduce oxidation, gas release, and dross formation; (ii) controlling melting and refining processes to manage inclusions, hydrogen, and residual elements (Fe, Cu, Zn, Pb); (iii) handling and valorizing dross and salt slag; and (iv) designing alloys and solidification strategies that ensure fluidity, structural integrity, and mechanical performance (Vallejo-Olivares *et al*., 2022, 2024; Milani & Timelli, 2023; Wu *et al*., 2025). In pre-treatment, recent research has quantified the effects of compaction and heating on dross formation and off-gas composition, defining process windows for rotary furnaces and salt fluxes (Vallejo-Olivares *et al*., 2024). Meanwhile, classic studies on scrap charging density have already demonstrated its impact on oxidation behavior (Steglich *et al*., 2020).

During melting and refining, new developments have emerged in degassing and melt cleaning, including high-shear processing applied to end-of-life automotive scrap (Al-Helal *et al*., 2021; Lázaro-Nebreda *et al*., 2022), chlorine-free degassing targeting TiB_2 particle behavior (Li *et al*., 2024), and fine-bubble systems that improve gas-removal efficiency (Kolínský *et al*., 2025). Recent reviews summarize advances in inclusion removal and melt purification for high-recycled-content casting alloys (Liu *et al*., 2024; Yang *et al*., 2025). At the alloy-design level, both upcycling opportunities—such as solid-phase alloying—and the mechanical penalties related to Fe-rich intermetallics have been noted, emphasizing the importance of optimized composition control and cooling strategies (Wang *et al*., 2024a, 2024b; Kotadia *et al*., 2025; De

Caro *et al*., 2023; Asghar *et al*., 2025; Šmalc *et al*., 2023).

Meanwhile, an increasing body of research on life-cycle assessment (LCA) and environmental product declarations (EPDs) for aluminum emphasizes the importance of measuring impacts from scrap pre-treatment through salt-slag management (European Aluminum, 2025a, 2025b; IAI, 2022). Broader social and governance issues are also becoming increasingly prominent, particularly in developing economies, where informal workers and small recyclers play a vital role in scrap collection and segregation (Pereira, 2025a, 2025b; Castro, 2025). At the same time, reusing dross and salt slag in cementitious and ceramic products presents promising options for material circularity (Muñoz-Vélez *et al*., 2023; Qin *et al*., 2025; Wu *et al*., 2025).

This review synthesizes the literature published between 2020 and 2025 on aluminum scrap recycling for foundry-alloy production, focusing on five interconnected dimensions: (1) scrap characterization and pre-treatment; (2) melting and refining processes; (3) alloy design and casting quality; (4) management and valorization of dross and salt slag; and (5) circular-economy and LCA perspectives, including social and regulatory factors. The goal is to consolidate operational best practices and process thresholds reported in recent studies, identify trade-offs between metallurgical performance and sustainability indicators, and outline research priorities for integrating higher recycled content without compromising product quality or safety (Padamata *et al*., 2021; European Aluminum, 2022, 2025a; IAI, 2022; Liu *et al*., 2024). The following section outlines the methodology used for identifying, screening, and analyzing the literature, ensuring the transparency and reproducibility of the review process.

METHODOLOGY

To promote transparency in methodology, this section describes the systematic methods used to identify, select, and analyze the literature.

Review Design

This study used a structured literature review approach, adapted from the JBI Manual for Evidence Synthesis (Aromataris & Munn, 2020), the PRISMA 2020 guidelines (Page *et al*., 2021), and best practices for systematic and critical reviews in materials science (Booth *et al*., 2021). The goal was to map and critically assess recent advances in aluminum scrap recycling for casting alloys, covering technological, environmental, and governance aspects reported from January 2020 to October 2025.

The review process included three main stages: (1) identifying peer-reviewed journal articles, institutional reports, theses, and technical standards; (2) screening based on predefined inclusion and exclusion criteria; and (3) evaluating eligibility and synthesizing findings through full-text analysis for methodological consistency, data completeness, and relevance to the research questions.

Databases searched included ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Taylor & Francis, Scopus, and Google Scholar. Additionally, grey literature sources such as ABAL, IAI, European Aluminum, and Brazilian theses repositories (e.g., USP, UNESP, UFRN) were reviewed to ensure regional coverage. Search strings combined keywords like “aluminum scrap”, “recycling”, “foundry alloys”, and “circular economy” using Boolean operators (AND, *OR*).

Inclusion Criteria

Publications were included if they m*et al*l of the following criteria: (1) timeframe: published or officially released between January 2020 and October 2025; (2) topic relevance: addressed at least one of the following areas—scrap characterization, pre-treatment, melting and refining, alloy design, dross/salt-slag valorization, or LCA and circular-economy frameworks; (3) source type: peer-reviewed journal articles, official technical reports from recognized institutions, or academic theses/dissertations; (4) language: English or Portuguese; and (5) data quality: sufficient quantitative or experimental detail for cross-study comparison.

Exclusion Criteria

Documents were excluded if they primarily focused on primary aluminum smelting or bauxite/alumina processing without specifically mentioning scrap recycling; if they were duplicates, preliminary abstracts, or lacked peer review; if they contained insufficient technical detail; if they addressed non-metallic recycling; or if they included outdated or retracted information before 2020.

Eligibility and Data Extraction

After deduplication, each record was screened by title and abstract. Eligible studies were reviewed in full text, and the following metadata were extracted: authors, year, source type, process stage, experimental variables, environmental indicators, and economic or governance aspects. The final dataset included 63 references, consisting of 45 peer-reviewed journal articles, 12 institutional reports and technical standards, and five academic theses or dissertations.

Quality Assessment and Synthesis

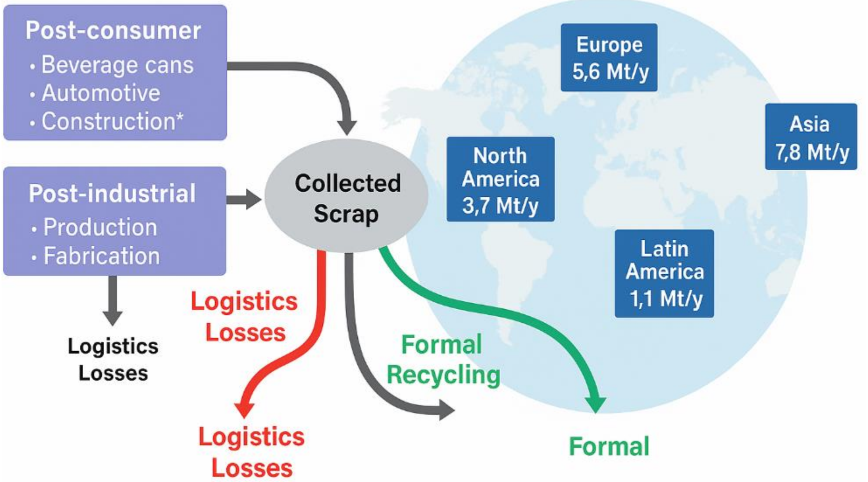
Each source was assessed for technical validity, data transparency, and comparability using a three-tier relevance matrix (high, medium, low) adapted from European Aluminum (2025a) and IAI (2022). Quantitative data (e.g., melting temperatures, gas flow rates, impurity thresholds) were converted to SI units for comparison, while qualitative insights (industrial practices, ESG trends, policy instruments) were grouped by theme. The screening and synthesis results guided the organization of this review according to the main stages of the aluminum recycling process, as outlined in the following sections.

Sources and Classification of Aluminum Scrap

Figure 2 shows the global flow of recycled aluminum from 2020 to 2025, differentiating between post-consumer sources (such as beverage cans, automotive parts, and construction materials) and post-industrial sources (including foundry and manufacturing scrap). The diagram highlights regional differences in collection and recycling efficiency: Europe and North America exhibit mature, formalized systems (green arrows); Asia displays mixed performance, characterized by significant informal recycling (gray arrows); and Latin America and Africa experience notable logistical challenges and structural gaps (red arrows).

This global panorama underscores the uneven development of recycling infrastructures worldwide. Industrialized regions maintain closed-loop systems supported by Extended Producer Responsibility (EPR) regulations and digital traceability tools, whereas emerging economies still depend primarily on informal collection networks. These discrepancies impact both the environmental performance and economic sustainability of aluminum recycling, underscoring the need for harmonized global standards and policy integration.

Figure 2. Global aluminum recycling flow diagram (2020–2025).



Source: Adapted from IAI (2025); European Aluminum (2025); ABAL (2025)

Table 1 summarizes the leading indicators of aluminum recycling performance worldwide from 2020 to 2025. The data emphasize regional differences in recycling efficiency, feedstock composition, technological maturity, and environmental impact. Formal recycling systems in Europe and North America demonstrate high recovery rates and significant reductions in CO_2 emissions. In contrast, developing regions continue to face logistical challenges, diverse scrap quality, and limited industrial capacity. These differences reflect both technological and governance gaps across the aluminum value chain.

