Comparative analysis of circular economy models with application to the aluminum industry in Mozambique

Análisis comparativo de modelos de economía circular con aplicación a la industria del aluminio en Mozambique

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Abstract: The aluminum industry in Mozambique generates substantial industrial waste, with recent studies revealing that up to 87.96% of this waste consists of recoverable aluminum and other valuable metals. However, the absence of circular economy practices results in the underutilization of these resources, posing significant environmental and economic challenges. This study presents a comparative analysis of three international circular economy models -those of the Ellen MacArthur Foundation, China, and Germany- evaluating their applicability to the aluminum sector in Mozambique. Using qualitative data from institutional interviews and secondary sources, the analysis identifies key gaps in policy, technology, and economic incentives. The findings suggest that a hybrid approach, combining regulatory frameworks with market-driven solutions, could offer a viable pathway for Mozambique. The study concludes with recommendations for phased implementation, starting with legal reforms and small-scale recovery initiatives, leading to a comprehensive national circular economy system.

Keywords: non degradable waste, waste treatment, metal treatment

Resumen: La industria del aluminio en Mozambique produce cantidades significativas de residuos industriales. Estudios recientes demuestran que hasta el 87,96 % de estos residuos está compuesto por aluminio recuperable y otros metales valiosos. Sin embargo, la ausencia de principios de economía circular da lugar a una subutilización de estos recursos, lo que supone importantes retos medioambientales y económicos. Este trabajo presenta un análisis comparativo de tres modelos internacionales de Economía circular -los de la Fundación Ellen MacArthur, China y Alemania- y evalúa su aplicabilidad al sector del aluminio en Mozambique. A partir de datos cualitativos procedentes de entrevistas institucionales y fuentes secundarias, el análisis identifica las principales lagunas en materia de políticas, tecnología e incentivos económicos. Los resultados demuestran que un enfoque híbrido, que combine marcos normativos con soluciones orientadas al mercado, podría ofrecer una vía viable para Mozambique. El estudio concluye con recomendaciones para una implementación por fases, comenzando con reformas legales e iniciativas de recuperación a pequeña escala, que conduzcan a un sistema nacional integral de economía circular.

Palabras clave: residuos no degradables, tratamiento de residuos, tratamiento de metal

Introduction

The aluminum industry plays a pivotal role in modern economies due to its lightweight, corrosion resistance, and high recyclability (Moustafa *et al.,* 2023; Ferreira da Rosa *et al*., 2024; Holzschuh *et al.,* 2024; Espindola-Díaz, 2025). In Mozambique, industrial activities related to aluminum production, notably from bauxite processing and smelting, generate significant amounts of industrial waste. Alarmingly, recent analyses show that these wastes contain up to 87.96 % aluminum, along with other valuable metallic elements. Despite this, these by-products are largely underutilized, posing both environmental and economic challenges.

The circular economy (CE) concept has become popular in recent years as a model which links the environment and economics. The term "circular economy" was used for the first time, by Pearce and Turner in 1990, but the concept itself was described much earlier, in 1966, by Kenneth Boulding in the essay "The Economics of an

Approaching Spacecraft Earth" (Heshmati, 2015). Since that time many CE definitions have been developed and many articles reviewing the CE definitions have been written (Jaki & Siuta-Tokarska, 2019; Figge, Thorpe & Gutberlet, 2023; Vogiantzi & Tserpes, 2023; Alivojvodic & Kokalj, 2024; Yoatian, Han & Shankar, 2025).

Principles and benefits of the circular economy model

For a long time, the traditional economy has been linear, whereby raw materials were used to make products, and afterwards, all waste was thrown away. This was a linear process, optimized towards high volume and low production costs in conditions of wide availability of resources and materials at low cost.

Recently, there has been a shift to a circular economy, where materials are reused, and if new materials are needed, they must be obtained sustainably so that the environment is not damaged Guerrero *et al.,* 2024; Barra Novoa, 2025). Thus, the aim of a circular economy is to ensure low environmental impact by minimizing waste and resource use through re-use, re-manufacture, re-cycle, waste reduction, etc. (Stahel, 2016; Czikkely *et al.,* 2019).

