INTEGRATING THE CIRCULAR ECONOMY INTO ENVIRONMENTAL ENGINEERING: SUSTAINABLE STRATEGIES FOR RESOURCE MANAGEMENT AND REDUCING ENVIRONMENTAL IMPACT

Assoc. Prof. PhD Eng. Alin NIOAȚĂ,
Engineering Faculty, "Constantin Brâncuşi" University of Tg-Jiu, ROMANIA
Assoc. Prof. PhD Eng. Alin STĂNCIOIU,
Engineering Faculty, "Constantin Brâncuşi" University of Tg-Jiu, ROMANIA

ABSTRACT: The circular economy is a model of sustainable economic development based on the principles of reduction, reuse, remanufacturing, and recycling of materials, with the main objective of optimizing resource flows and minimizing environmental impact. In this context, environmental engineering plays an essential role in designing and implementing the technologies needed to make resource use more efficient and reduce pollutant emissions, facilitating the transition from a linear to a circular economic model.

This study analyzes the interdependence between the circular economy and environmental engineering, highlighting technological strategies and legislative instruments designed to support the development of a sustainable economic system. It addresses concepts such as eco-design, which integrates circular economy principles into the product design stage, industrial symbiosis, which promotes collaboration between different sectors to optimize secondary raw material flows, and the use of renewable energies in industrial processes to reduce the carbon footprint. At the same time, it discusses key issues regarding resource efficiency, waste minimization, and waste recovery through advanced recycling and recovery technologies for critical materials.

The paper includes an analysis of the main challenges encountered in implementing the circular economy, including technological, economic, and legislative barriers. It also proposes future research directions and solutions for improving the efficiency of the circular economy, emphasizing the need for a coherent regulatory framework and an interdisciplinary approach to ensure an effective transition to sustainability.

KEY WORDS: circular economy, environmental engineering, sustainability, recycling, environmental policies.

1. INTRODUCTION

In the context of accelerated growth in natural resource consumption and significant environmental impact, the transition from a linear economy to a circular model is becoming a pressing necessity to ensure economic and ecological sustainability.

The circular economy is a sustainable development model based on a systemic approach that integrates fundamental principles such as reducing primary resource consumption, reusing materials and products, remanufacturing used components, and recycling waste. This paradigm promotes the optimization of material and energy flows through intelligent product and industrial process design, with the main objective of extending the life of resources and creating a self-regenerating industrial metabolism. By implementing circular mechanisms, the aim is to reduce pressure on natural ecosystems, reduce the amount of waste disposed of in the environment, and reduce pollutant emissions resulting from economic activities. [1].

The concept of circular economy is based on closing material loops, transforming traditional linear flows – characterised by extraction, production, consumption and disposal – into cycles of continuous resource use. This involves optimising the life cycle of products by developing advanced eco-design strategies, making efficient use of secondary resources and applying innovative technologies for material recovery and regeneration. In this context, the circular economy not only reduces dependence on primary resources, but also contributes to the creation of a more resilient economic system, capable of reducing the risks associated with raw material price volatility and critical resource shortages. Therefore, the implementation of this model requires an interdisciplinary approach that combines environmental engineering, industrial economics, and public policy to facilitate the transition to a sustainable economic system with both environmental and socio-economic benefits.This paradigm is essential for mitigating environmental problems such as resource depletion, pollution, and climate change, with direct implications for economic policies and industrial strategies.

Environmental engineering plays a crucial role in this transition, given its ability to develop and implement innovative technologies that support the efficient use of resources and reduce the ecological impact of human activities. Environmental engineering contributes to the development of advanced solutions for sustainable waste management, recovery of valuable materials, use of renewable energies, and optimization of industrial processes in line with the principles of the circular economy. Adopting circular economy strategies not only supports environmental protection, but also offers significant economic benefits, such as increased industrial competitiveness, reduced costs associated with the use of primary resources, and stimulation of technological innovation. In this context, this paper explores the interaction between the circular economy and environmental engineering, highlighting the strategies, technologies, and policies needed for an effective transition to a sustainable development model [2].

The implementation of the circular economy brings numerous benefits from both an ecological and economic point of view. From an environmental perspective, this model contributes to reducing pollution, lowering greenhouse gas emissions, and conserving biodiversity by limiting the extraction of natural resources. From an economic perspective, adopting a circular system leads to cost efficiencies by reducing dependence on expensive raw materials, stimulating innovation, and creating new business opportunities. Furthermore, by developing industries based on reuse and recycling, the circular economy promotes the creation of sustainable jobs and supports the transition to a more resilient and competitive economic model [3,4].

