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Essay

Agro-industrial waste management: a circular bioeconomy approach

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Abstract

This essay aimed to show how the management of agro-industrial waste can contribute not only to its valorization but also to the reduction of pollution, contributing to economic and environmental sustainability. The study was for the period from 2017 to 2024 in the region known as the Comarca Lagunera in north-central Mexico. At the beginning of this work, we present the results of a local process that, with its limitations, adds contextual value and regional applicability by treating waste, generating energy, and producing organic fertilizer and sustainably treated water. The improvement and updating of these local processes that started several years ago are compared to Ellen MacArthur's butterfly diagram in a version adapted to the region's dairy farms. The bibliographic review of experiences documented in scientific journals where the following is discussed: the extraction of valuable compounds before biodigestion, integrated anaerobic digestion and composting, the types of agro-industrial waste, the application for new generation biomass, and the analysis of the life cycle to evaluate the environmental impact. Finally, the valorization of waste for biorefinery and circular bioeconomy processes is highlighted. It was concluded that the bioeconomy offers benefits, although its adoption faces challenges, requiring complementation with economic studies, in particular, the design of efficient processes for the collection of valuable waste based on a supply chain that not only manages to make waste capture more agile but also efficient production and distribution processes.

Keywords:

agro-industrial waste, biomass, composting.

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The research question of this essay is: how can the circular bioeconomy provide solutions to problems in Mexico's agro-industrial sector by efficiently managing agro-industrial waste in a sustainable way?

Development

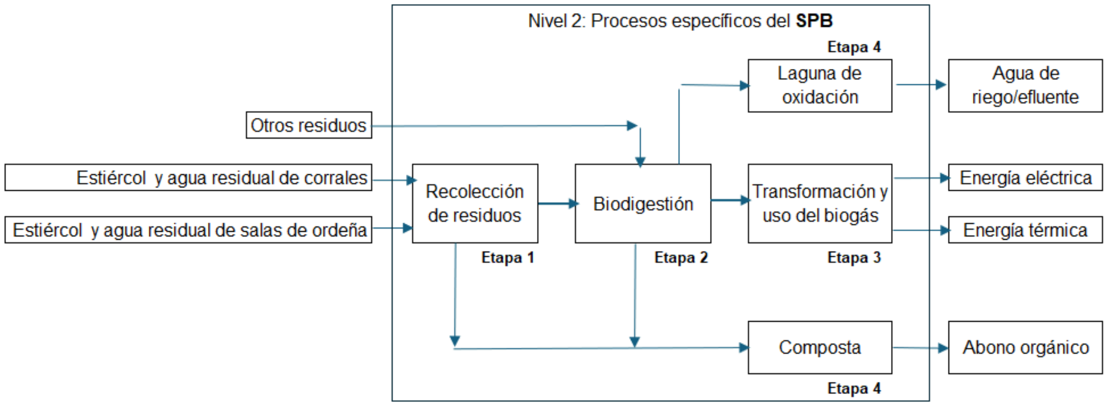
The essay is structured in five sections, each of which discusses theoretical or practical perspectives.

Section I: The Comarca Lagunera region: its approach to sustainability and its comparison with the biological cycle of EMF (2022)

Subsection I a

This proposal is based on a previous study in the Comarca Lagunera by López *et al*. (2017), which describes a biogas production system (BPS) with a sustainability approach of four stages defined for waste management and the obtaining of biogas and other useful products. In stage 1 of Figure 1, manure from dairy cows and wastewater from pens and milking parlors are collected.

Figure 1. Specific processes of the biogas production system. Adapted from CienciAcierta (2017).



In stage 2, the waste goes to biodigestion, where it is transformed into biogas and byproducts. In stage 3, the biogas is transformed into electrical and thermal energy, optimizing resources. Finally, in stage 4, the solid waste is converted into fertilizer through composting, and the liquid is deposited and treated in an oxidation pond, it will be used as irrigation water. This integrated process treats waste, generates energy and produces fertilizer and sustainably treated water. Biogas can be referred to as biomethane, in which organic matter is converted to methane and CO2 in the absence of oxygen (Aghel *et al*., 2022). The knowledge on the subject treated in this essay is derived from fieldwork in dairy farms in the Comarca Lagunera. According to studies by López *et al*. (2017); Espinoza-Arellano *et al*. (2018); Molina *et al*. (2020).

Subsection I b: Ellen MacArthur's biological cycle analyzed in the context of La Comarca Lagunera

The left side of Figure 2, (EMF cycle) shows the loops of the biological cycle or cascades that return nutrients to the soil and help to regenerate the biosphere within an agronomic context.