One may then state that the concept of the circular economy is crucially different from a traditional linear concept. In general, a circular economy fosters reuse and extends service life through repair. According to the European Commission, "in a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimized. It "remanufactures, upgrades, retrofits and turns old goods into as-new resources by recycling the materials" (Stahel, 2016).

This study aims to conduct a comparative analysis of circular economy (CE) models and assess their applicability and effectiveness in addressing the challenges associated with aluminum waste in Mozambique. Through this, we propose strategic interventions that align with sustainable industrial development and environmental stewardship.

Materials and Methods

This research employed a qualitative and comparative design, combining case study methodology with a literature review and expert interviews. Mozambique's aluminum sector was analyzed against international CE models applied in countries such as Germany, China, and Canada.

Data Collection

- Primary data: Collected through semi-structured interviews with professionals from Mozal (Mozambique Aluminium), the Ministry of Environment, and academic researchers.
- Secondary data: Obtained from government reports, scholarly articles, and technical documentation on CE strategies and aluminum waste recycling technologies.

Analytical framework

Three circular economy models were selected for comparison:

-The Ellen MacArthur Foundation Model (UK) (2015)
-China's Circular Economy Promotion Law (2009)
-Germany's Closed Substance Cycle and Waste Management Act

Evaluation criteria included:

a) Resource recovery efficiency
b) Policy support
c) Technological adaptation
d) Economic viability
e) Environmental impact mitigation

Results and Discussion

Aluminum waste profile in Mozambique

Waste generated by aluminum smelting shows high aluminum content (87.96%), yet is disposed of without extraction or reuse. Lack of policy enforcement, technological infrastructure, and financial incentives limits CE practices. Table 1 shows a comparison of different circular economy models around the world.

Table 1. Comparison of Circular Economy Models

Criteria	Ellen MacArthur Model	China's CE Model	Germany's Model	Mozambique
Resource Efficiency	High	Moderate	High	Low
Policy Framework	Strong, business-driven	Centralized, top-down	Regulatory and incentive-based	Weak enforcement
Technology Use	Advanced recycling	Emerging tech	Mature tech	Limited
Economic Return	High	Moderate	High	Negligible
nvironmental Impact	Strong reduction	Controlled	High standards	Poorly managed

Waste composition chart

Figure 1 shows the percentage of industrial waste from aluminum in Mozambique compared to other metals.

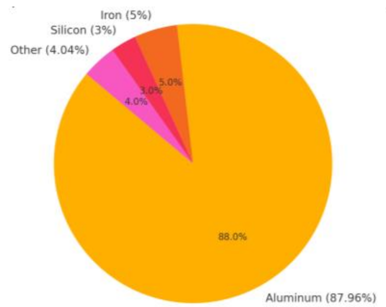

Figure 1. Composition of aluminum idustril waste in Mozambique.

Gaps and opportunities for Mozambique

- Adoption of technological solutions for residue processing, such as hydrometallurgical recovery.
- Creation of legal frameworks and incentives for aluminum recycling.
- Integration of local SMEs and informal sector in resource recovery chains.
- Public-private partnerships (PPPs) to facilitate investment in CE technologies.

Generally, the recycling process involves different steps. The process generally begins with a pre-treatment (dismantling, size reduction and physical separation), through which non-ferrous metals are separated from the other components (Rai *et al.*, 2021) Dismantling, size reduction and physical separation are consolidated approaches, and can be modified based on the successive steps to perform (Gautam *et al.,* 2022).

However, the formation of fine dust, as well as the high energy consumption accompanying the crushing step is among the obstacles involved in this process (Kumari & Samadde, 2022). Despite the pretreatment being widely employed on industrial scale, some authors have recently proposed the possibility of treating the printed circuit board as obtained after the dismantling (Chen *et al.,* 2021). This approach can certainly reduce the costs of the pre-treatment but can negatively impact on the dissolution efficiency, due to diffusive phenomena occurring in the system when the successive steps are performed.