2. MATERIALS AND METHODS

Environmental engineering plays an essential role in the transition to a circular economy by implementing sustainable technical solutions and strategies that enable the efficient use of natural resources and reduce the ecological footprint. This involves developing advanced technologies to prevent pollution, optimize industrial processes, and promote the use of recyclable materials. Environmental engineering also facilitates the integration of circular economy principles into industrial sectors by designing waste management systems and water and air treatment solutions. The implementation of innovative technologies plays a crucial role in improving resource efficiency and reducing environmental impact. These include advanced wastewater treatment processes, bioremediation of contaminated soils, the use of nanotechnologies for depollution, and the development of biodegradable materials. Furthermore, solutions based on artificial intelligence and the Internet of Things (IoT) enable the monitoring and optimization of resource consumption, thereby contributing to reducing losses and increasing the efficiency of industrial processes [5].

A fundamental objective of the circular economy is to minimize waste generation and reintegrate recoverable materials into economic cycles. Specific strategies include advanced material recycling, waste-to-energy conversion, biowaste composting, and the development of eco-design processes that promote product reuse and repair. By applying the principles of environmental engineering, selective collection and waste treatment can be optimized, thus ensuring a continuous flow of secondary raw materials for industry (Figure1).

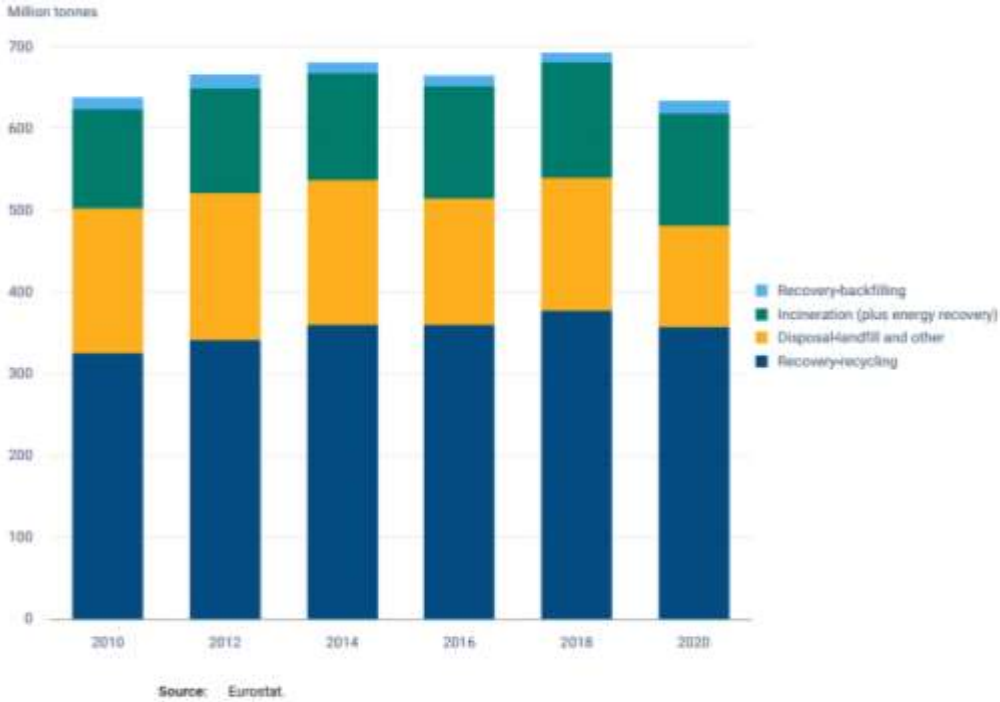

Figure 1 Waste treatment in the EU-27 (total waste excluding major mineral wastes)

The integration of renewable energy sources into industrial systems contributes to reducing dependence on fossil fuels and lowering greenhouse gas emissions. Solar, wind, hydroelectric, and biomass energy are increasingly used in production processes, providing sustainable solutions for energy efficiency. Advanced technologies, such as cogeneration and the use of green hydrogen, enable reduced energy consumption and sustainable optimisation of industrial processes, thus strengthening the transition to a circular and environmentally resilient economic model.

By applying these strategies and technologies, environmental engineering contributes significantly to the implementation of circular economy principles, facilitating the transition to a sustainable, efficient economic system with a low environmental impact. Integrating circular economy principles into environmental engineering is a fundamental strategy for reducing the ecological impact of human activities and creating a sustainable economic system. This process involves developing mechanisms for the efficient use of resources, reducing waste generation, and adopting innovative methods that allow materials to be reintegrated into the economic cycle.