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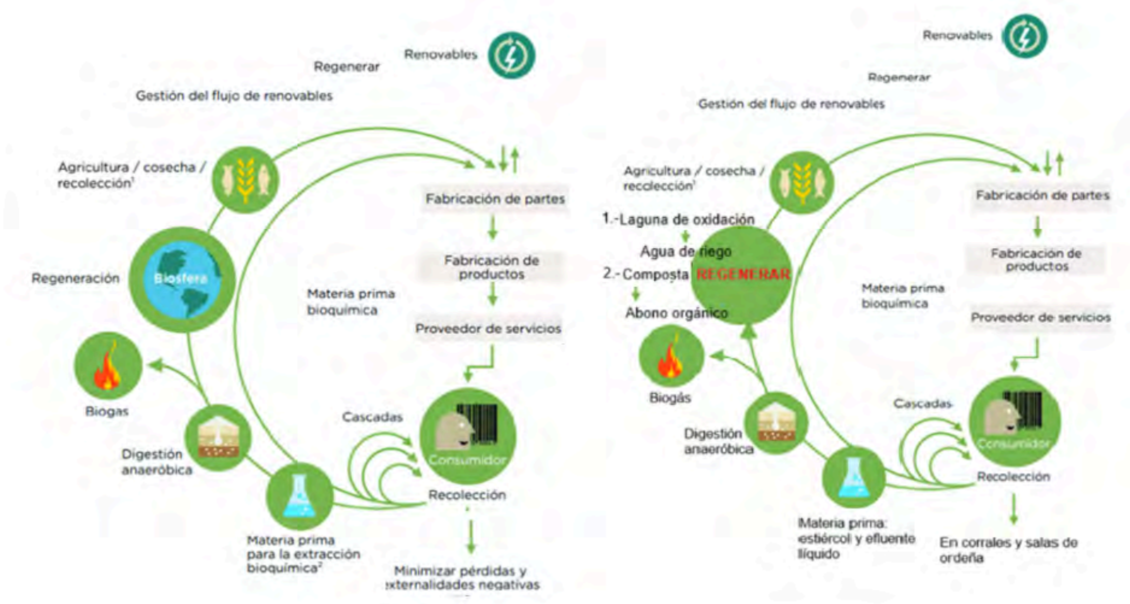
Figure 2. Butterfly diagram of circular economy. Based on EMF (2022), original cycle (left) and cycle adapted to the context of the Comarca Lagunera (right).



The right side of Figure 2 shows the adaptation made in this study, where the butterfly diagram is applied in the context of the BPS in dairy farms in the Comarca Lagunera. This figure is aligned with the aforementioned cascades as it promotes the use of its waste in a sustainable way and adds contextual and applicable value to the region.

Conclusions of the authors in section I

Ellen MacArthur's butterfly diagram of the biological cycle based on Braungarth's (2019) concept of 'cradle to cradle' was compared with a version adapted to the context of the dairy farms of the Comarca Lagunera, adapting the diagram to the local environment (right), considering the following steps: collection of raw material, manure and liquid effluent from pens and milking parlors; anaerobic digestion in biodigesters and biogas production, which, through combustion, allows methane to be burned and electricity and heat to be generated as a sign of the added value (Molina *et al*., 2020). This intermediate cycle is identified by EMF (2022) as 'regeneration in the biosphere', the experience or applied results presented by the authors, the cycle includes regeneration processes, either through compost-organic fertilizer or the use of wastewater for irrigation, which previously flows into an oxidation pond and then continues to the irrigation process.

Section II: Extraction of valuable compounds, anaerobic digestion, and composting: a leading biorefinery approach to agricultural waste (Fermoso *et al*., 2018)

In an increasingly environmentally conscious society, it is essential to assess the options for valorizing agricultural biomass in order to change its perception from waste to resource. The biorefinery approach is proposed as a way to increase the profits of the agricultural sector, ensuring environmental sustainability by converting biomass into fuels, energy, and chemicals. However, the author stresses that this proposal is less innovative compared to processes such as bioethanol

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production or white biotechnology. Although these processes have been proposed as units of operation to valorize agricultural waste, an exhaustive review of their individual or joint application has not yet been carried out in the literature. The objective was to review previous and current studies on the valorization of biomass from agricultural waste, focusing on the extraction of valuable compounds, anaerobic digestion, and composting, whether partial or fully treated waste. The Figure 3 represents a circular bioeconomic process, mainly focused on the treatment of lignocellulosic, vegetable, and fruit byproducts.

Figure 3. Circular bioeconomic process (Fermoso et al., 2018).

This process is sustainable and circular as it generates energy and compost and recovers biochemical compounds useful for various industries. In anaerobic digestion, microorganisms break down organic material without oxygen, producing biogas and nutrient-rich digestate. During and after digestion, valuable compounds, such as bioactives and fatty acids, are extracted. The remaining solid material is converted into compost, improving soil fertility and closing the cycle by integrating essential nutrients for future crops. Lakner *et al*. (2021) conclude that the contribution of sectors to the bioeconomy is complex, so it is necessary to have strategic planning and an optimal allocation of resources to meet the objectives and to analyze their role in the linear economy and their future effects.