After the pretreatment, the common techniques for the effective metal recovery are pyrometallurgical, hydrometallurgical and biohydrometallurgical routes. Pyrometallurgical approach can be considered as the most consolidated technique for metal recovery, in which the main advantage is represented by the possibility of minimizing mechanical pretreatment of the solid waste. The separation of the desired metals from WEEE occurs through the use of high temperatures. Specifically, the waste materials are subjected to incineration, sintering, and melting at high temperatures, with smelting furnace or plasma processes among the most used incinerator employed (Krishnan *et al.,* 2021).

Among the disadvantages, high energy requirement and costs, low selectivity, and the emission of hazardous gases are the most important and highlight the necessity of developing possible different solutions (Sethurajan *et al.,* 2019).

Hydrometallurgy is the second most reported technique for metal recovery, involving different steps such as leaching, purification and recovery. The process is carried out in aqueous solution, with advantages as the lower costs and environmental impact with respect to the pyrometallurgical ones, as well as the good control of impurities. The leaching step is typically performed in the presence of strong acids (H_2SO_4, HNO_3, HCl).

Despite the better characteristics with respect to the pyrometallurgy, these processes have low selectivity for the valuable metals (precious metals), and the production of large amounts of wastewater and emissions of chlorine gas (Islam *et al.,* 2021).

Recently, there has been a growing interest in the bio-hydrometallurgical pathways as a possible alternative option for the dissolution of metals from e-waste, due to their cost-effectiveness and eco friendliness (Magoda *et al.,* 2021). With reduced greenhouse gas emissions, the mechanism leads the selective recovery of some metals from WEEE, through the use of bacteria, which are able to secreting acids, ligands, and lixiviants for solubilization. However, this technology is still at a pilot scale, and several researchers are currently devoted to (i) the possibility of using bacteria with high resistance to different environments and (ii) the optimization of the factors affecting the leaching efficiency (Desmarais *et al.,* 2020).

Process intensification in metal recovery has gained great attention due to the possibility of increase the profit. As a result of the PI, process plants are smaller, the environmental impact and the energy consumption are reduced, and some disadvantages of the existing technologies are overcome. Some years ago, some authors proposed the combination of extraction and stripping (single stage) in the liquid emulsion membrane process as a PI for the extraction of Ru, avoiding the stripping stage commonly adopted in these processes (Kankekar *et al.,* 2010).

Comparative discussion of CE models

The Ellen MacArthur model emphasizes systems thinking, where businesses redesign their operations to eliminate waste entirely. This approach is highly applicable to advanced industrial economies with innovation capacity and capital access. Mozambique currently lacks the infrastructure to fully adopt this model but can implement its principles gradually through pilot programs and partnerships.

China’s model is characterized by top-down implementation supported by national legislation and strict oversight. This approach may be relevant for Mozambique considering its centralized governance structure. However, challenges include bureaucratic inertia and limited institutional capacity to enforce policies.

Germany’s model integrates both regulatory mandates and market-based incentives, leading to high compliance and innovation. This hybrid approach is perhaps the most adaptable for Mozambique in the long term, combining government intervention with industry-driven initiatives. However, its successful adoption will depend on capacity building, local adaptation of technologies, and the development of monitoring mechanisms.

Mozambique’s context reflects a fragmented and under-regulated system with minimal integration of CE principles. A phased strategy combining policy reform, investment in infrastructure, and stakeholder engagement is necessary. Learning from the global models, Mozambique should prioritize:

-Short-term: Establishing regulatory frameworks and awareness campaigns.
-Medium-term: Piloting localized CE initiatives in partnership with private industry.
-Long-term: Scaling successful models and building national CE systems across the value chain.

Conclusions

Mozambique's aluminum industry possesses a significant untapped potential for circular economy integration, primarily due to the high aluminum content in its industrial waste. Comparative analysis reveals that successful CE implementation depends on a combination of robust policy, technological readiness, and economic incentives.

To achieve sustainable industrial development, Mozambique must:
- Develop national CE legislation and policies.
- Invest in technology for metal recovery.
- Foster collaboration between government, industry, and academia.

Adopting international best practices adapted to local realities will position Mozambique to transition from a linear to a circular model, thereby maximizing environmental and economic benefits.

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