An essential element of this approach is the application of the eco-design concept, which aims to optimize the life cycle of products, from raw material extraction and processing to use and recycling. By using sustainable materials, reducing energy consumption, and designing products that are easy to disassemble and recycle, a significant reduction in waste and natural resource consumption can be achieved. Innovation in product design thus contributes to the creation of an efficient circular system, reducing the need for primary resources and minimizing pollution generated by industrial processes [6].

Another central component of the circular economy in environmental engineering is the implementation of sustainable resource and waste management. By applying advanced recycling and material recovery technologies, the life span of resources can be extended and the impact on the environment significantly reduced. Selective collection programs, advanced wastewater treatment, and the use of biotechnologies for soil remediation are just a few of the methods used to optimize waste management. Furthermore, promoting economic models based on reuse and reconditioning contributes to reducing pressure on the environment and increasing economic efficiency.

Industrial symbiosis is an essential mechanism in the integration of the circular economy, facilitating collaboration between different economic sectors to optimize resource use. This approach allows waste from one industry to become a resource for another, thereby reducing material and energy losses. The implementation of such strategies requires cross-sectoral coordination and the development of appropriate infrastructure for managing material and energy flows between different industrial units. This collaboration contributes to the creation of a more resilient and sustainable economic ecosystem, capable of significantly reducing the ecological footprint of human activities.

Thus, applying circular economy strategies in environmental engineering provides viable solutions for the efficient use of resources and reduction of pollution. Through technological innovation, product life cycle optimization, implementation of efficient resource management, and development of industrial synergies, the transition to a sustainable and ecologically balanced economic system can be ensured. Adopting these practices not only minimizes environmental impact, but also contributes to increased economic competitiveness, promoting a sustainable development model for future generations.

To conduct this study on the integration of the circular economy into environmental engineering, analytical and comparative methods were used, as well as qualitative and quantitative research techniques. The study of the integration of the circular economy into environmental engineering involves the use of advanced analytical and comparative methods to assess the effectiveness of sustainable strategies and technologies. The analysis was conducted using a multidisciplinary approach, combining quantitative and qualitative methods to determine the impact of the transition to a circular economic model on resource management and reducing environmental impact.

The circular economy model represents a fundamental paradigm in sustainable resource management and reducing the ecological impact of economic activities. Unlike the traditional linear model, which involves the exploitation of resources, their use, and the disposal of waste, the circular model is based on regeneration, reuse, and recycling. This concept aims to optimize the use of natural resources by reintegrating secondary raw materials into the economic cycle, thus minimizing losses and environmental impact (Figure 2).

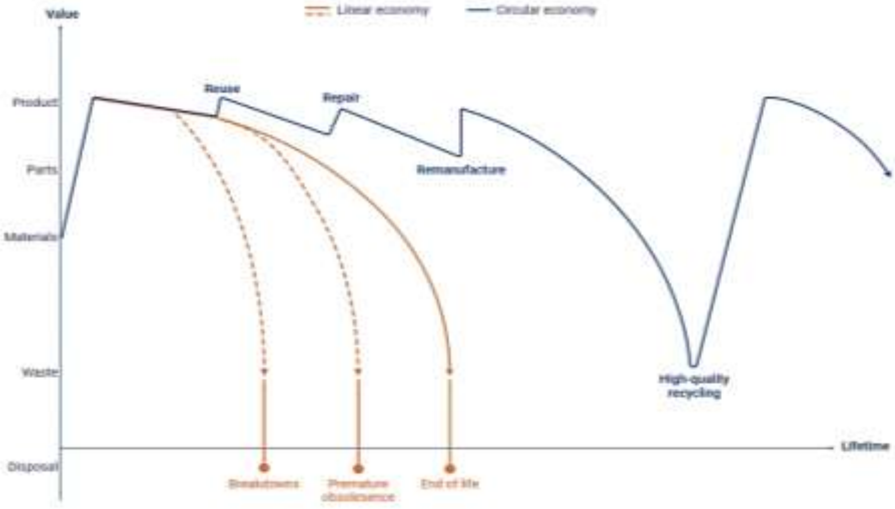

Figure 2 Circular actions and their effect maintaining product and material value
(Sursa: European Environment Agency)

3. RESULTS and DISCUSSIONS

The circular economy is a sustainable model of economic development focused on optimizing resource use and reducing waste through recycling, reuse, and regeneration processes. In this context, environmental engineering plays an essential role in implementing technical and ecological solutions that promote resource efficiency and minimize impact on ecosystems. To assess the effectiveness of circular economy strategies, advanced analytical methods are used to monitor environmental parameters, analyze product life cycles, analyze material flows, perform cost-benefit analyses, etc. In addition, comparative methods are applied to identify the most effective practices and technologies by evaluating the performance of different resource management and waste reduction systems, energy efficiency, product sustainability, etc.

