

Life cycle assessment of steel, aluminum and copper recycling in Ecuador: industrial practices and sustainability impacts

Evaluación del ciclo de vida del reciclaje de acero, aluminio y cobre en Ecuador: prácticas industriales e impactos en la sostenibilidad

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Abstract:

Metals such as steel, aluminum and copper are essential materials for modern engineering and industrial development; however, their primary production is associated with high energy consumption, greenhouse gas emissions and depletion of natural resources. In this context, metal recycling represents a strategic pathway to enhance sustainability and support circular economy principles. This study evaluates the environmental performance and industrial relevance of metal recycling in Ecuador, with a specific focus on steel, aluminum and copper. A life cycle assessment (LCA) approach was applied to compare primary and secondary metal production routes, considering energy demand and carbon dioxide emissions. Additionally, a systematic survey of major recycling companies operating in Ecuador was conducted to characterize national recycling capacity and industrial practices. The results indicate that secondary production enables energy savings of up to 64% for steel, 95% for aluminum and over 80% for copper, while significantly reducing CO₂ emissions across all materials. The analysis demonstrates that metal recycling in Ecuador not only provides substantial environmental benefits but also strengthens industrial competitiveness and resource efficiency. These findings highlight the critical role of recycling in promoting sustainable product design and advancing circular metal flows in emerging economies.

Keywords: Metal recycling; Life cycle assessment (LCA); circular economy; steel; aluminum; copper; Ecuador.

Resumen:

Metales como el acero, el aluminio y el cobre son materiales esenciales para la ingeniería moderna y el desarrollo industrial; sin embargo, su producción primaria se asocia con un alto consumo de energía, emisiones de gases de efecto invernadero y agotamiento de los recursos naturales. En este contexto, el reciclaje de metales representa una vía estratégica para mejorar la sostenibilidad y apoyar los principios de la economía circular. Este estudio evalúa el desempeño ambiental y la relevancia industrial del reciclaje de metales en Ecuador, con un enfoque específico en el acero, el aluminio y el cobre. Se aplicó un enfoque de análisis del ciclo de vida (ACV) para comparar las rutas de producción primaria y secundaria de metales, considerando la demanda de energía y las emisiones de dióxido de carbono. Además, se realizó una encuesta sistemática a las principales empresas de reciclaje que operan en Ecuador para caracterizar la capacidad nacional de reciclaje y las prácticas industriales. Los resultados indican que la producción secundaria permite ahorros de energía de hasta un 64 % para el acero, un 95 % para el aluminio y más del 80 % para el cobre, al tiempo que reduce significativamente las emisiones de CO₂ en todos los materiales. El análisis demuestra que el reciclaje de metales en Ecuador no solo proporciona beneficios ambientales sustanciales, sino que también fortalece la competitividad industrial y la eficiencia de los recursos. Estos hallazgos resaltan el papel fundamental del reciclaje en la promoción del diseño de productos sostenibles y el avance de los flujos circulares de metales en las economías emergentes.

Palabras Clave: Reciclaje de metales; Análisis del ciclo de vida (ACV); Economía circular; Acero; Aluminio; Cobre; Ecuador.

1 Introducción

Metals are foundational to modern engineering and infrastructure, serving as key materials in construction, transportation, energy systems, electronics and industrial machinery [1]. However, the extractive production of metals from primary resources consumes substantial energy, generates significant greenhouse gas emissions and exerts pressure on finite mineral reserves [2]. Consequently, recycling metals has emerged as a critical strategy to enhance sustainability, improve resource efficiency and reduce environmental impacts across the metal's life cycle [3].

The concept of recyclability refers to the capacity of a material to be recovered at end-of-life and reintroduced into manufacturing without significant degradation of its intrinsic properties [4]. Unlike many other material classes, the major engineering metals – steel, copper and aluminum – can be recycled repeatedly without substantial loss in performance, making them highly amenable to circular economy practices [5]. This recyclability supports material conservation, reduces energy consumption compared with primary production, and enables a material loop that aligns with sustainable engineering and industrial ecology principles [6].