Table 1. Global aluminum recycling Indicators (2020–2025).

Region	**Recycling Rate (%)**	**Main Feedstock Type**	**Key Technologies**	**CO_2 Reduction vs Primary (%)**	**Notes**
Europe	75–80	Post-consumer	Rotary + Induction	95	Advanced EPR systems
North America	70–75	Industrial scrap	Reverberatory	92	Mature market
Asia	55–65	Mixed	Rotary	88	Rapid growth, informal sector
Latin America	40–55	Beverage cans	Rotary	90	High potential
Africa	<30	Automotive & mixed	Small-scale	85	Infrastructure gaps

Source International Aluminum Institute (IAI, 2025); ABAL (2025); GlobalData (2024)

The results shown in Table 1 indicate uneven progress in aluminum recycling systems worldwide. Industrialized countries, particularly in Europe and North America, have achieved high recycling rates (70–80%) by employing integrated collection methods, energy-efficient rotary furnaces, and advanced refining and degassing technologies. These regions also benefit from Extended Producer Responsibility (EPR) programs and digital traceability systems, which enhance supply chain transparency and help meet the targets of a circular economy.

In contrast, Asia, despite being the world's largest producer and consumer of aluminum, has a diverse recycling landscape that combines advanced industrial sectors with extensive informal recovery systems. The high variability in feedstock purity and limited control over alloy composition continue to create challenges for producing consistent secondary alloys.

Latin America and Africa have the lowest levels of industrial integration, heavily relying on manual collection and re-melting of post-consumer scrap, especially beverage cans. Latin America has one of the highest can-recycling rates globally, driven by successful public–private partnerships (e.g., ABAL and Abralatas programs); however, it faces significant material losses in other sectors, such as construction and automotive recycling. Africa’s limited technological capacity and fragmented logistics hinder the development of continuous recycling loops.

From an environmental perspective, secondary aluminum production reduces CO_2 emissions by up to 95% compared to primary production (IAI, 2025; European Aluminum, 2025). However, these environmental advantages heavily rely on energy sources, flux and salt-slag management, and the regional electricity mix.

Besides dross and salt slag, another important residue is Spent Pot Lining (SPL), whose valorization and safe handling have been recently discussed (Pereira, 2025c).

Overall, Table 1 highlights the need to combine technological upgrades with policy coordination to close global material loops. Bridging the divide between developed and developing regions will require investment in infrastructure, data tracking, and circular economy management, ensuring aluminum recycling moves toward a globally balanced and sustainable system.

Scrap Categories

Aluminum scrap is broadly classified into two major categories: post-consumer and post-industrial (also known as new scrap). This distinction is crucial for selecting recycling routes, determining melt treatment requirements, and controlling impurities (European Aluminum, 2022; IAI, 2025).

Post-consumer scrap originates from end-of-life products, including beverage cans, automotive parts, architectural profiles, window frames, and building materials. This stream is typically more heterogeneous, often contaminated with coatings, lubricants, plastics, or other metals. Its recycling requires sorting, decoating, and melting operations that minimize oxidation and dross formation (ABAL, 2025; Wu *et al*., 2025).

Post-industrial scrap, in contrast, refers to fabrication residues, such as machining chips, offcuts, extrusion butts, and foundry returns. This material is typically clean and well-characterized in terms of alloy composition, making it suitable for direct remelting or internal recycling within the same plant. Industrial scrap can account for up to 30–50% of total scrap flows in advanced casting facilities (Chen *et al*., 2025; Kotadia *et al*., 2025).

The balance between post-consumer and post-industrial fractions determines not only the chemical variability of the charge but also the energy requirements and refining effort. Foundries producing critical components such as cylinder heads or structural castings often restrict post-consumer content to < 20 % to meet mechanical property specifications (Vallejo-Olivares *et al*., 2024).

Classification Standards

Scrap classification systems vary across regions but share the objective of defining composition, contamination limits, and alloy family for trade and processing. The main international standards are:

a) ABNT NBR 16598 (2020) – Aluminum and its alloys — Definitions and calculation methods for determining the recycled content in extruded, rolled, and cast products. This Brazilian standard defines the methodology for assessing recycled content in aluminum products (ABNT, 2020)..

b) ISO 209-1:2020 – Aluminum and aluminum alloys — Chemical composition and form of wrought products — Part 1: Scrap classification. This ISO document provides criteria for grouping aluminum scrap by alloy type, contamination level, and physical form (ISO, 2020).

c) ASTM B221/B221M and ASTM E716-10 – Standards specifying alloy composition ranges and terminology for aluminum scrap used in casting feedstocks (ASTM International, 2023).

Trade specifications, such as the European Aluminum Scrap Grades and the Institute of Scrap Recycling Industries (ISRI) codes (e.g., Taint/Tabor, Twitch, Tread), enhance these standards by standardizing terminology for global trade (European Aluminum, 2025a; IAI, 2025).

Adherence to classification standards ensures traceability, supports alloy segregation (e.g., 1xxx, 3xxx, 6xxx, 7xxx series), and reduces the risk of contamination during melting. Foundries often use spectroscopic sorting and magnetic or eddy-current separation methods aligned with these standards.

Table 2 summarizes the main aluminum alloy series used in global recycling and casting processes. Each series is characterized by its primary alloying element(s), which influence physical properties, recycling compatibility, and contamination risks. Keeping segregation by alloy family (1xxx–8xxx) is crucial to maintaining melt quality, preventing intermetallic formation, and complying with international classification standards (ISO 209-1:2020; ASTM E716-10; ABNT NBR 16598:2020).

Foundries usually use spectroscopic sorting, eddy-current separators, and magnetic detection systems to ensure alloy purity meets these standards.

Table 2. Main aluminum alloy series and their typical characteristics in scrap classification.

Alloy Series	Principal Alloying Elements	Key Properties	Recycling Considerations	Typical Applications
1xxx (Pure Aluminum Series)	≥ 99.0% Al (minimal alloying additions)	Excellent electrical and thermal conductivity; high corrosion resistance; low strength.	High recyclability and purity; easily remelted; contamination with Cu, Zn, or Fe reduces conductivity.	Electrical conductors, heat exchangers, and chemical processing equipment.
2xxx (Al–Cu Alloys)	Copper (2–6%), Mg, Mn	High strength and machinability; moderate corrosion resistance.	Limited recyclability — requires segregation from other series due to Cu reactivity; often diluted in foundry blends.	Aerospace and automotive structural parts.
3xxx (Al–Mn Alloys)	Manganese (0.5–1.5%), small Si and Fe	Good formability, corrosion resistance, and moderate strength.	Common in beverage cans and sheet scrap; highly compatible with 5xxx and 6xxx recycling streams.	Beverage cans, roofing, heat exchangers.
4xxx (Al–Si Alloys)	Silicon (4–13%), possible Cu or Mg	Low melting point; excellent castability and fluidity.	Widely used in foundry scrap; easily recycled; excessive Fe may form brittle phases.	Welding wires, brazing alloys, and automotive castings.
5xxx (Al–Mg Alloys)	Magnesium (2–5%), Mn, Cr	High strength, good weldability, and corrosion resistance in marine environments.	Compatible with 3xxx and 6xxx in mixed recycling; Mg losses occur through oxidation during melting.	Marine structures, pressure vessels, transport components.
6xxx (Al–Mg–Si Alloys)	Magnesium (0.6–1.2%),	Excellent extrudability; good	Highly recyclable; key feedstock for automotive	Automotive profiles, structural

	Silicon (0.4–1.0%)	strength after heat treatment.	alloys; precise Mg–Si ratio must be maintained.	extrusions, building materials.
7xxx (Al–Zn–Mg Alloys)	Zinc (4–8%), Mg, Cu	Very high strength; lower corrosion resistance.	Must be carefully segregated; presence of Zn and Cu limits blending with low-alloy series.	Aerospace components, high-strength fittings, sporting goods.
8xxx (Other Alloys, e.g., Al–Li, Al–Fe–Si)	Lithium, Iron, Silicon (variable)	Tailored properties: lightweight, improved stiffness, specialized conductivity.	Often recycled in closed-loop systems due to composition sensitivity.	Foils, packaging, advanced aerospace structure

Source: Adapted from ISO 209-1:2020; ASTM E716-10 (Reapproved 2023); ABNT NBR 16598:2020; European Aluminum (2025a); Institute of Scrap Recycling Industries – ISRI (2025).

Table 3 summarizes the primary international and national standards that govern aluminum scrap classification, composition control, and determination of recycled content. These documents—issued by ABNT, ISO, ASTM, and trade organizations such as European Aluminum and ISRI—provide harmonized criteria for identifying alloy families, limiting contamination, and ensuring traceability throughout recycling chains.