3.1. Analytical methods

One of the main methods used in this study is Life Cycle Assessment (LCA), which allows the environmental impact of a product, process, or service to be assessed throughout its entire life cycle [7]. This includes the stages of raw material extraction, production, use, and disposal/reuse, with the aim of identifying critical points and proposing improvements to reduce resource consumption and pollutant emissions.

In this study on the integration of the circular economy into environmental engineering using Life Cycle Assessment (LCA), we generated Table 1 with data on CO_2 emissions, energy consumption, and water use for different stages of the life cycle of an industrial product, as well as a graph highlighting these values (Figure 3).

Table 1.

No.	**Stage**	**CO2 emissions (kg/unit)**	**Energy consumption (MJ/unit)**	**Water consumption (liters/unit)**
1.	Extraction of raw materials	120	500	100
2.	Production	200	700	150
3.	Transport	50	300	60
4.	Use	80	400	90
5.	Disposal/Recycling	30	200	40

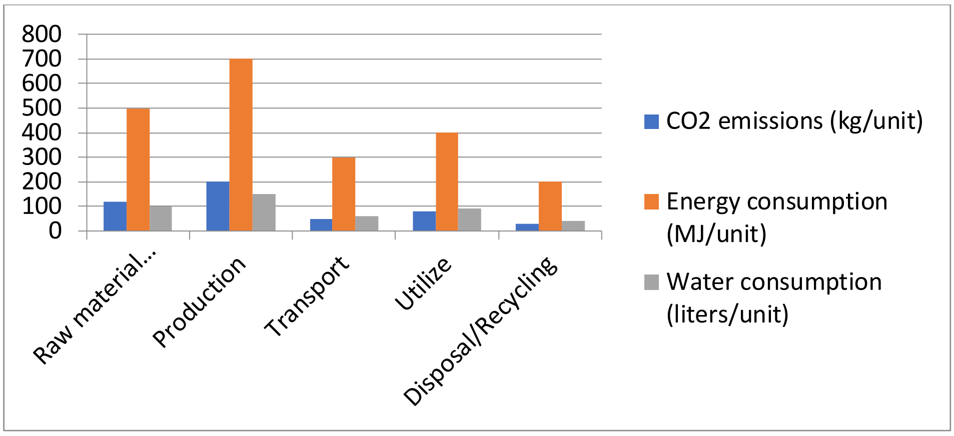

Figure 3 Life cycle assessment (LCA) for an industrial product

In this study, we developed one of the methods for integrating the circular economy into environmental engineering using life cycle assessment (LCA). It includes a table with data on CO_2 emissions, energy consumption, and water use for different stages of an industrial product's life cycle, as well as a graph highlighting these values.

The interpretation of the results of the life cycle assessment (LCA) carried out for an industrial product highlights the environmental impact at each stage of the life cycle: raw material extraction, production, transport, use, and disposal/recycling. The assessment was based on three key indicators: CO_2 emissions (kg/unit), energy consumption (MJ/unit), and water consumption (liters/unit), namely:

CO_2 emissions

- The highest CO_2 emissions are generated during the production stage (200 kg/unit), followed by raw material extraction (120 kg/unit). This suggests that industrial processes are responsible for most of the climate impact;
- Transport has a significantly lower impact (50 kg/unit), which indicates either the optimization of transport routes or the use of more efficient energy sources;
- The use stage (80 kg/unit) and disposal/recycling (30 kg/unit) have moderate emissions, suggesting that strategies such as reuse and recycling can reduce the product's total emissions.

Energy consumption

- The largest amount of energy is consumed in production (700 MJ/unit), confirming the high environmental impact of industrial processes;
- Raw material extraction (500 MJ/unit) also represents significant consumption, which highlights the importance of using recycled materials to reduce dependence on natural resources;
- Transport (300 MJ/unit) and use (400 MJ/unit) have moderate values, while disposal/recycling (200 MJ/unit) consumes the least energy.

Water consumption

- Production has the highest water consumption (150 liters/unit), indicating intensive water use in industrial processes;
- Raw material extraction requires 100 liters/unit, reflecting the high impact of the extractive industry on water resources;
- Product use (90 liters/unit) and transport (60 liters/unit) have a moderate impact, while disposal/recycling requires the least water consumption (40 liters/unit).

LCA analysis shows that raw material production and extraction are the stages with the greatest environmental impact, in terms of CO_2 emissions, energy consumption, and water use. The circular economy can be effectively integrated by using recycled and environmentally friendly alternative materials to reduce dependence on natural resource extraction, by optimizing industrial processes to reduce emissions and energy consumption, and last but not least, by adopting renewable energy sources to lessen the ecological impact of production and improving recycling and reuse systems to extend the life cycle of products and reduce the impact of their disposal [5].

