International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

Scrap Management and Circular Economy Strategies in the Aluminum Industry

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International Journal of Science and Research Archive, 2025, 17(02), 1227-1236

Publication history: Received on 02 October 2025; revised on 06 November 2025; accepted on 09 November 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.17.2.3023

Abstract

Aluminum is a critical raw material that is highly applicable in the transport, construction, and packaging sectors because it has excellent resistance and can be recycled. The growth of demand for primary aluminum worldwide, coupled with environmental concerns, has increased interest in sustainable alternatives. This will be reviewed in the context of scrap management and the circular economy in the aluminum industry, considering technology, economic, and policy factors. It highlights the potential of advanced sorting systems, alloy separation methods, and computerized tracking systems to enhance the efficiency of the recycling process. The review also focuses on other regulatory strategies (extended producer responsibility), and the complexity of alloys, contamination of materials, and design inefficiency are mentioned as hindering circular flows. One of the proposed theoretical frameworks is the explanation of how to integrate scrap management systems into the design of recycling, urban mining, and carbon responsibility, aiming to help production become closed-loop. The further prospects include the use of Industry 4.0 instruments, adopting the same recycling practices globally, and incorporating the principles of eco-design. The findings underscore the need for a multidimensional approach to achieve a sustainable and circular economy for aluminum.

Keywords: Aluminum Recycling; Circular Economy; Scrap Management; Secondary Aluminum; Design for Recycling; Advanced Sorting Technologies; Extended Producer Responsibility; Lifecycle Assessment; Urban Mining; Alloy Separation

1. Introduction

The fact that aluminum has a great strength-to-weight ratio, remains highly non-corrosive, and can be recycled, makes it a major industrial metal used in transportation, building construction, packaging, and electrical engineering. The recent decades have seen a significant rise in global demand for aluminum, driven by technological advancements, urbanization, and the increasing need for lightweight materials to enhance the efficiency of energy production and transportation systems [1]. This type of demand has sparked environmental concerns about the sustainable production of aluminum, particularly in the exploitation of waste generated during manufacturing and in the responsible termination of its use.

The management of scrap in the aluminum industry is at the epicenter of explanations for resource management, environmental impact reduction, and energy consumption. The energy-consuming process of producing primary aluminum out of bauxite ore is quite energy-demanding, given that the amount of electrical energy required to mine one ton of the metal is around 14-16 MWh, which translates to a relatively high volume of carbon emissions [2]. Instead, recycling aluminum scrap requires only approximately 5 percent of the energy needed for primary production, making it a very important process in improving the sustainability of the entire industry [3]. Therefore, the successful scrap collection, sorting, and remelting processes also contribute to reducing the environmental impact of aluminum production, and they are economically competitive as well.

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Meanwhile, the concept of a circular economy has become extremely popular in the world policy and industry. The model focuses on the long-term decoupling of economic progress and resource consumption, waste reduction, and the encouragement of material reuse [4]. Some of the circular economy plans adopted in the aluminum industry include designing products that are more sustainable and recyclable, enhancing the scrap recovery system, developing a closed-loop recycling system, and implementing more modern scrap sorting and alloy separation technologies [5]. The plans will focus on extending the life of Aluminium materials and minimizing waste and environmental degradation.

Although recycling of aluminum is at its technological best, questions remain about whether it is possible to achieve a full circle economy of aluminum. Loss of material quality brought about by recycling, also referred to as downcycling, is one of the greatest deterring factors. The scrap is often contaminated, a mixed alloy, poorly sorted, and of relatively poor quality, and is reused as untainted aluminum that is not reintroduced into high-performance systems, such as aerospace or car structures [6]. Moreover, other causes of inefficiency within scrap management systems include differences in the performance of scrap collection in the international environment, unequal regulatory standards, and market uncertainty [7].