Table 3. Main standards for aluminum scrap classification and traceability.

Standard / Institution	Scope and Coverage	Main Criteria	Industrial Application / Remarks
ABNT NBR 16598:2020 – Aluminum and its alloys — Definitions and calculation methods for determining the recycled content	Defines methods to quantify the recycled content in extruded, rolled, and cast aluminum products.	Percentage of recycled aluminum in the final product. - Traceability of pre-consumer and post-consumer sources. - Calculation methodology for mixed batches.	Ensures compliance with Brazilian environmental labeling programs and LCA reports. Widely applied in foundries and semi-finished products.
ISO 209-1:2020 Aluminum and aluminum alloys — Chemical composition and form of wrought products — Part 1: Scrap classification	Establishes a global framework for scrap classification by alloy family, contamination level, and physical form.	Grouping by alloy series (1xxx–7xxx). - Limits for oils, coatings, and oxide contamination. - Form: chips, turnings, plates, foils, etc.	International reference standard for recycling plants and traders; used for customs codes and industrial sorting.
ASTM B221/B221M; ASTM E716-10 (Reapproved 2023)	Defining composition ranges and nomenclature for aluminum alloys used in casting and recycling streams.	Elemental ranges for major and minor alloying components. - Chemical tolerances for scrap feedstocks. - Terminology for scrap and dross.	Applied in North American foundries and casting shops; used to ensure consistency of melt composition in remelting operations.
European Aluminum Scrap Grades (2025)	Trade specifications adopted across the EU for scrap type and quality categories.	Grades based on purity, coating, and alloy family. - Conforms to ISO 209-1.- Example grades: TAINT/TABOR, TREAD, TWITCH.	Used by European recycling facilities and brokers to harmonize market terminology; facilitates cross-border scrap trading.
ISRI Specifications (Institute of Scrap Recycling Industries),	Defines commercial grades and marketable categories of	Visual inspection criteria. - Maximum contamination limits.- Minimum aluminum content (%).	Global benchmark for scrap commerce and customs documentation; harmonized with ISO 209-

e.g., Taint/Tabor, Tread, Twitch, Telic, etc.	aluminum scrap for international trade.		1 and ASTM E716 terminology.

Source: Adapted from ABNT (2020); ISO (2020); ASTM International (2023); European Aluminum (2025a); Institute of Scrap Recycling Industries – ISRI (2025)

Typical Impurities

The impurity profile of aluminum scrap directly affects melt quality, refining costs, and the potential recycled content in casting alloys (Milani & Timelli, 2023; Kotadia *et al.*, 2025). The most common contaminants include:

1. Iron (Fe): Introduced mainly from steel fasteners, cutting tools, or mixed ferrous scrap; promotes the formation of Fe-rich intermetallics (β-Al_5FeSi) that reduce ductility and corrosion resistance (Wang *et al.*, 2024a).
2. Zinc (Zn): Common in galvanized components and die-cast alloys; may volatilize during melting and contribute to dross formation or porosity.
3. Magnesium (Mg): Present in 5xxx–6xxx alloys; excessive Mg oxidizes readily and increases hydrogen solubility, demanding stricter flux control.
4. Lubricants, oils, and greases: Surface contaminants typical of machining scrap; they can cause hydrogen pickup and flame emissions during melting, hence the need for pre-drying or decoating (Qin *et al.*, 2025).

Trace elements such as Cu, Ni, Pb, Sn, and Ti are also monitored due to their impact on corrosion and casting performance. ISO 14373 and EN 13920 specify maximum levels for these elements based on alloy series and intended use.

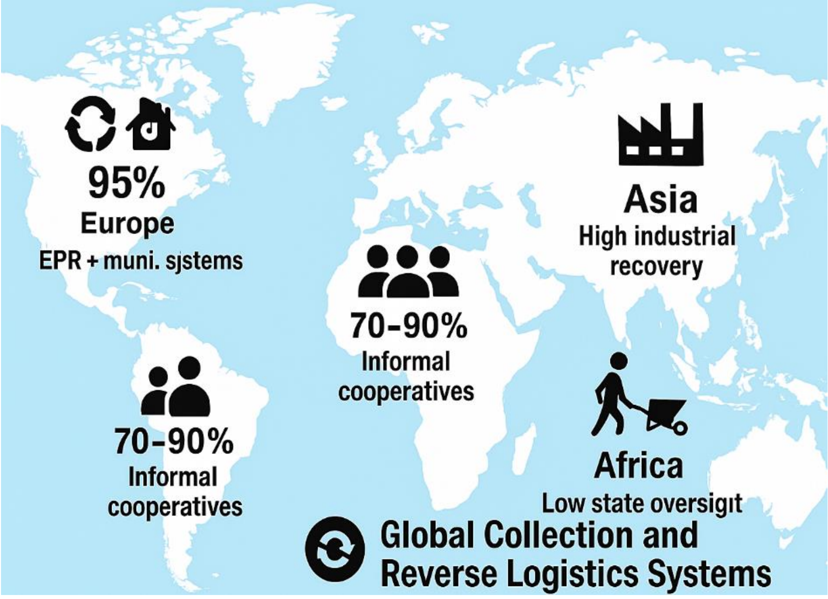
In high-quality foundry alloys, Fe is typically limited to ≤ 0.6 wt% %, and total tramp elements (Cu + Zn + Ni + Sn + Pb) to ≤ 1.0 wt% %. For automotive structural castings, targets are often more stringent (< 0.3 wt %) (IAI, 2024; European Aluminum, 2025b).

PREPARATION AND TREATMENT OF ALUMINUM SCRAP

This world map (Figure 3) highlights the main collection and reverse logistics models for aluminum scrap worldwide. Europe exhibits high formalization, with Extended Producer Responsibility (EPR) and municipal systems achieving recovery rates exceeding 95%. North America combines curbside and deposit-return programs, achieving recovery rates of around 80–85%. Latin America relies heavily on informal cooperatives and voluntary initiatives—especially for beverage cans—achieving a 70–90% recovery rate. In contrast, most Asian and African countries have fragmented systems, marked by high industrial recovery but low institutional oversight.

The color intensity indicates the collection rate, while icons identify the dominant collection mechanism in each region.

Figure 3. Global collection and reverse logistics systems.



Source: Adapted from International Aluminum Institute (2025); ABAL (2025); European Aluminum (2025)

The figure provides a comparative overview of global disparities in aluminum scrap collection systems, illustrating how institutional maturity and policy frameworks directly impact recycling efficiency. The formalized systems in Europe and North America demonstrate the success of deposit-return mechanisms and EPR legislation in achieving high recovery rates. Conversely, reliance on informal sectors in developing regions underscores both the social aspects of recycling and the lack of infrastructure for traceability and environmental management.

Adding this visual supports the article's discussion of the circular economy by linking technological recycling efficiency with policy and governance capacity, preparing the way for the following sections on environmental impacts and future outlooks.

Collection and Reverse Logistics

Efficient scrap collection and reverse logistics are essential for achieving high recycling rates and preserving material quality. In industrialized nations, formal collection systems operate through Extended Producer Responsibility (EPR) schemes and coordinated trade networks that connect municipalities, scrap dealers, and foundries (European Aluminum, 2022; IAI, 2025). In developing economies like Brazil, the collection chain remains partly informal, relying on waste pickers, cooperatives, and small-scale intermediaries who supply post-consumer scrap to larger consolidators (ABAL, 2025; Castro, 2025).

Reverse logistics programs often incorporate deposit–refund systems or digital tracking platforms for beverage cans and automotive parts, ensuring alloy traceability and reducing contamination at the source (Pereira, 2025a, 2025b). Advanced facilities use closed-loop supply agreements with OEMs and extrusion companies to ensure consistent, uniform post-industrial scrap streams (Kotadia *et al*., 2025).

Sorting and Identification

The sorting of aluminum scrap determines the success of downstream melting and alloy control. Traditional manual sorting—still standard in mixed-metal scrap yards—is gradually being complemented by automated and AI-based systems (Guo & Zhang, 2025).

Automated sorting technologies encompass:

1. Eddy-current separators for removing non-ferrous metals from mixed residues.
2. Near-infrared (NIR) spectroscopy is used to distinguish coated from uncoated materials.
3. Laser-induced breakdown spectroscopy (LIBS) and X-ray fluorescence (XRF) enable quick alloy identification, such as distinguishing between the 5xxx and 6xxx series.
4. Machine-learning algorithms that classify scrap based on spectral or image datasets, enhancing throughput and purity (Chen *et al*., 2025; European Aluminum, 2025b).

Artificial intelligence integration has achieved sorting accuracies exceeding 95% for post-consumer scrap, reducing the need for manual rework and boosting furnace yield.