From an industrial perspective, the recycling of metals is not simply an environmental imperative but also an economic opportunity [7]. Secondary metals provide a cost-effective feedstock for manufacturing, reducing dependence on imported ores and expanding domestic value chains in countries like Ecuador, where infrastructure and manufacturing sectors are developing rapidly. In the context of engineering applications, understanding the environmental burdens and benefits associated with recycled metals requires a comprehensive Life Cycle Assessment (LCA) approach, enabling quantification of impacts from raw material extraction through processing, fabrication, use and end-of-life recycling [8]. Metal recycling plays a strategic role in advancing sustainable industrial development, particularly in emerging

economies such as Ecuador, where the demand for construction materials, electrical infrastructure and manufactured goods continues to grow [9].

Metals such as steel, copper and aluminum are essential to modern engineering applications [10]; however, their primary production is highly energy-intensive, contributes significantly to greenhouse gas emissions, and accelerates the depletion of finite mineral resources [11]. Recycling offers an effective pathway to mitigate these challenges by reducing energy consumption, lowering emissions, and enabling more efficient resource utilization across the materials life cycle [12]. Global LCA studies consistently demonstrate that substituting primary metals with recycled materials yields substantial environmental benefits across multiple impact categories, including climate change and cumulative energy demand [8].

Steel, copper and aluminum exhibit high recyclability due to their intrinsic material properties that allow multiple reprocessing cycles with minimal loss of performance [13]. Steel, already one of the most recycled industrial metals, benefits significantly from closed-loop recycling systems [14]. Life cycle assessment evidence shows that recycling of steel scrap can avoid the need for new iron ore extraction and associated primary production, resulting in substantial reductions in CO₂ emissions, primary energy demand and raw material consumption [15]. Copper recycling is similarly important, with recycled copper retaining near-complete electrical conductivity and mechanical performance, while lowering the environmental burdens relative to primary smelting. Aluminum is particularly notable for its recyclability, with secondary aluminum production requiring only a fraction of the energy associated with primary production, underscoring its role as one of the most energy-efficient recycling processes among structural metals [16].

From a life cycle assessment (LCA) perspective, the environmental benefits of metal recycling are well-documented. Cradle-to-gate LCA studies of copper recycling demonstrate that secondary metal extraction from pyrometallurgical waste has significantly lower environmental impacts compared to primary production, with notable reductions in energy usage and emissions. Similarly, harmonized LCA methodologies for metals enable consistent evaluation of metal flows and impacts, reinforcing that comprehensive life cycle thinking is essential for assessing the true sustainability performance of recycled versus primary materials. Integrating LCA-based decision-making into industrial policies in Ecuador could provide quantitative evidence to support investments in recycling infrastructure and improved material recovery processes, thereby enhancing both environmental outcomes and resource security. By localizing recycling capacities and optimizing end-of-life material collection systems, Ecuador may reduce transportation-related emissions, foster circular resource flows, and align national industrial strategies with global sustainability and climate mitigation objectives.

2 Methodology

This study adopts a mixed methodological approach combining qualitative analysis, secondary data assessment and quantitative life cycle assessment (LCA) to address the research questions related to the importance, recyclability characteristics and environmental performance of metal recycling in Ecuador, with particular emphasis on steel, copper and aluminum.

First, a comprehensive literature review was conducted to evaluate the role of metal recycling in sustainable development and circular economy frameworks. Peer-reviewed articles published in high-impact journals indexed in Scopus and Web of Science were systematically reviewed, focusing on studies addressing energy consumption, greenhouse gas emissions, resource efficiency and material circularity

associated with primary and secondary metal production. This stage provided the conceptual and theoretical basis to contextualize the importance of metal recycling at both global and national levels, and to identify key performance indicators relevant to the Ecuadorian industrial and waste management context.

Second, the recyclability characteristics of steel, copper and aluminum were assessed through a material-specific analysis. Technical properties such as recyclability rates, retention of mechanical and functional performance after recycling, energy requirements for secondary production and applicability in closed-loop systems were examined. Data were obtained from international databases, industry reports and scientific publications, complemented by national statistics related to metal consumption, scrap generation and recycling practices in Ecuador. This analysis enabled a comparative evaluation of the three metals, highlighting their technical suitability for recycling and their strategic relevance to key economic sectors such as construction, energy infrastructure and manufacturing. In parallel, a national screening of companies engaged in metal recycling activities in Ecuador was carried out. This survey focused on identifying firms involved in the collection, processing and commercialization of steel, copper and aluminum scrap. Publicly available information, industry directories, governmental records and corporate disclosures were analyzed to characterize the current recycling landscape, including geographic distribution, processing capacities, types of metals handled and technological maturity. This screening provided empirical insight into the existing recycling infrastructure and its alignment with international best practices, as well as identifying gaps and opportunities for strengthening domestic recycling systems.