Additionally, the alloys used in modern products are sophisticated, and the introduction of more types of composite materials further complicates the recycling of these products. The lack of frequent product labeling and material tracking systems would hinder effective sorting and recovery, ultimately resulting in higher landfill and/or lower-value recycling streams [8]. It utilizes the issues to describe the need to change and innovate the system and processing of scrap, as well as policy and industrial cooperation, to establish a circular economy for aluminum.

The available literature will provide sufficient data regarding the personal qualities of the aluminum recycling process and circular economy practices. However, no extended synthesis is available that integrates the concept of scrap management with the expanded circle strategies of the aluminum value chain. The literature available is based on the technical part of recycling or policy and economics, but, in the majority of cases, does not consider the interface between the two [9]. The purpose of the proposed review is to critically assess the current situation in the field of scrap management and to determine the application of circular economy concepts in the aluminum industry, with reference to existing practices, technological solutions, and structural problems.

2. Literature Review

Table 1 Summary of Key Research Studies on Scrap Management and Circular Economy in the Aluminum Industry

Research Focus	Methodology	Key Findings / Contributions	Reference
Comprehensive overview of aluminum recycling processes, technologies, and industry practices.	Literature review and technical analysis.	Provided an in-depth explanation of the physical and chemical processes involved in aluminum recycling, including energy efficiency and material recovery rates. Established foundational knowledge for further research on aluminum circularity.	[10]
Quantitative assessment of aluminum flows within China's economy, including domestic production, consumption, and international trade.	Material Flow Analysis (MFA) over a 10-year period.	Identified rapid growth in aluminum demand and production in China, highlighting inefficiencies and imbalances in material flow. Provided data critical for policy development and sustainable material management.	[11]
Exploration of metal recycling within the framework of the circular economy, particularly for clean technologies.	Policy review and case study analysis.	Emphasized the importance of establishing closed-loop systems for metals. Highlighted the role of regulatory frameworks and industry cooperation in promoting efficient metal recovery from end-of-life products.	[12]
Investigation of circular economy (CE) initiatives implemented in a Chinese aluminum industrial park.	Empirical case study of an aluminum industry cluster.	Demonstrated how CE measures (e.g., industrial symbiosis, waste-to-resource conversion) enhanced economic performance and reduced environmental impact. Served as a model for CE-based industrial upgrades.	[13]

Life Cycle and Cost Analysis of Recovering Alumina from Aluminum Dross	Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).	Concluded that alumina recovery from dross can be both environmentally beneficial and economically viable, depending on the scale and technology used. Supported secondary resource utilization in the aluminum industry.	[14]

3. Proposed Theoretical Model and System Interaction Diagram

The aluminum industry comprises various interrelated units that form a comprehensive system, encompassing the extraction of raw materials, core production, product manufacturing, consumer use, and scrap recovery. The shift to the circular economy requires a model that encompasses all these steps and utilizes feedback mechanisms, government policies, and new technologies to maximize material recovery and reuse.