Pre-Treatment Operations

Before melting, aluminum scrap typically undergoes cleaning, size reduction, and separation steps to remove contaminants, homogenize the feed size, and enhance thermal efficiency (Vallejo-Olivares *et al*., 2024; Wu *et al*., 2025).

Degreasing and Decoating

Two primary methods are used for removing surface oils, paints, and lacquers:

1. Thermal decoating occurs in rotary kilns or fluidized-bed furnaces at 400–550 °C. This process volatilizes organics but requires strict control of oxygen levels to prevent metal oxidation (Milani & Timelli, 2023).
2. Chemical degreasing using alkaline or solvent baths (e.g., NaOH or surfactant-based agents) at 50–80 °C, followed by rinsing and drying. It effectively removes oily machining scrap and can be combined with wastewater recovery systems (Qin *et al*., 2025).

Both approaches reduce hydrogen pickup and improve melt cleanliness.

Shredding and Size Classification

After cleaning, scrap is shredded to a uniform size distribution—typically 10–50 mm particles—to optimize melting kinetics and furnace loading density. Granulometric classification ensures even heating and reduces oxidation during charging (Wang *et al*., 2024a).

Vibrating screens or air-classification systems separate fines (< 5 mm), which are often compacted into briquettes to minimize dust and oxidation losses (Vallejo-Olivares *et al.,* 2024).

Magnetic and Density Separation

Residual ferrous metals are removed via magnetic separators, protecting refractory linings and avoiding Fe enrichment in the melt. For non-ferrous contaminants, density-based separation (sink-float or air-table systems) discriminates aluminum ($\rho \approx 2.7$ g cm^{-3}) from heavier alloys and copper fragments (IAI, 2024).

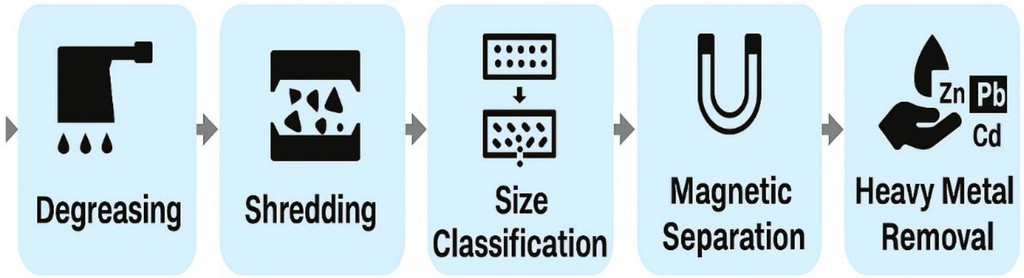
Detection and Removal of Heavy Metals

The final purification step targets toxic or low-melting metals—especially Zn, Pb, and Cd—that can vaporize during the melting process or compromise alloy properties. Detection methods include XRF mapping, ICP-OES, or LIBS inline sensors (European Aluminum, 2025b). When contamination levels are high, scrap can be treated through selective oxidation, chlorination refining, or mechanical segregation before being charged into the furnace (Wu *et al*., 2025).

Environmental and occupational regulations (ABNT NBR 10004, 2004; ISO 14021:2016) classify Zn- and Pb-bearing residues as hazardous, requiring proper capture and disposal of off-gases and dross fines.

Figure 4 summarizes the sequential operations performed prior to aluminum scrap melting, which are essential for ensuring feed uniformity, removing contaminants, and improving melting efficiency. The diagram outlines four integrated steps: (1) degreasing and decoating through thermal or chemical treatment, (2) shredding and size classification for improved furnace loading and heat transfer, (3) magnetic and density separation to remove ferrous and heavy nonferrous contaminants, and (4) detection and removal of heavy metals via spectrometric or chemical methods. These combined stages minimize oxidation losses and hydrogen pickup while enhancing melt cleanliness and alloy consistency.

Figure 4. Pre-treatment Operations for Aluminum Scrap Recycling.



Source: Adapted from Vallejo-Olivares *et al*. (2024); Milani & Timelli (2023); Wu *et al*. (2025); European Aluminum (2025).

The pre-treatment stage is one of the most critical steps in secondary aluminum production, as it significantly impacts the efficiency, safety, and environmental footprint of subsequent melting processes.

Thermal and chemical degreasing and decoating remove organics that could otherwise generate hydrogen gas and dross, while size homogenization (10–50 mm particles) improves furnace loading density and melting kinetics. The addition of magnetic and density separation increases process reliability by preventing Fe and Cu contamination, which are common causes of intermetallic formation in recycled alloys.

Moreover, the final heavy metal detection and removal phase (using XRF, ICP-OES, or LIBS sensors) reflects the increasing trend toward inline quality monitoring and process automation. This step aligns with recent circular-economy standards (ISO 14021:2016; ABNT NBR 10004), which specify the traceable segregation and safe disposal of Zn- and Pb-bearing residues.

Overall, Figure 4 emphasizes how integrated pre-treatment systems not only enhance metal yield and product quality but also decrease emissions, waste, and occupational hazards—serving as a key element in sustainable aluminum recycling.

Table 4 presents quantitative indicators that describe the operational performance of aluminum scrap pre-treatment steps, including duration, energy consumption, costs, and metal recovery rates. These are compared across thermal, chemical, and mechanical methods used to prepare scrap before melting. The data, gathered from industrial benchmarks and recent literature (Vallejo-Olivares *et al*., 2024; Wu *et al*., 2025; European Aluminum, 2025; IAI, 2024), provide an empirical foundation for evaluating process efficiency and sustainability.

Table 4. Performance Indicators for Aluminum Scrap Pre-treatment Operations (2020–2025).

Process Step	Typical Duration	Energy Demand (kWh t^{-1} scrap)	Operating Cost (USD t^{-1} scrap)	Metal Recovery (%)	Main Output / Benefit
Thermal Decoating	0.5–1.5 h	80–120	35–50	97–99	Removes paints, lacquers, and organics; reduces hydrogen pickup.
Chemical Degreasing	0.25–0.75 h	20–40	25–40	96–98	Eliminates oils and machining lubricants; allows water recovery.
Shredding & Classification	0.2–0.4 h	10–20	10–25	98–99	Ensures particle size uniformity (10–50 mm) and improved heat transfer.
Magnetic / Density Separation	0.1–0.3 h	5–10	15–30	99–99.5	Removes Fe, Cu, and heavy alloys; improves melt purity.
Heavy Metal Detection & Removal	0.2–0.5 h	15–25	40–60	98–99	Selective elimination of Zn, Pb, Cd; reduces emissions and dross reactivity.

Source: Adapted from Vallejo-Olivares *et al*., 2024; Wu *et al*., 2025; European Aluminum, 2025; IAI, 2024

The results show that the thermal and chemical cleaning stages account for the majority of total energy use, comprising approximately 70–80% of the pre-treatment energy (150–250 kWh per ton of scrap). However, they achieve high metal recovery (≥ 97%) and significantly reduce hydrogen and oxide inclusions in the melt.

Mechanical and density-based separations have low energy consumption and brief residence times. However, they are essential for ensuring alloy purity by removing ferrous and heavy-metal contaminants before charging the furnace.

From an economic perspective, the total operating cost stays below $150 per tonne, which is less than 1% of the total primary aluminum production cost, while also avoiding oxidation losses that could surpass 5% of the metal yield.

Finally, the integration of detection technologies (e.g., XRF or LIBS sensors) demonstrates the digitalization trend in recycling plants, aligning with ISO 14021:2016 and ABNT NBR 10004 standards for traceable, low-impact recycling operations.

Integration and Circular-Economy Relevance

Well-designed pre-treatment chains enhance material yield and reduce the carbon footprint, resulting in a decrease of up to 25% in energy use per ton of secondary aluminum produced (IAI, 2025). The integration of reverse logistics, intelligent sorting, and pre-treatment automation within circular economy frameworks supports the traceability required by EPD and ISO 14067 carbon footprint standards (European Aluminum, 2025a; IAI, 2022).

After preparing and decontaminating the scrap, the material is moved to the melting and refining stages, where process parameters determine the final metal yield and impurity removal efficiency.

MELTING AND REFINING PROCESSES

Furnace Technologies

Aluminum scrap melting involves furnace setups optimized for throughput, alloy control, and dross reduction. Three primary furnace types dominate secondary aluminum processes: rotary, reverberatory, and induction furnaces (Padamata *et al*., 2021; Milani & Timelli, 2023).

Rotary Furnaces

Rotary furnaces are often used for melting mixed or contaminated scrap and salt-flux processes. Their tumbling action enhances heat transfer and ensures consistent melting of the charge. Modern models incorporate oxy-fuel burners and recuperative air preheating, achieving energy use of 0.7–1.0 MWh per ton and metal yields exceeding 90% (Vallejo-Olivares *et al.*, 2024).