This interpretation highlights the need to adopt sustainable strategies in environmental engineering in order to transform the circular economy into a feasible and efficient model.

Another analytical method applied is Material Flow Analysis (MFA), which examines the circulation of materials in an economic and industrial system. This technique provides a clear perspective on resource use and losses generated, facilitating the optimization of recycling and reuse processes [8].

In this study on the integration of the circular economy into environmental engineering using material flow analysis (MFA), we generated a table with data on CO_2 emissions, energy consumption, and water use for different stages of the life cycle of an industrial product, as well as a graph highlighting these values, presented in Table 2 and Figures 4 and 5.

Table 2.

No.	Stage	Material inputs (kg)	Waste output (kg)	Recycled materials (kg)
1.	Raw materials	1000	200	0
2.	Production	800	100	50
3.	Distribution	700	150	30
4.	Use	600	200	100
5.	Recycling	500	50	500

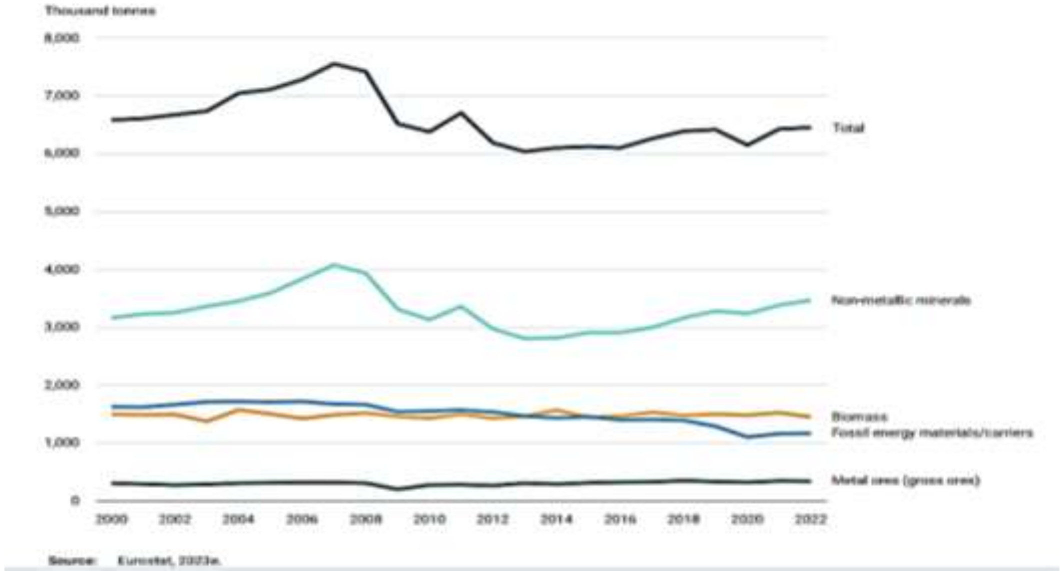

Figure 4 Evolution of domestic material consumption in the EU for main resource groups

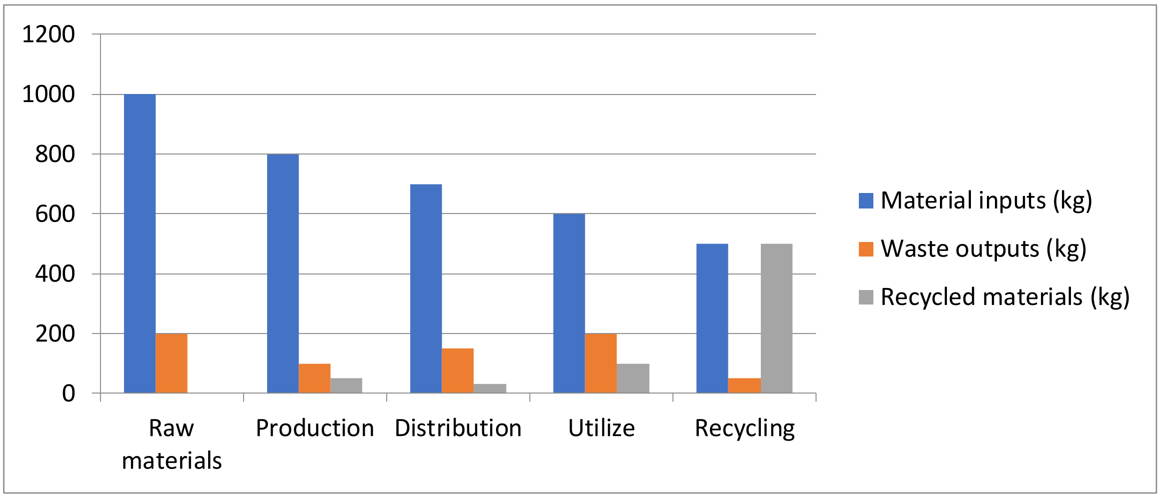

Figure 5 Material Flow Analysis (MFA) for an industrial product

In this case, Material Flow Analysis (MFA) was used to integrate the circular economy into environmental engineering. This includes a table with data on material inputs, waste outputs, and the amount of recycled materials for each stage of the production and use cycle, as well as two graphs highlighting these flows.