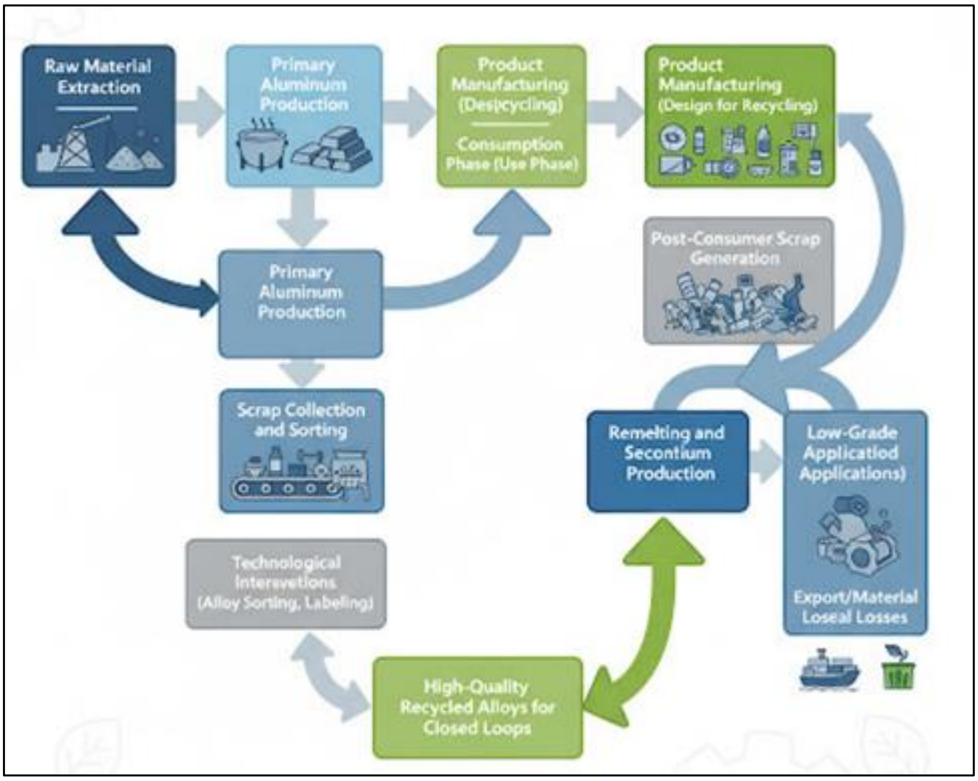

Figure 1 Circular Economy-Oriented Scrap Management in the Aluminum Industry

3.1. Theoretical Model: Integrated Scrap-Circularity Loop Framework (ISCLF)

The framework, known as the Integrated Scrap-Circularity Loop Framework (ISCLF), illustrates how the production model of the aluminum industry has evolved from a traditional linear model to a more circular one. It bridges the gap between scrap management on the one hand and design transformation, digital tracking systems, and policy tools on the other to achieve closed material loops.

3.2. Model Components and Interactions

3.2.1. Scrap Source Integration

There are three primary sources of aluminum scrap: pre-consumer (production offcuts), post-industrial (manufacturing waste), and post-consumer (end-of-life products). Very accurate tracking systems and digital material passports enhance the process of identification and segregation in addition to minimizing the chances of contamination [15].

3.2.2. Advanced Sorting and Alloy Separation

This recycling system is impeded by the fact that alloys and impurities are mixed. The combination of methods, including laser-induced breakdown spectroscopy (LIBS) and X-ray fluorescence (XRF) sorting, allows one to achieve the separation of an alloy with an awesome amount of precision, and by extension, less downcycling and an increase in the number of applications of the recycled material in high-quality operations [16].

3.2.3. Design for Disassembly (DfD) and Recycling

The efficiency of the recycling process is significantly dependent on the product design factor. Much higher recovery rates can be achieved through the adoption of principles of easier disassembling, part labeling, and the use of mono-materials when it comes to the recycling phase [17].

3.2.4. Policy and Regulatory Mechanisms

The incentives are in the form of Extended Producer Responsibility (EPR), landfill taxes, and recycled content requirements, which encourage stakeholders to prioritize recycling and waste reduction as the first option. The problems resulting from the variations in recycling infrastructures and collection efficiencies can be resolved through alignment of policies at the regional level [18].

3.2.5. Market Dynamics and Economic Feasibility

The scrap markets for aluminum can be impacted by fluctuations in commodity prices and global trade policies. Both the closed-loop model and the open-loop model are unrealistic without a constant supply chain of clean scrap, which is maintained by economic tools such as carbon pricing [19].

3.2.6. Environmental Impact Feedback

Life Cycle Assessment (LCA) measures provide quantitative feedback on energy consumption, emissions, and resource savings. Recycling aluminum would reduce the energy used by 95 percent normally required to produce the primary product, consequently resulting in a significant reduction of environmental effects during the lifecycle [20].