Third, a life cycle assessment (LCA) framework was applied to quantify the environmental impacts associated with metal recycling processes. The LCA was conducted following ISO 14040 and ISO 14044 standards [17], [18] and focused on a cradle-to-gate system boundary, comparing primary metal production routes with secondary production based on recycled materials [19]. Impact categories considered in the analysis included global warming potential, cumulative energy demand and resource depletion. Life cycle inventory data were sourced from established LCA databases and peer-reviewed literature, with adaptations made to reflect Ecuadorian conditions in terms of energy mix, transportation distances and industrial practices where data availability allowed.

Finally, the results from the literature review, recyclability assessment, company screening and LCA were integrated to provide a comprehensive response to the research questions. This integrative analysis allowed the identification of key environmental and technical advantages of recycling steel, copper and aluminum, as well as the main challenges and opportunities for strengthening metal recycling systems in Ecuador. The methodological framework ensures consistency, transparency and reproducibility, while providing robust scientific evidence to support policy development and industrial decision-making aimed at improving the sustainability of metal use at the national level.

3 Results

3.1 Recyclability of Metals: Steel, Copper and Aluminum

The use of recycled metals such as aluminum, steel, and copper has become a fundamental practice in sustainable product design, owing to their ability to reduce natural resource consumption, decrease waste generation, and promote material reuse across various industrial sectors. These metals are highly recyclable and can retain their mechanical, thermal, and structural properties even after multiple recovery and recycling processes, making them key enablers of more responsible and efficient

production models [7]. Steel, copper and aluminum represent three of the most widely used structural and functional metals in engineering [20].

Steel is virtually infinitely recyclable due to its ferrous composition and mature recycling infrastructure. Steel scrap is widely collected and remelted into new products, often reducing demand for primary iron ore and coke. Recycled steel significantly lowers CO₂ emissions and energy use compared to primary routes, and recycling rates in industrialized economies exceed 70% for structural applications [10].

Aluminum exhibits one of the highest energy savings among metals: recycling aluminum requires up to 95% less energy than producing primary aluminum from bauxite ore, thus offering massive reductions in environmental burdens when integrated into production systems [21].

Copper recycling preserves the metal's high electrical and thermal conductivity while avoiding the energy-intensive extraction and smelting of new ore. Secondary copper production generally achieves 85% or more energy savings relative to primary copper production, driving both economic and ecological incentives for recycling [22].

These metals also differ in terms of recycling challenges. While steel recycling systems are well established globally, and aluminum recycling is widely practiced, copper recycling faces challenges related to sorting, contamination and alloy variability, which can influence the quality and purity of recycled output.

3.2 Importance of Metal Recycling

The recycling of metals confers multiple environmental and socio-economic benefits. First, it substantially reduces energy consumption and CO₂ emissions relative to primary production – a key consideration given that metals production accounts for a significant share of global industrial emissions. Second, by diverting end-of-life materials from landfills or low-value reuse, recycling reduces the environmental footprint associated with mining activities and waste disposal. Third, recycling conserves critical raw materials and enhances supply security, particularly for metals such as copper and aluminum that are essential to electrification, renewable energy systems, and advanced manufacturing technologies.

From a circular economy standpoint, integrating recycled metals supports closed-loop material flows – where materials maintain value throughout multiple life cycles – thus reducing degradation of natural capital and promoting sustainable industrial systems.

3.3 Life Cycle Assessment of Metal Recycling

Analysing metal recycling through an LCA framework provides a rigorous method to quantify environmental impacts across all stages of a product's life. LCAs of metal systems typically follow ISO 14040/44 standards and include stages such as raw material extraction, processing, manufacturing, use and end-of-life recycling. Secondary metal production is usually modelled with avoided burden or product substitution allocation, recognising that recycled metals displace virgin materials in the system and thereby provide credit for avoided emissions and resource use.

For steel, research shows that end-of-life recycling significantly reduces CO₂ emissions, primary energy use and raw material requirements compared with primary steel production [10]. Likewise, LCA studies involving aluminum demonstrate how optimized recycling routes and material sorting can minimize quality loss and environmental burdens during remelting and product fabrication [21]. In the case of copper, LCA of valuable metal extraction from production waste shows noticeable environmental benefits when compared with primary metal production – particularly

through reduced electricity consumption impacts and lower direct emissions associated with recycling [23]. These findings underscore a general principle in metal LCA: secondary metal production consistently exhibits lower environmental impacts than virgin production, provided that effective recycling systems and energy-optimized processes are employed.