Interpretation of the results of the material flow analysis (MFA)

Material Flow Analysis (MFA) was used to examine how materials are managed in an industrial system and to identify opportunities for optimizing resource use through circular economy principles. The assessment included three main indicators for each stage of the production and use cycle: material inputs (kg), waste outputs (kg), and the amount of recycled materials (kg), as follows:

Material inputs

• Raw materials represent the largest volume of materials entering the system (1000 kg), highlighting a high dependence on primary resources.

• In the production stage, the material flow decreases to 800 kg, indicating minor losses or optimizations in the manufacturing process.

• As materials move through the distribution (700 kg) and use (600 kg) stages, the flow gradually decreases, reflecting successive transformations and potential losses through wear and tear or disposal.

• In the recycling stage (500 kg), a significant percentage of materials is recovered, indicating a partial integration of circular economy principles.

Waste outputs

• In the raw materials stage, 200 kg of waste is generated, reflecting losses from the extraction and processing of materials.

• Production generates only 100 kg of waste, suggesting an efficient process, but with further potential for reduction.

• In distribution, the volume of waste increases to 150 kg, which can be attributed to packaging and losses in the logistics chain.

• Product use leads to a significant increase in waste (200 kg), indicating a high disposal rate for used products.

• In recycling, only 50 kg of materials end up in the waste stream, suggesting a good recovery rate.

Recycled materials

• In the early stages of the life cycle, no recycled materials are used (0 kg in the raw material stage), highlighting a lack of integration of secondary materials.

• In production, 50 kg of recycled materials are reintegrated, suggesting partial recovery.

• In distribution, the use of recycled materials is limited (30 kg), and in the use stage, the amount recovered increases to 100 kg, reflecting initiatives to collect used products.

• Recycling makes the largest contribution, with 500 kg of materials recovered, demonstrating the effectiveness of a well-implemented waste management system.

The MFA analysis shows that production and product use are the stages that have the greatest influence on material flows. The current system has a relatively high level of recycling in the final stage, but the use of recycled materials in production is limited. The main directions for optimizing material flow in the context of the circular economy include reducing dependence on raw materials by increasing the use of recycled materials in production, optimizing the distribution chain to minimize losses from packaging and transport, extending the life of products through sustainable design and efficient repairs, and improving recycling systems to maximize the recovery of valuable materials and reduce the amount of waste disposed of.

Implementing these measures can contribute to a more circular and sustainable economy, reducing environmental impact and making resource use in environmental engineering more efficient. To quantify the benefits of the circular economy, cost-benefit analysis (CBA) was also used, which assesses the economic feasibility of implementing circular strategies in different industries [9, 10]. This method helps to compare the initial costs of adopting sustainable technologies with the long-term economic and environmental benefits, as shown in Table 3.

Table 3

No.	Scenario	Production costs ($)	Waste management costs ($)	Energy costs ($)	Benefits from recycling ($)	Benefits from sales ($)	Total benefits ($)
1	Linear economy	500000	100000	80000	20000	600000	620000
2	Circular economy	450000	30000	60000	90000	620000	710000

In Figure 5, we compared the costs between the linear economy and the circular economy, and in Figure 6, we compared the benefits between the linear economy and the circular economy.

We can also discuss the integration of the circular economy into environmental engineering using cost-benefit analysis (CBA), comparing the linear economy with the circular economy, highlighting the differences in terms of production costs, waste management costs, energy costs, as well as the benefits obtained from recycling and sales, all presented in the table with data on costs and benefits for both economic models, as well as in the two comparative graphs, one illustrating

the cost differences and the other showing the financial benefits generated by the circular economy.
Cost-benefit analysis (CBA) compares the economic impact of a linear production model with a circular model, taking into account the operational costs and financial benefits achieved by implementing circular economy strategies. The interpretation of these CBA results leads to the integration of the circular economy into environmental engineering, so that the results obtained show how to reduce operational costs and increase revenues by reusing resources, optimizing energy consumption, and reducing waste management costs. In the long term, this strategy can lead to increased economic competitiveness and a sustainable production model [11].