3.3. Model Output

The results of the projections, which are generated by the framework of Integrated Supply Chain and Lifecycle Framework (ISCLF) can be used to demonstrate how the flow of aluminum may be directed by the various alternatives of recycling and how the streams may be directed to achieve the end goal of a generalized circular economy. According to the model, there exist two major directions in which recycling can be performed: closed-loop recycling and open-loop downcycling, which are dependent on technological goodwill, political intervention, and the quality of the materials.

The reuse of scrap aluminum in the manufacture of the same or a higher-grade product, such as an automotive component, aerospace frame, or a can to hold drinks, is called closed-loop recycling. This process does not significantly reduce the material quality. The achievement of this route will require the assistance of the powerful regulatory and policy authorities. Manufacturers should be motivated to design products that can be recovered at end-of-life, so that the challenging alloy separation, contamination, and remelting technologies can be supported. The effectiveness of its solution would be determined by the standardization of material labeling, the product tracing system, investment in a high-quality scrap collection system, and sorting devices. The closed-loop systems, when effectively adopted, will minimize the wastage of resources, reduce the quantity of energy consumed, and decrease the production of carbon, thereby enhancing the sustainability of the entire value chain of aluminium.

However, open-loop downcycling is the reuse of good-quality scrap aluminum in lower-grade applications, resulting from issues with alloy, contamination, poor sorting, or incompatible finishes. Although the same route will be used for resource conservation, material performance and economic value will be gradually lost through numerous recycling operations. The overall implications of downcycling can be determined when post-consumer scrap cannot be detected, or even in cases where alloy separation is not possible due to technological limitations. According to the ISCLF, none of the secondary aluminum will be recycled to form a fully closed loop until the systems are modified to manage waste, implement digital tracing, and establish alloy standardization. This will limit the industry's ability to operate as a fully circular system.

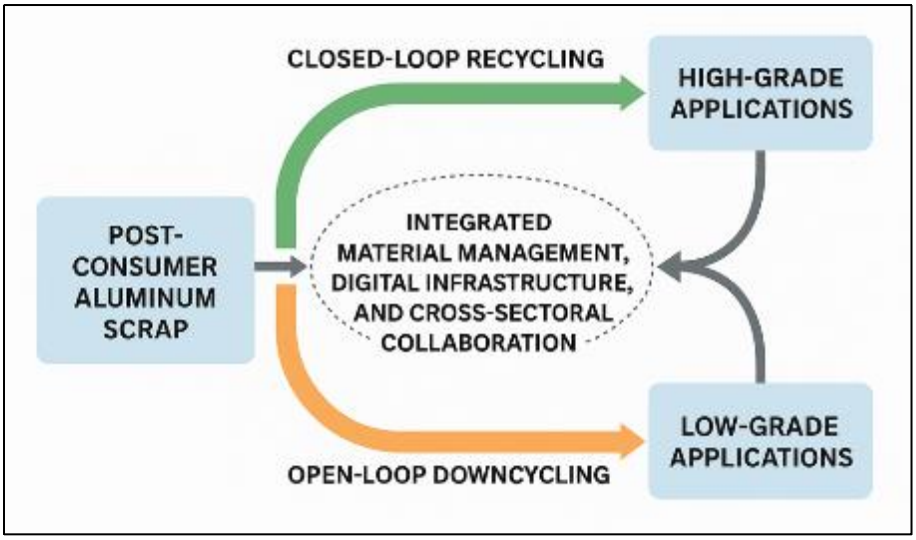

Figure 2 Forecasted Aluminum Recycling Pathways under the ISCLF

3.4. Model Predictions and Quantitative Insights

The ISCLF (Integrated Supply Chain and Lifecycle Framework) yields a numerical forecast of how the aluminum recycling paths are likely to shift under various circumstances of applying the circular economy. The model also considers input values, including the availability of scrap, the quality of the alloy, the rate of energy consumed in the process, and the rate at which the policy is adopted, to estimate the results of the material flow in 2035, carbon saved, and closed-loop recycling efficiency.