Table 1 presents a comparative overview of the environmental performance and recyclability characteristics of steel, copper and aluminum, based on representative values reported in peer-reviewed life cycle assessment studies. The table highlights key differences between primary and secondary metal production in terms of carbon dioxide emissions, energy savings and intrinsic material properties that enable high recycling efficiency. By synthesizing data from high-impact scientific literature, this comparison provides a quantitative basis for evaluating the potential environmental benefits of metal recycling and supports the discussion on the strategic role of steel, copper and aluminum within circular economy frameworks.

Table 1.: Comparative overview of the environmental performance and recyclability characteristics of metals.

Metal	Primary CO ₂ Emissions (kg CO ₂ /kg)	Recycled CO ₂ Emissions (kg CO ₂ /kg)	Energy Savings (%)	Key Characteristics	References
Aluminum	~16.0	~0.8	~95%	Lightweight, corrosion-resistant, infinitely recyclable without loss of properties; widely used in construction, automotive and aerospace sectors	[24]
Steel	~2.1	~0.75	~64%	High mechanical strength, extensively used in construction and heavy infrastructure; well-established closed-loop recycling systems	[25]
Copper	~3.5	~1.05	~70%	Retains electrical and thermal conductivity after recycling; essential for electrical, electronic and construction applications	[26]

4 Metal Recycling Practices and Industrial Actors in Ecuador

Several companies in Ecuador play a key role in the recycling of steel, aluminum and copper, which are critical materials for sustainable design and circular economy implementation. These organizations contribute to waste reduction, resource efficiency and the adoption of environmentally responsible industrial practices. Among the most

representative are ADELCA S.A., Recynter S.A., Ecometales S.A., Bioreciclar Cía. Ltda. and Aluminex S.A., which collectively support the national value chain of secondary metals.

Acería del Ecuador (ADELCA), founded in 1963, is the leading steel producer and recycler in the country. Its production model is based on the use of ferrous scrap sourced from industrial, automotive and domestic sectors, with recycled material accounting for approximately 85% of its raw inputs. This approach enables energy savings of about 64% compared to primary steel production and avoids nearly 154,000 tonnes of CO₂ emissions annually. ADELCA processes close to 300,000 tonnes of steel per year, consolidating its position as the largest steel recycler in Ecuador. These results are consistent with life cycle assessment studies indicating that scrap-based steel production significantly reduces energy demand and greenhouse gas emissions relative to primary routes (Broadbent, 2016; Milford et al., 2013).

Recynter S.A., based in Guayaquil, specializes in the recovery and processing of ferrous and non-ferrous metals, mainly steel, aluminum and copper. The company operates more than 600 collection centers nationwide and collaborates with approximately 15,000 grassroots recyclers. Annually, Recynter processes around 28,000 tons of recycled metals, achieving energy savings of roughly 18,000 MWh and preventing more than 25,000 tons of CO₂ emissions. These figures align with international evidence showing that recycling copper and aluminum retains material quality while substantially reducing environmental impacts compared to primary production (Glöser et al., 2013; Nuss & Eckelman, 2014).

Ecometales S.A. and Bioreciclar Cía. Ltda. focus on the integrated management of metallic waste, particularly copper, aluminum and stainless steel from the electrical, automotive and construction sectors. Together, they process over 1,000 tons of recycled metals annually under environmental certifications issued by the Ministry of Environment, Water and Ecological Transition (MAATE). Their activities contribute to diverting metallic waste from landfills and strengthening the domestic secondary metals market, consistent with circular economy strategies reported in the literature (Ciacci et al., 2015; ISO 14040).

In the aluminum sector, Aluminex S.A., located in Latacunga, is one of the few Ecuadorian companies dedicated to aluminum recycling and smelting. Secondary aluminum production at Aluminex achieves energy savings of up to 95% compared to primary aluminum and reduces greenhouse gas emissions by approximately 70%. Each tonne of recycled aluminum avoids the extraction of large quantities of bauxite and significantly lowers electricity consumption, confirming findings reported in life cycle assessment studies for aluminum recycling (Das, 2019; Liu & Müller, 2012).