Atmosphere management is essential: maintaining low-oxygen or reducing conditions helps prevent oxidation and hydrogen absorption. Ongoing exhaust treatment systems remove chlorinated and fluoride compounds during salt-flux refining (Wu *et al.*, 2025).

Reverberatory Furnaces

Reverberatory furnaces are used on an industrial level for processing large batches of clean scrap, remelting dross, or achieving alloy uniformity. They offer high efficiency, with capacities reaching up to 150 tons per day, and ensure even temperature distribution due to the reflection of flames from the roof.

Longer residence times and open-flame operation result in higher oxidation losses, ranging from 3% to 5%, and an energy use of 1.1–1.4 MWh per ton (Liu *et al.*, 2024). Adding flue-gas recirculation and oxygen enrichment has increased thermal efficiency by up to 15% (IAI, 2025).

Induction Furnaces

Induction furnaces heat metals using electromagnetic methods, offering precise temperature control and minimizing oxidation. This makes them ideal for high-purity or specialty alloys, such as the 7xxx series and Al-Si-Mg systems. Although they are limited to smaller capacities (up to 10 tons), they enable quick alloy changes and produce clean melts suitable for foundry recycling loops (Asghar *et al.*, 2025).

Energy consumption averages 0.5–0.7 MWh per ton, with CO_2 emissions 70–80% lower than gas-fired systems when powered by renewable electricity (IAI, 2024).

Table 5 summarizes the operational features of the three main furnace types used in secondary aluminum production. Each system shows a different balance between energy efficiency, process flexibility, and alloy quality. Rotary furnaces are good at handling scrap variations; reverberatory units achieve high industrial throughput; and induction furnaces provide purity and precision for foundry alloys.

Table 5. Comparative parameters of furnace technologies for aluminum scrap melting.

Parameter	**Rotary Furnace**	**Reverberatory Furnace**	**Induction Furnace**
Main Application	Mixed or contaminated scrap; salt-flux operations	Large-scale melting of clean scrap and dross	High-purity or specialty alloys (7xxx, Al–Si–Mg)
Typical Capacity (t/day)	20–80	Up to 150	≤10
Energy Demand (MWh t^{-1} Al)	0.7 – 1.0	1.1 – 1.4	0.5 – 0.7
Metal Yield (%)	88 – 92	90 – 95	95 – 98
Oxidation Loss (%)	2 – 4	3 – 5	< 1
Fuel / Energy Source	Oxy-fuel or natural gas	Natural gas or fuel oil	Electric (induction)
Atmosphere Control	Reducing or low O_2	Open flame, partial flue-gas recirculation	Inert or controlled
CO_2 Emissions (t CO_2 t^{-1} Al)	0.6 – 0.8	0.9 – 1.1	0.2 – 0.3 (renewable electricity)
Key Advantages	Handles contaminated scrap; high flexibility	High productivity; stable temperature field	Excellent composition control; clean melt
Main Limitations	Requires salt-flux treatment; dross generation	High oxidation losses; large footprint	Limited capacity; higher capital cost
Modern Improvements	Oxy-fuel burners, regenerative air preheaters	Flue-gas recirculation; oxygen enrichment	AI-based temperature control; high-frequency coils

Source: Adapted from Vallejo-Olivares *et al*. (2024); Milani & Timelli (2023); Asghar *et al*. (2025); International Aluminum Institute (2025).

The comparison highlights the trade-off between scale and efficiency in scrap-melting technology. While reverberatory furnaces remain indispensable for large-volume operations, rotary furnaces dominate when feedstock variability and contamination require robust salt-flux treatment. Induction systems, on the other hand, align with low-carbon foundry loops, offering minimal emissions when powered by renewable grids.

Integrating digital control and waste-heat recovery across all furnace types could further reduce energy consumption by 10–20%, reinforcing the technological foundations of a circular and low-emission aluminum industry.

Atmosphere Control

Atmosphere composition during melting directly affects oxidation, dross formation, and gas absorption. Nitrogen (N_2) and argon (Ar) are commonly used as protective or inert gases, especially in rotary and induction furnaces. Controlled reducing atmospheres ($CO + H_2$) further reduce oxide formation (Vallejo-Olivares *et al*., 2022).

Excess oxygen promotes Al_2O_3 film growth and increases hydrogen solubility, whereas controlled gas injection stabilizes the melt surface and facilitates degassing (Milani & Timelli, 2023). Using flue-gas analyzers ensures that the oxygen partial pressure stays below 10^{-5} atm, which is essential for high-yield operations.

Degassing and Hydrogen Removal

Hydrogen is the most important dissolved gas in aluminum melts, causing porosity and weakening the mechanical properties of cast alloys. Degassing systems introduce inert gases (N_2 or Ar) through rotary impellers or porous plugs, encouraging bubble formation and gas diffusion (Lázaro-Nebreda *et al.*, 2022; Kolínský *et al.*, 2025).

Advanced rotary-impeller degassers achieve hydrogen levels below 0.1 mL H_2 per 100 g Al while reducing dross. Additives such as hexachloroethane (C_2Cl_6) or chlorine-free flux tablets enhance gas removal, although environmental restrictions are encouraging the use of chlorine-free methods (Li *et al.*, 2024).

Process parameters—gas flow rate (0.1–0.3 $m^3\ h^{-1}\ kg^{-1}$ Al), rotation speed (400–600 rpm), and treatment duration (5–15 min)—are optimized to avoid turbulence and oxide entrainment (Liu *et al.*, 2024).

Flux Addition and Inclusion Control

Fluxes are vital for refining molten aluminum by eliminating oxides, salts, and non-metallic inclusions. Based on composition and purpose, fluxes are categorized as:

1. Applying fluxes ($NaCl$–KCl–Na_3AlF_6 mixtures) to shield the melt surface and absorb oxides.
2. Refining fluxes containing cryolite, CaF_2, and Na_2SO_4, which facilitate the coalescence of metal droplets.
3. Cleaning fluxes for dross treatment, designed to recover entrapped aluminum and separate salts for recycling (Milani & Timelli, 2023).

Flux consumption varies from 10 to 30 kg t^{-1} Al, and effective flux management can cut dross formation by 15–20% (Wu *et al.*, 2025). Recycling of spent flux and salt slag is now a top environmental priority (Vallejo-Olivares *et al.*, 2024).

Energy and Environmental Impact

Secondary aluminum production is much more energy-efficient than primary smelting. The International Aluminum Institute (IAI, 2025) reports the following typical values (Table 6):

Table 6. Comparative energy demand and CO_2 emissions in aluminum production.

Process	**Energy Demand (MWh t^{-1} Al)**	**CO_2 Emissions (t CO_2 t^{-1} Al)**
Primary (Hall-Héroult)	13.0–15.0	10.0–12.0
Secondary (scrap remelting)	0.5–1.0	0.4–0.6

Source: Adapted from International Aluminum Institute (IAI, 2025) and European Aluminum (2025).

Recycling aluminum saves up to 95% of energy and 90% of CO_2 emissions compared to primary production (IAI, 2024; ABAL, 2025). These benefits make aluminum recycling a crucial component of low-carbon metallurgy and circular economy initiatives. Figure 2 shows a schematic of the technological steps involved in recycling aluminum scrap for foundry alloy production. The process begins with sorting and cleaning the scrap, followed by thermal and chemical pretreatment, melting, refining, alloy adjustment, and culminating in casting. This flow diagram highlights the main operational stages, focusing on the shift from mixed scrap inputs to standardized secondary aluminum alloys ready for industrial use. It provides a clear overview of the aluminum scrap recycling process, illustrating the connection between mechanical, thermal, and metallurgical steps in a continuous flow. The diagram illustrates how each stage contributes to recovering materials, controlling impurities, and standardizing alloys—technological Sequence in Foundry Scrap Recycling. Adapted from International Aluminum Institute (IAI, 2025); European Aluminum (2025); ABAL (2025).

The initial stages (scrap classification, sorting, and cleaning) are crucial for reducing contaminants such as iron, zinc, and organic residues, which directly influence downstream energy use and melt quality. Automated sorting systems—including eddy current separators, X-ray sensors, and AI-driven vision systems—have significantly enhanced the accuracy of this stage in advanced recycling facilities. However, their use remains limited in developing regions.

During pre-treatment, both thermal degreasing and chemical cleaning are essential for removing oils, paints, and oxides that could cause porosity or hydrogen pick-up during melting. The melting and refining stages (steps 4 and 5) form the core of the recycling process. Rotary and reverberatory furnaces are used for high-volume operations, while induction furnaces are preferred for specialty alloys due to their better control over atmosphere and temperature.

Alloy adjustment and casting complete the loop by transforming the refined molten aluminum into secondary alloys with specific chemical compositions. The addition of master alloys (Al–Si, Al–Mg, Al–Cu) enables precise control of mechanical and corrosion properties, ensuring the recycled product meets industry standards such as EN 1706 or ASTM B179.