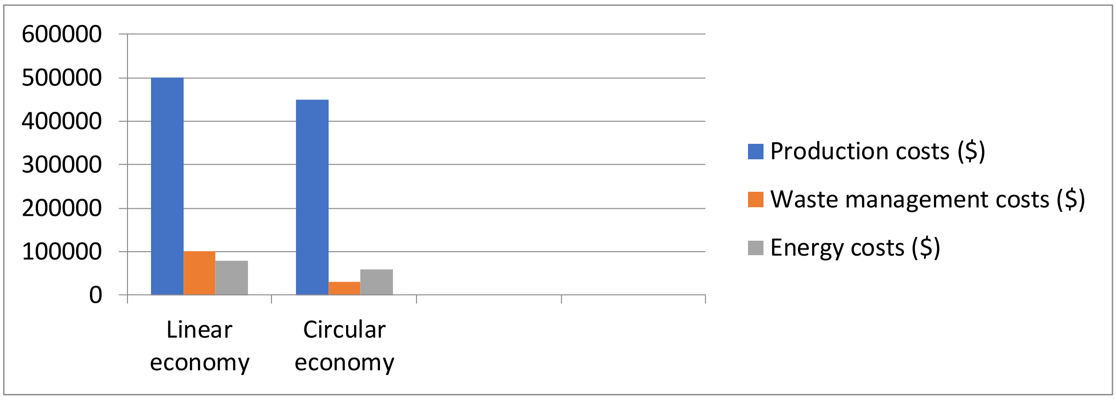

Figure 5 Cost analysis between linear and circular economies for an industrial product

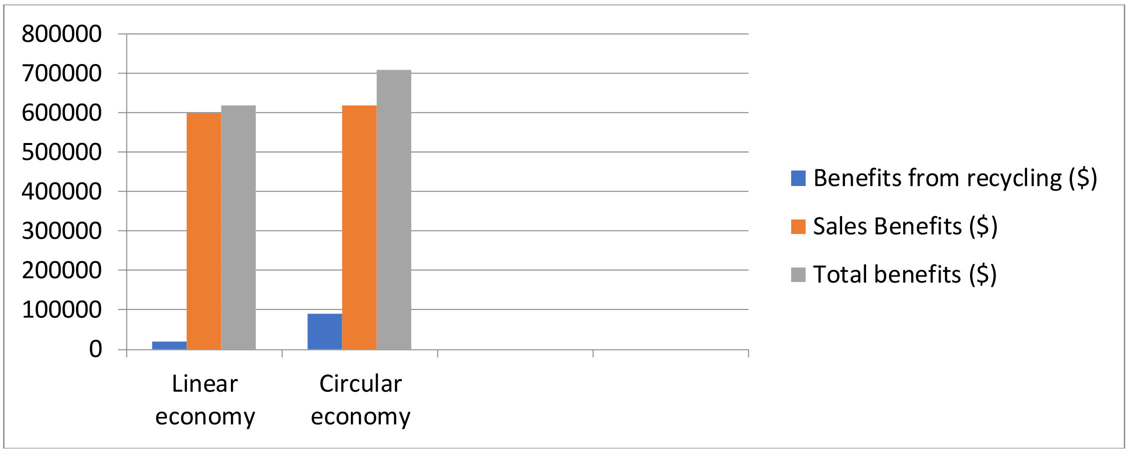

Fig. 6 Analysis of benefits for an industrial product

1. Production costs

• In a **linear economy**, production costs are higher ($500,000) because recycled materials are not used and there is greater dependence on primary resources.

• In the **circular economy**, production costs fall to $450,000 due to the use of recovered materials, process optimization, and reduced waste.

2. Waste management costs

• The linear model generates $100,000 in waste management costs because products quickly reach the end of their life cycle and are disposed of.

• The circular model drastically reduces these costs to $30,000 because materials are recovered, recycled, and reused, minimizing the amount of waste disposed of.

3. Energy costs

• The linear model has high energy consumption, generating $80,000 in energy costs.

• The circular model optimizes resource consumption and introduces renewable sources, reducing costs to $60,000.

4. Benefits from recycling

• In the linear economy, recycling is limited, generating minimal benefits of $20,000.

• The circular economy increases material recovery, generating $90,000 in financial benefits.

5. Total benefits

• The linear economy produces a total revenue of $620,000, but with high costs.

• The circular economy achieves benefits of $710,000 with lower costs, showing increased profitability and a lower environmental impact.

4. CONCLUSIONS

The integration of the circular economy into environmental engineering represents a sustainable solution for efficient resource management and reducing environmental impact. The analysis highlights the benefits of applying this model by reducing raw material consumption, optimizing production flows, and minimizing waste generation. The adoption of advanced technologies and the implementation of supportive policies can facilitate the transition to a balanced and ecologically resilient economic system.