Conclusions of the authors in section II

Although their biorefinery approach is less innovative compared to others that produce bioethanol or white biotechnology, their case mainly refers to the treatment of lignocellulosic, vegetables, and fruits byproducts. The anaerobic digestion process proposed by Fermoso *et al*. (2018) is a widely used method in the valorization of organic waste, characterized by the homogeneity of its procedures and results. The key contribution of this proposal is that high-value compounds (bioactives, volatile fatty acids, or other biochemical products) are previously extracted from the digestate or intermediate products formed in the process. Therefore, what reaches the composting process is a remaining solid material that can be applied as a nutrient to the soil, closing the cycle by returning essential nutrients, thus supporting the growth of future crops. The authors understand

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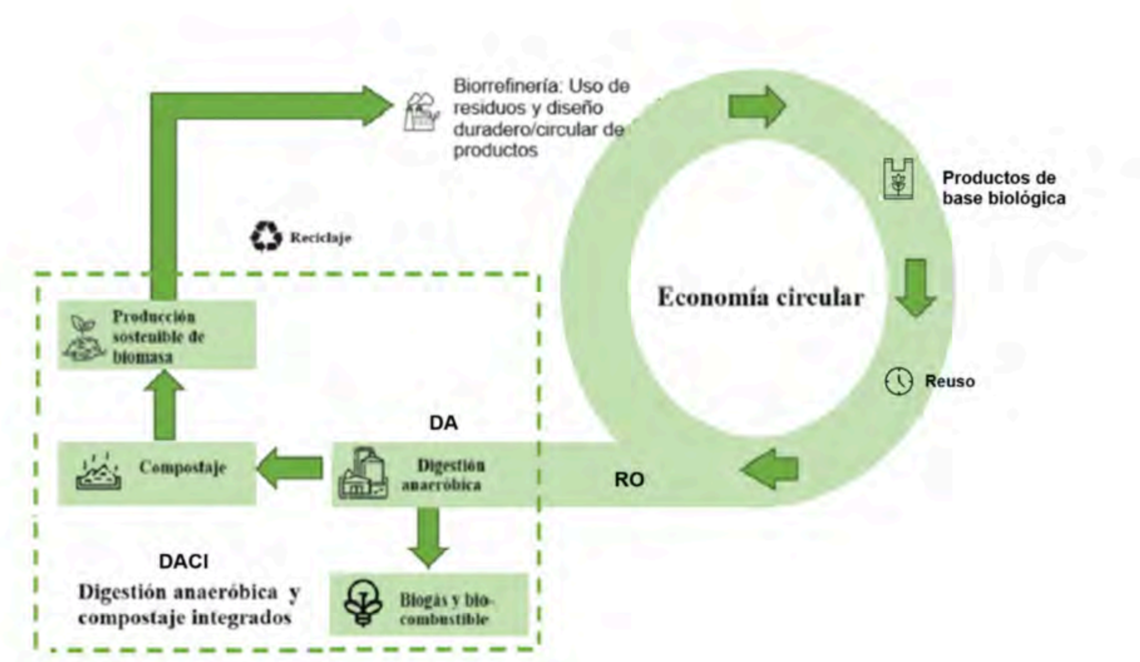
that it is something that has no prospects in La Laguna since its applicability would depend on the value of the extracted compounds, as well as the demand and the scale of production.

Section III: Integration of anaerobic digestion and composting to promote the recovery of energy and materials from organic waste within the framework of the circular economy in Europe (Cucina, 2023)

This work emphasizes biodigestion and composting, where it points out (Figure 4) that the production of biogas from anaerobic digestion and integrated composting (ADIC) is the process that mainly improves the overall sustainability of organic waste (OW) treatment.

Figure 4. Graphic summary of the process of integration of anaerobic digestion and composting (Cucina, 2023).



Therefore, improving anaerobic digestion (AD) performance becomes mandatory to improve the implementation of ADIC for OW management. Biogas production from sparsely biodegradable OW (green municipal waste GMW, agro-industrial waste AIW, and sludge from wastewater treatment plants ST) can be effectively improved by pretreatment of the raw material before AD (Atelge *et al*., 2022; Janz *et al*., 2022; Yaser *et al*., 2022). Although different pretreatment technologies have been applied to improve biogas production from biomass while maintaining net production of energy (mechanical, thermal, chemical), there are no ADIC studies where OW is pretreated before DA. Therefore, this type of biorefinery (pretreatment followed by ADIC) should be investigated to assess its overall sustainability (Figure 4). When applying heterogeneity analyses, ownership, scale, industry, and regional factors are considered (Qi *et al*., 2022).