From a systems perspective, the diagram highlights how process steps depend on one another: faults in upstream sorting or pre-treatment can spread through melting and refining, resulting in lower metal yield and increased environmental impact. Conversely, effective integration of these steps enhances energy efficiency, reduces CO_2 emissions, and ensures alloy consistency—key performance indicators in circular foundry operations.

Finally, Figure 4 highlights the necessity of digital process integration—utilizing real-time composition monitoring and data-driven quality control—to transition from traditional batch recycling to smart, traceable, and low-emission foundry systems aligned with Industry 4.0 standards.

CHEMICAL COMPOSITION CONTROL

Real-time Analysis and Monitoring

Accurate chemical management during melting and alloying is essential to ensure consistent mechanical and corrosion resistance qualities in recycled aluminum alloys. As scrap composition becomes increasingly variable—especially in post-consumer sources—there is a growing need for real-time analytical tools to provide immediate feedback and enable adjustments (Liu *et al*., 2024; Kotadia *et al*., 2025).

Modern foundries rely on optical emission spectroscopy (OES) and X-ray fluorescence (XRF) as the primary tools for real-time compositional monitoring. OES quickly measures the levels of major and minor alloying elements (Si, Fe, Cu, Mn, Mg, Zn, Ti) with detection limits of less than 10 ppm, making it ideal for process control in both rotary and induction furnaces.

Portable XRF analyzers are used to verify incoming scrap, assist in alloy sorting before melting, and prevent cross-contamination between series (e.g., 3xxx vs. 6xxx). Recent advances in laser-induced breakdown spectroscopy (LIBS) and machine learning-assisted spectral analysis enable continuous monitoring of molten metal in the furnace, thereby improving accuracy and reducing sampling delays (Chen *et al*., 2025; Guo & Zhang, 2025).25).

Alloy Adjustment and Master Alloy Addition

Once the preliminary analysis is completed, the melt composition is adjusted using master alloys—highly concentrated additions of alloying elements such as silicon (Si), magnesium (Mg), copper (Cu), zinc (Zn), and iron (Fe) in aluminum matrices (Datta *et al*., 2025). These materials enable controlled alloying without localized reactions or prolonged dissolution times.

1. Silicon (Si): Added to improve castability and reduce shrinkage; target levels in Al–Si alloys range from 7–12 wt%.
2. Magnesium (Mg): Strengthens solid-solution and precipitation-hardened systems; typical additions are 0.2–1.0 wt%.
3. Copper (Cu) and Zinc (Zn): Increase strength and hardness in wrought and die-cast alloys but reduce corrosion resistance.
4. Iron (Fe): Generally controlled as an impurity (< 0.5 wt%) but occasionally added in small quantities to adjust intermetallic morphology in high-recycled-content alloys (Wang *et al*., 2024; Kotadia *et al*., 2025).

Precise alloying guarantees compliance with standards such as ABNT NBR 15975 and ASTM B179, which specify the compositional limits for aluminum casting alloys. Automated addition systems, combined with spectrometric feedback loops, now enable composition adjustments within ±0.02 wt%, thereby enhancing reproducibility in large-scale recycling operations (Liu *et al*., 2024).

Standardization Challenges in Foundry Alloys

The push for high recycled content creates new challenges in maintaining alloy standardization, as different impurity profiles often cause deviations from the nominal specifications of casting alloys (Padamata *et al*., 2021; Asghar *et al*., 2025).2025).

Al–Si Alloys

Al–Si alloys, such as A356, A380, and AlSi7Mg0.3, dominate the global foundry market because of their excellent castability, fluidity, and corrosion resistance. However, when produced from secondary feedstocks, these alloys can contain excess Fe, Cu, or Zn, which promote the formation of intermetallic phases (β-Al_5FeSi, Al_2Cu, Mg_2Si) that weaken ductility and fatigue resistance (Šmalc *et al.*, 2023).

Standardization strategies include:

a) Tight control of Fe below 0.5 wt%.
b) Addition of Mn to modify Fe-rich phases into less harmful morphologies.
c) Flux-assisted refining and filtration prior to casting.

Automotive and Special Alloys

Automotive alloys—such as AlSi10Mg, AlMg5Si2Mn, and AlZnMgCu1.5—require precise control of their microstructure to achieve mechanical and thermal performance goals. High-recyclability alloys are being developed with reduced sensitivity to impurities, enabling up to 80% recycled content without compromising properties (Asghar *et al.*, 2025; Datta *et al.*, 2025).

New alloy design frameworks utilize computational thermodynamics (CALPHAD) and artificial intelligence to predict phase stability and guide master alloy additions, thereby accelerating the optimization of composition (Chen *et al.*, 2025). These tools are becoming increasingly vital for integrating diverse scrap sources into circular metallurgical systems.

ALLOY QUALITY AND PROPERTIES

With the chemical composition properly adjusted, it becomes essential to evaluate the metallurgical and mechanical properties of the recycled alloys to ensure compliance with international quality standards.

Influence of Impurities on Microstructure

The quality of recycled aluminum alloys depends significantly on the type and amount of residual impurities, which influence phase formation, grain structure, and ultimately, mechanical performance (Šmalc *et al.*, 2023; Kotadia *et al.*, 2025). Even tiny traces of unwanted elements can lead to significant microstructural deterioration during the solidification process.

Table 7 outlines the primary metallic and nonmetallic impurities present in recycled aluminum alloys, their effects on the microstructure, and related mitigation strategies. The data incorporate both industrial experience and recent analytical studies (2020–2025), highlighting how impurity control directly influences the mechanical and corrosion performance of foundry alloys.

Table 7. Impurities and their effects on alloy properties in recycled aluminum.

Impurity Element	**Typical Concentration Range (wt%)**	**Main Effects on Alloy Microstructure**	**Consequences for Mechanical / Corrosion Properties**	**Corrective Actions / Mitigation**
Fe (Iron)	0.5–1.5	Formation of β-Al_5FeSi plate-like intermetallics	Increases brittleness; reduces ductility and machinability	Use of Mn additions to transform β-phase into α-phase; improved sorting to reduce Fe input.
Zn (Zinc)	0.3–1.0	Substitutional solid solution in Al matrix	Enhances strength but may cause galvanic corrosion in presence of Cu	Controlled addition; alloy homogenization and coating strategies.
Mg (Magnesium)	0.2–0.8	Formation of Mg_2Si and MgO inclusions	Improves strength and hardness; excessive levels cause oxidation and porosity	Protective atmosphere (N_2 or Ar) during melting; refining fluxes.
Cu (Copper)	0.5–2.0	Strengthening through Al_2Cu precipitates	Increases mechanical strength but reduces corrosion resistance	Limiting Cu in recycled feed; post-casting heat treatment.
Si (Silicon)	6–12 (in Al–Si alloys)	Eutectic phase formation controlling castability	Improves fluidity and reduces shrinkage; excessive levels embrittle alloy	Controlled alloy adjustment; degassing to remove hydrogen.
Pb / Sn / Cd (Trace metals)	<0.1	Form low-melting segregated phases	Promote hot cracking and localized corrosion	Strict scrap control; use of refining fluxes and filtration.
Oil / Grease residues	—	Oxidation during melting, hydrogen pick-up	Porosity and inclusion defects in castings	Pre-cleaning and thermal degreasing before melting.

Source: Adapted from IAI (2025); ASTM B179; EN 1706; Pereira (2025); European Aluminum (2025).

Controlling impurities is essential for ensuring the reliability of recycled aluminum alloys. Among these, iron (Fe) is the most significant contaminant in post-consumer scrap, promoting the formation of brittle β-Al_5FeSi intermetallics. Adding manganese as a modifier element effectively stabilizes the α-phase morphology, enhancing ductility and machinability.

Zinc (Zn) and copper (Cu), while beneficial for strength through solid-solution and precipitation hardening, can speed up galvanic corrosion, especially in mixed-alloy scrap streams. Keeping a balance through controlled alloy adjustment is therefore crucial. Similarly, magnesium (Mg) enhances mechanical strength but also increases oxidation tendency and hydrogen solubility, requiring protective atmospheres and degassing treatments during melting.

Nonmetallic impurities—such as oils, greases, and coatings—indirectly contribute to gas porosity and inclusion formation, highlighting the importance of effective pre-treatment and cleaning steps (as shown in Figure 4). In summary, Table 2 emphasizes the delicate balance between mechanical performance and chemical purity, underscoring the need for real-time compositional monitoring, better scrap sorting, and adaptive refining strategies in modern circular foundry operations.

Iron (Fe)

Iron is the most common contaminant in secondary aluminum and forms brittle intermetallic compounds such as β-Al_5FeSi and α-$Al_{15}(Fe,Mn)_3Si_2$. These plate-like or needle-shaped phases act as stress concentrators, reducing ductility and toughness in Al–Si casting alloys (Wang *et al*., 2024; Datta *et al*., 2025).