The study's findings highlight the need for an integrated approach to promoting the circular economy, involving both the private sector and government institutions. Optimizing the life cycle of products, developing recycling infrastructure, and supporting industrial symbiosis initiatives are essential measures for strengthening this model. Adapting the legislative framework and creating financial mechanisms to encourage sustainable practices can contribute to a more effective implementation of the circular economy.

To improve existing policies and practices, stricter regulations on resource use and waste management need to be developed, and economic incentives to support industries in their transition to sustainability need to be promoted. Raising awareness and educating the public about the benefits of the circular economy is another key factor in accelerating the process of change.

The prospects for transitioning to a sustainable circular model depend on society's ability to adopt new production and consumption models based on the principles of efficiency and sustainability. Technological innovation, the digitization of industrial processes, and the development of circular value chains will play a major role in consolidating this economic model. The active involvement of the private sector, the support of regulatory institutions, and international collaboration are key elements in the success of the transition to a circular economy. In this context, the implementation of clear and coherent strategies will contribute to the creation of an economic system capable of responding to current and future challenges related to environmental protection and the efficient use of natural resources.

The implementation of the circular economy in environmental engineering faces multiple challenges, particularly in terms of inadequate infrastructure, the high costs of new technologies, and the need for a paradigm shift at the economic and social levels. An effective transition requires a rethinking of production and consumption patterns, which implies a significant effort on the part of governments, industry, and consumers. In this context, it is essential to develop coherent policies and economic incentives that facilitate the widespread adoption of circular practices.

One of the main obstacles is the lack of adequate infrastructure for waste management and material recycling. In addition, economic inertia and the lack of business models adapted to new sustainability requirements hinder the adoption of circular practices. Resistance to change on the part of industry, together with the high initial costs of developing sustainable technologies, are important limiting factors. Close collaboration between the public and private sectors is needed to develop effective and affordable solutions for all industries.

In the future, research in the field of circular economy will need to focus on optimizing recycling and material recovery processes, developing integrated economic models, and designing effective public policies. An interdisciplinary approach combining environmental engineering with economics, sociology, and technology is needed to identify innovative and widely applicable solutions. Investments in education and training will also play a crucial role in developing the skills needed to implement sustainable strategies.

The outlook for the future depends on society's ability to adopt an economic model based on sustainability and efficiency. International collaboration and the exchange of best practices will facilitate the adoption of the circular economy globally, thereby contributing to reducing environmental impact and creating a more resilient economic system. By promoting integrated strategies and supporting innovation, the circular economy can become a central pillar of sustainable development for future generations.

REFERENCES

[1] Geissdoerfer, M., Savaget, P., Bocken, N.M.P. & Hultink, E.J., The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, Vol. 143, pp.757–768, 2017, https://doi.org/10.1016/j.jclepro.2016.12.048;
[2] Kirchherr, J., Reike, D. & Hekkert, M., Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling, Vol. 127, pp. 221–232. https://doi.org/10.1016/j.resconrec., 2017;
[3] Pasăre M., On the applicability of composites materials, Fiability & Durability / Fiabilitate si Durabilitate, 2018, Issue 2, p. 83
[4] Pasăre M. M., Approach regarding composite electrodepositions, Confereng 2020, Annals of the „Constantin Brancusi" University of Targu Jiu, ISSN-L 1842-4856, ISSN 2537-530X (online), Engineering Series, No. 2/2020, Pg.100-104, Nov. 2020.
[5] Ghisellini, P., Cialani, C., & Ulgiati, S., A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, Journal of Cleaner Production, Vol. 114, pp. 11-32, 2016;
[6] Lieder, M., & Rashid, A., Towards circular economy implementation: A comprehensive review in context of manufacturing sector, Journal of Cleaner Production, Vol. 115, pp. 36-51, 2016;
[7] Hauschild, M.Z., Rosenbaum, R.K., & Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice, Springer, 2017. (https://doi.org/10.1007/978-3-319-56475-3)
[8] Ellen MacArthur Foundation, Completing the Picture: How the Circular Economy Tackles Climate Change. Retrieved from https://ellenmacarthurfoundation.org/completing-the-picture, 2021;
[9] Ghisellini, P., Ripa, M., & Ulgiati, S., Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector, Journal of Cleaner Production, Vol.178, pp. 618-629, 2018.
doi: 10.3989/ic.92607
[10] Wijkman, A., & Skånberg, K., The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency, Club of Rome. Retrieved from https://clubofrome.org/publication/the-circular-economy-and-benefits-for-society, 2018.
[11] Stahel, W.R., The Circular Economy, Nature, Vol. 531(7595), pp. 435-438, 2016.
doi: 10.1038/531435a