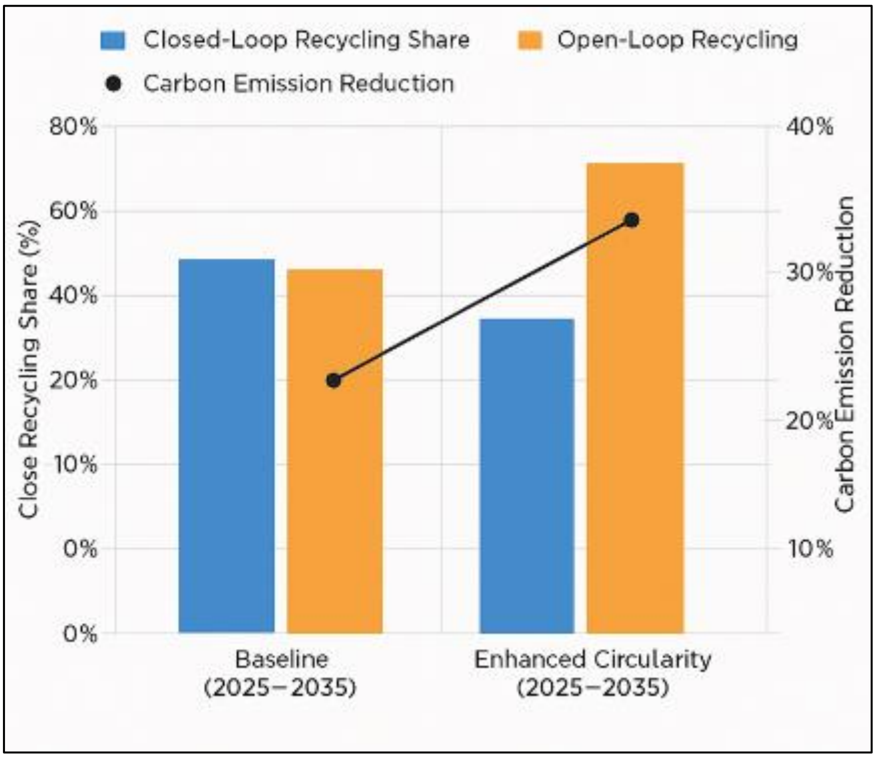

Figure 3 Quantitative Forecast of Aluminum Recycling Scenarios under the ISCLF

In that case, the model also predicts that in the case of minor alterations in the technological and policy interventions (i.e., in the case of the baseline situation), the share of the post-consumer aluminum recycled to open-loop recycling will also be approximately 55-60 percent, and this will result in low-grade uses and moderate carbon emission cuts. Compared to this, the scenario of increased circularity, characterized by intensive policy incentives, digital infrastructure, and improvements in scrap management, is projected to undergo significant changes: by 2035, up to 70-75 percent of the aluminum scrap can be directed into closed-loop systems. The result of this shift will be a 35-40 percent reduction in life cycle carbon and a 25 percent increase in material recovery. In addition, as the projections of ISCLF note, operational losses can be reduced by approximately 15 percent with the help of Industry 4.0 technologies in the field of remelting and sorting facilities, which will also be used to increase the energy efficiency of the recycling chain. The results of these findings indicate that the degree of policy, technology, and material management integration and coordination will determine how successful the process of the aluminum industry becoming a circle can be. Figure 3 below compares the model-projected flow of aluminum with the corresponding environmental impacts in the model under different dissimilar conditions.

4. Real-Time Examples of Scrap Management and Circular Economy in the Aluminum Industry

The aluminum industry's circular economy strategies have already had substantial implementation in various geographical locations. The instances below indicate the ways through which the companies, governments, and regions manage wastes and resources and how these practices can be incorporated into the entire cycle of aluminum production and consumption.