Mitigation strategies consist of:

- Maintaining Fe content below 0.5 wt%.
- Adding Mn to transform β-Al_5FeSi into the less harmful α-$Al_{15}(Fe,Mn)_3Si_2$ morphology.
- Employing filtration, grain refinement (e.g., Al–Ti–B additions), and controlled cooling rates (Liu *et al*., 2024).

Zinc (Zn)

Zinc contamination, often from galvanized scrap or mixed die-cast alloys, can lead to galvanic corrosion when combined with other alloying elements. Zn-rich areas act as anodic sites, accelerating localized corrosion and pitting in humid or chloride-rich environments (Padamata *et al*., 2021; Kotadia *et al*., 2025).

Although Zn enhances strength in wrought 7xxx alloys, its uncontrolled presence in foundry alloys reduces corrosion resistance, necessitating careful dilution or selective refining (European Aluminum, 2025b).

Mechanical and Metallographic Testing

Mechanical and microstructural analysis of recycled alloys is crucial for verifying their suitability for casting applications. Standard tests include:

a) Tensile testing (ASTM B557, ISO 6892-1): Determination of ultimate tensile strength (UTS), yield strength (YS), and elongation.
b) Hardness testing (Brinell or Vickers, per ASTM E10/E92): Evaluation of solid-solution hardening and casting soundness.
c) Impact testing (Charpy, ASTM E23): Verification of toughness and notch sensitivity.
d) Metallography (ASTM E3/E407): Optical and scanning electron microscopy for phase identification, dendritic arm spacing, and porosity quantification.

Microstructural studies often reveal refined α-Al dendrites, eutectic Si modification, and reduced porosity when effective degassing and filtering are employed (Lázaro-Nebreda *et al*., 2022; Liu *et al*., 2024). Foundries that incorporate real-time spectroscopy and filtration typically achieve UTS values of 240–280 MPa and elongations exceeding 8% for secondary Al–Si alloys, approaching those of their primary counterparts (Asghar *et al*., 2025).

International Quality Standards

To ensure consistency and interoperability, recycled aluminum alloys must comply with international chemical and mechanical standards that govern composition, properties, and testing methods. Major frameworks include:

a) ABNT NBR 15975 — defines chemical designations for primary and foundry aluminum alloys (ABNT, 2020).
b) ASTM B179-21 — Standard Specification for Aluminum Alloys in Ingot and Molten Form for Castings.
c) EN 1706:2020 — Aluminum and Aluminum Alloys — Castings — Chemical Composition and Mechanical Properties.
d) ISO 10049:2019 — Aluminum alloys — Determination of tensile properties of castings.
e) European Aluminum EPD Rules (2025) — outline environmental and quality metrics, integrating recycled content verification (European Aluminum, 2025a).

Adhering to these standards ensures traceability and reproducibility throughout global supply chains. Certification schemes—such as IAI's Aluminum Stewardship Initiative (ASI) and EPD verification programs—now incorporate quality and sustainability indicators, connecting metallurgical performance to circular economy goals (IAI, 2025).

ENVIRONMENTAL IMPACTS AND THE CIRCULAR ECONOMY

CO_2 Emission Reduction in Recycling

Aluminum recycling is one of the most energy-efficient methods in modern metallurgy, using only 5–10% of the energy needed for primary smelting and reducing CO_2 emissions by up to 95% (IAI, 2025; ABAL, 2025). The International Aluminum Institute (IAI) states that the global average carbon footprint of secondary aluminum is 0.5–0.6 tons of CO_2 per ton, compared to 10–12 tons of CO_2 per ton for primary production using the Hall–Héroult process.

Energy recovery and optimized furnace designs—such as oxy-fuel rotary furnaces and reverberatory systems with regenerative burners—further reduce fuel consumption (Vallejo-Olivares *et al*., 2024). Electrically powered induction furnaces using renewable energy can achieve near-zero net emissions, positioning aluminum as a key material for low-carbon manufacturing (Liu *et al*., 2024).

Recycling also reduces the environmental impact of bauxite mining and alumina refining, which account for approximately 70% of the primary aluminum life-cycle emissions (European Aluminum, 2022).

Dross and solid Waste Management

While the recycling process offers clear environmental benefits, it also generates byproducts such as dross and salt slag that require responsible disposal. Dross contains trapped aluminum metal, aluminum oxides, nitrides, and salts; improper handling can cause the release of ammonia (NH_3) and hydrogen gas when it comes into contact with moisture (Wu *et al*., 2025).

Current valorization strategies include:

a) Mechanical recovery of metallic aluminum via crushing and screening.
b) Hydrometallurgical treatment of salt slag to recover NaCl and KCl for reuse in flux formulations.
c) Encapsulation or inertization of oxides and salts for safe landfilling, following ABNT NBR 10004 (2004) and EU Directive 2008/98/EC on hazardous waste.

Closed-loop systems have achieved recovery efficiencies of over 95% of metallic aluminum and 80% of salts, significantly reducing waste generation and enhancing material circularity (Vallejo-Olivares *et al*., 2024; Qin *et al*., 2025).

Integrated Recycling Chains in the Circular Economy

In the context of the circular economy, aluminum is a permanently recyclable metal that retains its fundamental properties through multiple life cycles (European Aluminum, 2025a). The creation of integrated recycling chains—spanning collection, sorting, remelting, and remanufacturing—forms a closed material loop that benefits both economic and environmental sustainability.

Institutions such as ABAL and Abralatas emphasize Brazil's global leadership, achieving a recycling rate of over 97% for aluminum beverage cans, supported by reverse logistics networks and cooperative waste-picker systems (ABAL, 2025; Abralatas, 2024).

In Europe, the Circular Aluminum Action Plan and the Global Recycling League Table (IAI, 2024) establish strategic goals for high-value recycling, ensuring that post-consumer scrap is returned to similar applications (e.g., can-to-can, car-to-car).

The shift to innovative recycling systems combines digital traceability (blockchain), automated alloy identification (AI-driven LIBS), and eco-design principles that support future recovery and reuse (Guo & Zhang, 2025).

Certifications and Carbon Credits

Environmental certification and carbon-accounting mechanisms reinforce the economic Viability of aluminum recycling under international sustainability frameworks. The Aluminum Stewardship Initiative (ASI), endorsed by the IAI, sets standards for performance and chain-of-custody covering responsible sourcing, emission reduction, and circularity indicators (IAI, 2025).

Furthermore, Environmental Product Declarations (EPDs) and ISO 14021:2016 self-declared environmental claims facilitate transparent communication of recycled content and carbon footprints to end-users (European Aluminum, 2025b).

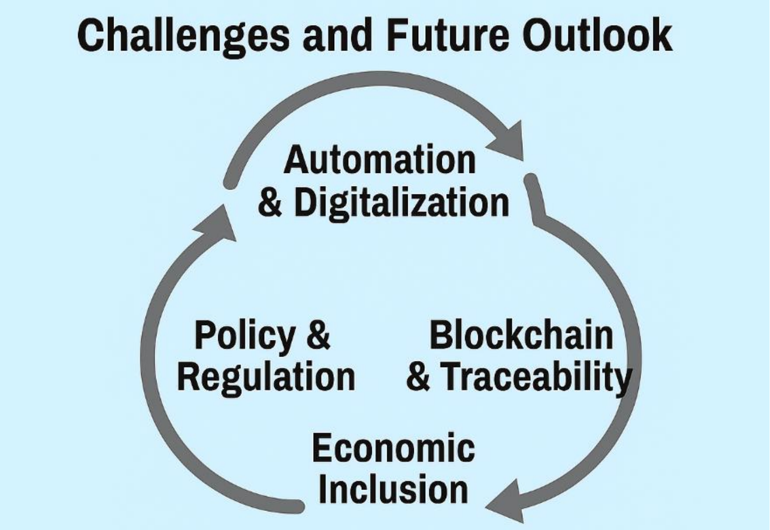
Recycling plants that demonstrate verifiable emission reductions can participate in carbon credit markets, earning certified emission reductions (CERs) in accordance with ISO 14064 and

UNFCCC standards. These credits boost the competitiveness of secondary aluminum producers and attract green financing for plant upgrades and digital improvements.

CHALLENGES AND FUTURE PERSPECTIVES

Figure 5 synthesizes the multidimensional challenges and emerging trends shaping the Future of aluminum recycling: The diagram combines four interconnected pillars: (1) Automation & Digitalization, (2) Blockchain & Traceability, (3) Policy & Regulation, and (4) Economic Inclusion. Arrows between these elements show the mutual dependence between technological innovation, economic sustainability, and governance. Together, they form the structural backbone of next-generation circular systems for the aluminum industry.