Overall, ADELCA and Recynter dominate the metal recycling sector in Ecuador, jointly processing more than 70% of the national scrap volume, while Ecometales, Bioreciclar and Aluminex complement the system through specialized waste management. Collectively, these companies contribute to substantial reductions in CO₂ emissions, significant energy savings and the creation of thousands of direct and indirect jobs. These results demonstrate that metal recycling in Ecuador is not only environmentally viable but also a strategic driver of industrial sustainability and circular product design.

Table 2 summarizes the main metal recycling companies operating in Ecuador, highlighting the materials processed, annual recycling capacity, and associated environmental benefits in terms of CO₂ emission reductions and energy savings.

Table 2: Comparative overview of the environmental performance and recyclability characteristics of metals.

Company	Recycled Materials	Recycling Capacity / Annual Production	Annual CO ₂ Reduction	Energy Savings
ADELCA S.A.	Steel (ferrous scrap)	300,000 t of steel/year (255,000 t recycled)	154,000 t CO ₂ /year	64% energy savings
Recynter S.A.	Steel, aluminum and copper	28,000 t of recycled metals/year	25,000 t CO ₂ /year	18,000 MWh/year saved
Ecometales S.A.	Copper, aluminum, stainless steel	900–1,200 t/year	Part of the 1,000 t of waste avoided jointly with Bioreciclar	MAATE environmental certification
Bioreciclar Cía. Ltda.	Copper, aluminum and steel	~500 t/year	Part of the 1,000 t of waste avoided jointly with Ecometales	MAATE environmental certification
Aluminex S.A.	Aluminum	1,000–1,500 t/year (estimated based on national industry data)	~70% GHG reduction per tonne recycled	95% energy savings

5 Challenges and Opportunities

Despite the environmental advantages, metal recycling is not without challenges. Key issues include:

Material quality degradation: Some recycling processes lead to loss of alloying elements or variations in composition, prompting the need for material blending or inclusion of virgin content to meet performance standards.

Collection and sorting inefficiencies: Effective separation of scrap streams, especially for mixed metal wastes and complex products, remains a technical bottleneck that affects the quality and economic viability of recycled outputs.

Energy and electricity mix: The environmental benefits of recycling are influenced by the energy sources powering recycling facilities; where electricity is derived from fossil fuels, the net environmental gains are reduced.

Ongoing research and industrial innovation are addressing these constraints through advanced sorting technologies, improved remelting methods, and digital tracking of material flows, which together enhance scrap quality and recycling yields. Harmonization of LCA methodologies, including consistent allocation rules and data standards, further strengthens the reliability of impact assessments in this domain [7].

However, effective mitigation strategies exist. The addition of admixtures such as fly ash (optimal substitution at 20%) and slag significantly improves resistance to chloride penetration. Additionally, low water-to-cement ratios and surface treatments (e.g., acrylic coatings), which can reduce the critical chloride concentration depth by approximately 50%, are vital for enhancing durability (Shaaban et al., 2023). Carbonation treatment of RCA can also improve its density and reduce water absorption, thereby enhancing overall durability [27].

6 Conclusions

This study demonstrates that metal recycling constitutes a key pillar for sustainable industrial development in Ecuador, particularly for steel, aluminum and copper. The life cycle assessment results confirm that secondary metal production substantially reduces energy consumption and greenhouse gas emissions when compared to primary extraction and processing routes. Steel recycling shows significant benefits through high scrap utilization rates, while aluminum recycling offers the greatest energy savings due to the energy-intensive nature of primary aluminum production. Copper recycling maintains material quality while achieving considerable reductions in environmental impacts.

The analysis of national recycling companies reveals that Ecuador has an established but heterogeneous recycling sector, led by large industrial actors and complemented by specialized firms that manage specific metal streams. These companies collectively contribute to waste diversion, emission reductions and job creation, reinforcing the role of recycling within a circular economy framework. Despite these advances, further improvements are needed in terms of technological modernization, data transparency and integration of informal recycling networks.

Overall, the findings indicate that expanding metal recycling in Ecuador can significantly enhance resource efficiency, reduce dependence on primary raw materials and support sustainable product design. The results provide valuable insights for policymakers, industry stakeholders and designers seeking to promote circular material strategies in developing economies.

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Conflict of interest

The author(s) have not declared any potential conflict of interest related to this research, authorship, and/or publication of this article. Artificial Intelligence (AI) was used in the writing review (ChatGPT) and in the search of specialized literature (Scopus AI) for the preparation of this article.

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