4.1. Hydro Aluminium’s Closed-Loop Recycling System (Norway, Germany, UK)

Hydro, a company that ranks among the three largest aluminum producers worldwide, utilizes advanced closed-loop recycling systems, which are highly technologically advanced, for the recovery of both post-consumer and pre-consumer scrap, the latter sourced from its industrial customers. Hydro's CIRCAL product line now consists of aluminum with at least 75% recycled post-consumer scrap, and consequently, the company has one of the lowest CO_2 footprints in the industry (less than 2.3 kg CO_2/kg aluminum) already achieved.

In addition, the company is collaborating with the automotive and building sectors to establish closed loops, where scrap produced during the process is collected and returned to the company for recycling and remelting. Hydro has also invested in sorting technologies, such as laser-induced breakdown spectroscopy (LIBS), to enable the separation of alloys with very high precision. This way, the recycled aluminum is identical to the primary metal in terms of properties.

This system is a brilliant illustration of a successful industrial circular economy where scrap remains in the manufacturing ecosystem and is neither downcycled nor landfilled.

4.2. Novelis’ Recycling Center in Nachterstedt, Germany

The world’s largest aluminum recycler, Novelis, has begun a €200 million recycling center in Nachterstedt, Germany. The facility has a capacity of 400,000 metric tons of aluminum scrap per year, ranking it among the world's largest. The site accepts both industrial and household scrap. The main focus is on the recovery of UBCs (used beverage cans) and their further processing, along with automobile parts and building materials.

Novelis has managed to innovate the sorting of scraps and the control of the melting, thus ensuring high recovery efficiency and total quality control. The recycling circuit is integrated into Novelis’s automotive supply chain, enabling the use of recycled aluminum in premium applications, such as BMW and Jaguar Land Rover car body panels.

Such an event is indicative of the integration of circularity into a global supply chain, highlighting the necessity of modern infrastructure and a strong rapport with end users for the long term.

4.3. India's Aluminum Recycling Sector (Hindalco and Runaya)

India ranks among the top nations in terms of secondary aluminum production, with recycling of scrap being a major source of the local supply. Hindalco Industries, part of the Aditya Birla Group, has established aluminum recycling plants that not only cater to the local manufacturing ecosystem but also reduce the amount of primary aluminum, which requires a significant amount of energy and, implicitly, the demand for super energy-consuming primary aluminum. Additionally, Hindalco, in partnership with the startup Runaya, has established a zero-waste program to recover and recycle materials from various waste sources, including dross generated by industries. These processes transform dross, considered waste from aluminum recycling, into profitable goods such as fluxes and non-ferrous alloys, thereby ensuring a significant material efficiency.

The example of India demonstrates that developing countries can be resourceful in recycling industrial waste, especially when governing laws and the scarcity of raw materials drive industries toward the adoption of innovative circular systems.

4.4. European Aluminium's "Alu Loop" Initiative

The "Alu Loop" initiative, launched by the European Aluminium Association in collaboration with recyclers and governments, marks a significant step towards implementing circular economy strategies across the entire region. The primary objective is to establish common practices for scrap collection, enhance the transparency of the entire process, and promote recyclability throughout the entire value chain. The project sets 2030 as the target year for raising recycling rates from 60% to 90% through the application of a unified approach to eco-design and by investing in the recycling infrastructure. One of the success stories is working together with the construction sector, whereby modular aluminum and Facades are built for ease of dismantling and reclaiming at the end of their life.

The initiative embodies a circular economy approach supported by policy, which brings together a diverse range of stakeholders from industry, academia, and government to align their goals and practices.

4.5. Apple's "Daisy" Robot and Recycled Aluminum in Product Manufacturing

Apple has introduced the use of recycled aluminum in various product lines, particularly in the MacBook Air and iPad, which feature completely recycled aluminum enclosures. The aluminum is sourced from the company's internal production scrap and post-consumer materials. Through silicon, the company's disassembly robot, Daisy, helps recover aluminum and other valuable materials from the devices returned by customers. Circular product design in the high-tech industry is exemplified by the use of custom aluminum alloys designed to maintain the same performance even after multiple recycling cycles.