Figure 5. Challenges and future outlook in aluminum Recycling.



Source: Adapted from International Aluminum Institute (2025); European Aluminum (2025); ABAL (2025); Pereira (2025).

It visually captures the systemic interdependence among technology, policy, and socioeconomic inclusion in the aluminum recycling ecosystem.

a) Automation and Digitalization are central to the industrial transition, enabling real-time composition analysis, AI-based sorting, and predictive maintenance for furnaces and refining units. These technologies significantly improve energy efficiency and metal yield, aligning with the goals of Industry 4.0.
b) Blockchain and Traceability introduce transparency into supply chains, allowing producers and regulators to verify recycled content, emission footprints, and material

origin. Their adoption supports certification schemes under ISO 14021 and European EPD programs, helping to strengthen consumer trust and market competitiveness.

c) Policy and Regulation remain pivotal drivers. Regions with strong Extended Producer Responsibility (EPR) and clear waste management directives (e.g., EU Circular Economy Action Plan) demonstrate higher recovery efficiency and reduced carbon intensity. In contrast, emerging economies often face fragmented legal frameworks that hinder investment and traceability.

d) Economic Inclusion connects the technological and regulatory pillars by integrating informal recyclers, cooperatives, and SMEs into formal value chains. This dimension ensures equitable participation and strengthens local circular economies, particularly in Latin America and Africa.

Overall, the diagram illustrates that no single axis can achieve circularity on its own. Success in the future will rely on cross-sector collaboration, digital tools, inclusive business models, and adaptable regulations. This aligns with the article’s conclusion, which highlights that aluminum recycling is a vital component of sustainable industrial ecosystems.

Automation and Digitalization: Toward Industry 4.0 Recycling

The shift toward Industry 4.0 is transforming the aluminum recycling industry by adopting automation, artificial intelligence (AI), and data-based process control. Advanced sorting systems that utilize machine vision, laser-induced breakdown spectroscopy (LIBS), and AI-driven alloy recognition are achieving identification accuracy rates exceeding 95%, thereby reducing manual handling and enhancing efficiency (Guo & Zhang, 2025; Chen *et al.*, 2025).

Real-time data from sensors embedded in shredders, furnaces, and degassers enables predictive maintenance and energy efficiency, reducing unexpected downtime. Machine-learning models are being developed to forecast dross formation, hydrogen levels, and alloy variations during the melting process, thereby enhancing material yield and reducing emissions (Liu *et al.*, 2024).

In smart foundries, digital twins of melting and casting processes simulate real-time operations, allowing virtual testing of flux addition, gas flow, and temperature control before implementation. These advances mark a significant move toward fully autonomous and carbon-efficient recycling plants.

Blockchain for Traceability and Circular Supply Chains

Blockchain technology offers a transformative approach to ensuring traceability, authenticity, and circularity throughout the aluminum value chain. By tracking every transaction—from scrap collection and alloying to remelting and product certification—blockchain networks ensure unchangeable records of recycled content and carbon footprint (European Aluminum, 2025b).

This transparency aligns with emerging sustainability reporting frameworks, such as ISO 14067 and Environmental Product Declarations (EPDs), enabling downstream users to verify the proportion of secondary aluminum in final products (IAI, 2025).

Pilot initiatives in Europe and Asia have already demonstrated the feasibility of blockchain-based "digital passports" for aluminum, which track can-to-can and car-to-car transactions in real-time. Future integration with AI-driven material tracking and IoT sensors could enable automated certification and real-time lifecycle assessment (LCA).CA).

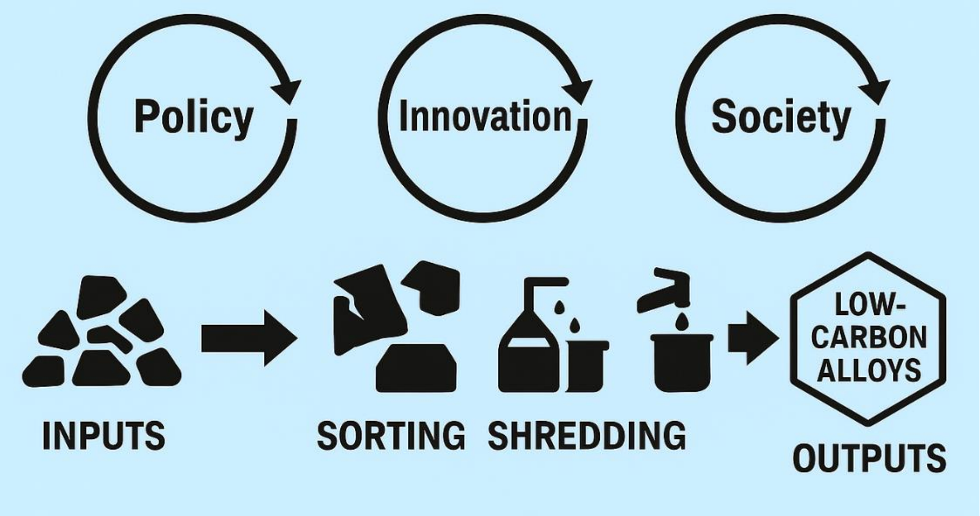
Public Policy and Economic Sustainability in Developing Countries

In developing economies, the expansion of aluminum recycling depends on coherent public policies, regulatory frameworks, and economic mechanisms that foster investment while formalizing informal collection systems. Effective governance should combine Extended Producer Responsibility (EPR) schemes, green financing, and public procurement incentives for low-carbon products.

At the same time, economic sustainability remains a major challenge. High capital costs, energy prices, and technological disparities often limit competitiveness. Strengthening the recycling chain requires innovative financial tools (such as carbon credits and green bonds), capacity building for workers in informal sectors, and regional integration of scrap flows to achieve economies of scale.

Figure 6 illustrates a conceptual model of the circular aluminum economy, which integrates technological, environmental, and socioeconomic factors within a closed-loop system. The diagram illustrates the continuous flow of materials from inputs (bauxite, scrap, and energy) through primary processes (melting, refining, alloying, casting, manufacturing, and use phase) to outputs (products, emissions, and waste). Feedback loops depict the mechanisms that maintain circularity: collection and recycling systems, policy and regulatory tools, innovation cycles, and societal involvement.

Figure 6. Conceptual Model of the Circular Aluminum Economy.



Source: Adapted from International Aluminum Institute (2025); European Aluminum (2025); ABAL (2025); Pereira (2025).

The technological loop—encompassing melting, refining, and alloying—forms the backbone of circularity, where process optimization and energy efficiency directly influence environmental performance. Between 2020 and 2025, advances in automation, sensor-based monitoring, and AI-assisted control have reduced the energy demand of secondary aluminum production by up to 25 % (European Aluminum, 2025).

The environmental loop focuses on mitigating emissions and conserving resources. Recycling aluminum requires only about 5% of the energy needed for primary smelting, resulting in up to 95% lower CO_2 emissions per ton of recovered metal (IAI, 2025). Yet, the sector continues to face challenges in salt-slag management, dross valorization, and control of fluorinated gases, particularly in developing economies where environmental oversight remains limited.

The socioeconomic loop emphasizes inclusive governance and effective reverse logistics. In Latin America and Africa, informal and semi-formal recyclers play a vital role in collection efficiency but often lack integration into fiscal and safety systems. Incorporating these actors through Extended Producer Responsibility (EPR) frameworks and green financing mechanisms is crucial to distributing the benefits of circularity equitably throughout the recycling chain.

Ultimately, this model represents the shift from linear to regenerative production systems, where recycling becomes a strategic pillar of innovation, employment, and sustainability—not merely the final stage of material recovery. Ensuring policy coherence and financial inclusion will be fundamental for recycling to drive not only decarbonization but also industrial resilience, job creation, and social equity in developing regions.

CONCLUSIONS

This review consolidates the technological, environmental, and policy dimensions of aluminum scrap recycling between 2020 and 2025. Major progress has been achieved in pre-treatment, melting, and refining operations, with metal yields exceeding 90% and energy demand decreasing to below 1 MWh t^{-1} Al. These advances position secondary aluminum as a cornerstone of low-carbon manufacturing.

Nevertheless, full circularity remains constrained by heterogeneous scrap streams, limited alloy standardization, and uneven regulatory frameworks. Future developments should focus on integrating real-time life-cycle assessment (LCA) into industrial monitoring, establishing global standards for high-recycled-content alloys (>80 %), and harmonizing Extended Producer Responsibility (EPR) policies across developing regions.

Looking forward, aluminum recycling will increasingly rely on digitalization—AI-driven sorting, blockchain-based traceability, and smart carbon accounting—to achieve transparent and resilient value chains.

Ultimately, aluminum stands not merely as a recyclable material but as a *permanent asset* enabling the energy transition, resource efficiency, and inclusive industrial growth toward 2030.

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