Such a scenario highlights the importance of product design, reverse logistics, and corporate sustainability in achieving circular economy outcomes.

4.6. Japan's UBC Recycling Model

Japan has one of the highest global recycling rates of aluminum cans, which exceeds 93%, primarily due to the use of automatic sorting, public cooperation, and the imposition of strict government policies that hold manufacturers accountable. The UBC recycling loop effectively connects participants through communities, collection companies, and aluminum producers.

The metal retrieved from soft drink cans is used for the production of new cans, thus forming a genuine closed-loop system. Besides efficient transport, the role of consumer awareness campaigns in the program's success is significant, making it a model for urban recycling as well as scrap valorization.

5. Challenges and Opportunities in the Transition to a Circular Aluminum Economy

The relocation of the aluminum business to the circular economy presents a complex set of technical, infrastructural, and logistical issues that must be addressed to achieve the benefits at a high level. Recycling is also limited by the level of operation due to contamination, the heterogeneity of alloys, and a lack of modernized remelting and sorting facilities. The above conditions decrease the yield and quality of secondary aluminum, making the process extremely expensive. In most areas, and even in areas with such systems, collection systems and reverse logistics networks are not uniformly established. In cases where such systems exist, it may be prohibitively expensive or technologically challenging in practice to physically separate mixed-material products (e.g., aluminum coated on polymers or coatings). These gaps will be filled by special investments in greater sorting (e.g., sensor-based separation) and remelt upgrades, as well as modular infrastructure that can be expanded to meet the demands of the local market.

There are also gaps in data, traceability, and digital infrastructure. The recycling streams cannot be optimised without the material composition that has already been proven, and without the stocks of in-use materials, it is challenging to match the secondary supply with manufacturing demand. There are three facets lacking, which stop visibility throughout the value chain and the effectiveness of the circular business model, including the lack of standardized digital identifiers, such as standardized material labels or electronic product passports. The material flow visibility can be enhanced significantly with the assistance of the digital twins, IoT-based sensors, and central data facilities; however, it is only possible in case there are standardized data standards and systems, cross-corporate and cross-national. Although the embodied energy of secondary aluminum is usually lower in comparison to the primary production, the changing prices of the products, the rivalry amid subsidies offered on virgin materials, and the intensity of the capital in the circular investments may discourage businesses from modifying their operations. There is also the risk that early incurring of expenditure and unpredictable payback is of particular risk to the SMEs. It is possible to overcome the obstacles with incentives, both open and closed, such as green procurement guidelines, tax breaks, low-interest financing of circular infrastructure, and high prices on certified low-carbon aluminum to change market signals and hasten its adoption.

Weaknesses in regulation and policies are also issues that make scale-up challenging. The variation in the collection of wastes into waste, the rules of the scrap trade across borders, and the extended producer responsibility (EPR) program cause administrative costs, which can annihilate the second-hand aluminum markets. The policy in most jurisdictions has not been able to realise its technological change or a material-flow reality, hence harmonisation of standards, mutual recognition of certifications, and definitions of claims of recycled content are on the policy-maker's agenda. Any good regulation must be able to strike a balance between the desire to include a rigid environmental protection, and a load of flexibility to permit innovation in the collection, processing, and product designing. Product architecture and consumer behaviour determine the design of products and demand. Most of the products made out of aluminum are designed in such a way that they cannot be pulled apart, and the material can be reused, but the fame of the potential of the product is not as evenly spread among the consumer community. To assure the greater solidness in the downstream markets for high-quality secondary aluminum, it can be the promotion of the concepts of eco-designs, i.e. of the alloys, fastening methods, and surface finishes, which can provoke recycling, and of the educational activities of the citizens and the development of take-back programmes. During the first stage of the product development cycle, the designers, manufacturers, and recyclers should communicate in such a way that the materials would not go to waste and, more importantly, the effectiveness of the product would not be affected.

In spite of these challenges, the transition to circularity is a future one. It is possible to combine IN4.0 (AI, ML, IoT), material science (alloy recycling development), and interactive enhancement of the traceability to improve the quality of recycled aluminum and its value. The assistance of cross-sector partnerships and blended financing mechanisms can be used to offer de-risk investments so that it can be demonstrated that their models can be scaled. Nonetheless, there is a multitude of additional climate and energy advantages of the augmented exploitation of the secondary aluminum, i.e., cutback of emissions and cutback of energy consumption, which furnish individuals with tremendous reasons to participate in a joint endeavor. The future directions have been built on these challenges and opportunities, thus ensuring the need to accelerate the transition to the circular economy with policy, technology, and market leverage tools.

6. Future Directions

The shift to the circular economy of the aluminum industry should be a long-term investment, with technological and cross-sectoral coordination. A number of future directions can be critical and direct research, policy, and industrial practice.

6.1. Creation of Closed-Loop Product Systems

The need to come up with products made of aluminum that are clearly meant to be recycled through the closed loop is increasing. This involves the use of standardized material labeling systems as well as the inclusion of electronic product passports that will be used to monitor material content during the life cycle of a product.

6.2. Industry 4.0 and ITS Implementation in Scrap Management

It is anticipated that future scrap management systems will combine both Industry 4.0 technologies (artificial intelligence, machine learning, IoT-based sensors) with the optimization of scrap sorting, monitoring of material flows, and predictive maintenance in remelting plants. The method allows tracking scrap quality and recovery efficiency in real time and provides more control.

6.3. International Standards and Policy Innovation.

The regulatory framework is to be changed to incorporate the principles of the circular economy into trade agreements, material classification systems, and extended producer responsibility. The standardization of the aluminum scrap category and standard across jurisdictions to reduce the inefficiencies and regulatory contradictions in the market is one of the priorities.

6.4. Green Product and Design Life Cycle.

The future development of products should focus on the concept of eco-design. The studies are required to incorporate the environmental considerations into the choice of alloys, joining processes, and coatings, which will not impede the recyclability. This requires cooperation among material scientists, product designers, and recyclers.

6.5. Secondary Resource Mapping and Urban Mining.

The recovery of materials in end-of-life products in cities, also known as urban mining, stands out as an important opportunity in the acquisition of secondary aluminum. Material flow analysis tools may help to plan the resources efficiently and invest in recycling infrastructure by providing accurate mapping of the in-use stocks and waste flows.

6.6. Carbon Accounting and Sustainability Measures.

It can be enhanced by the creation of effective carbon accounting and lifecycle assessment (LCA) procedures specific to recycled aluminum, which will enhance transparency and decision-making by stakeholders. Improving such tools in the future, by standardizing them across industries, would help in obtaining a comparison of the real environmental benefits of secondary aluminum.

7. Conclusion

The elements of scrap management and the circular economy have turned out to be a new key component of the sustainable change in the aluminum industry. In the review, it has been demonstrated that even though aluminum has an inherently positive potential in recycling, the realization of a fully-cycling system requires the integration of technology innovation, coordination of policies, and redesign of products. The major challenges that still lie between the recycling efficiency and cyclical flow of materials are downcycling, alloy complexity, contamination, and the absence of infrastructure.

The positive new developments are the promising sorting equipment (scrap), tracking electronics, and internationalization of the recycling standards. Another consideration is that the eco-design must be conducted in a manner that, upon expiry of the life of the product, separating and sorting of materials will be very easy. These regulatory tools, like landfill tax and producer responsibility, are very important in enhancing the idea of circular behavior across the value chain.

The recycling of aluminum is linked to the opportunities for implementing smart systems, cyclical design, and the promotion of policy, technology, and economic incentives. Such strategies will result in a minimal negative impact on the environmental footprint of aluminum production, and the material will be preserved as an effective and versatile raw material in future economies, with a long-term commitment.

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