Conclusions of the authors in section III

Although the proposed ADIC may be a valid strategy for a complete circular economy system in the treatment of OW, more research is required to overcome the identified gaps. Technically, there is a lack of information on the use of sludge from treatment plants ST as a raw material in the ADIC system; considering the potential for recoverable energy and nutrients, they can be composted as fertilizer, anaerobically processed for biogas, used in construction materials, used to recover

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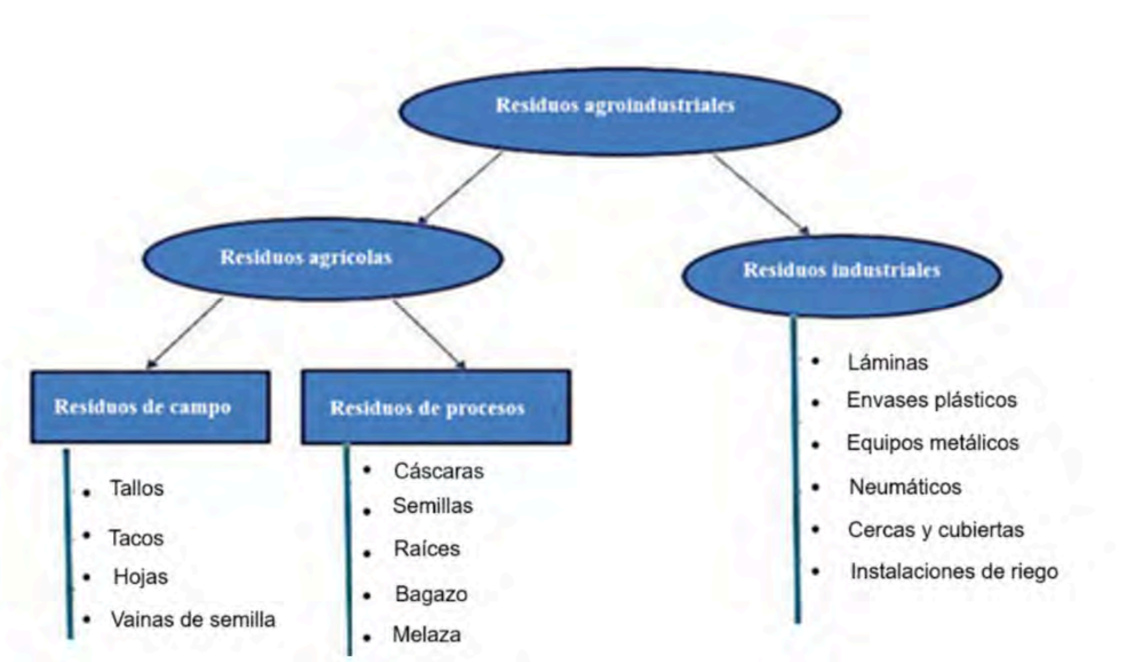
essential nutrients, such as phosphorus, or transformed into biochar and syngas by pyrolysis or gasification. Pilot-scale studies are useful but insufficient to assess sustainability, so it is necessary to implement large-scale studies that evaluate the environmental impact in real conditions, that is, the entire process of technological development must be addressed. The economic sustainability of ADIC has been little evaluated, and there is a need for more studies that consider the costs and benefits of energy and biofertilizer production and the time of return on investment.

Section IV: Agro-industrial waste management: the circular and bioeconomic perspective (Ogbu and Okey, 2023)

With the increase in the human and animal population, the demand and production of food will continue to increase, which will lead to an increase in waste generation and negative environmental challenges. Sustainable agricultural production, agro-industrial processing, and environmental, human, animal, and climate health depend substantially on effective waste management. Circular agricultural production and bioeconomic management models for agro-industrial waste are fundamental to achieving the objective of significantly reducing waste generation, reusing and recycling it. Agro-industrial waste can be classified into three big categories: recyclable and compostable, non-recyclable and non-compostable, and hazardous (Figure 5).

Figure 5. Three big categories of agro-industrial waste (Ogbu and Okey, 2023).



Compostable waste, such as pruning residues, straw, leaves, bagasse, and manure, is recyclable and reusable on farms or recycling plants. These primary residues come from agricultural and livestock production, whereas secondary waste, such as bones, shells, and slaughterhouse waste, result from agro-industrial processing. It is key to design the entire process of technological development and, in particular -the authors of the present essay point out- to define efficient and possible processes for the collection of valuable waste. This would be based on a functional supply chain that optimizes production processes and delivery to their final destination. On the other hand, non-recyclable waste, such as plastics, metal containers, and machinery, is difficult to handle due to its volume. Finally, hazardous waste, such as phytosanitary products, chemical packaging, and contaminated wastewater, require careful handling due to the risks they represent. Vargas-Canales

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et al. (2023) point out that in Mexico 'research focuses on socioeconomic issues and to a lesser extent on technological development'.

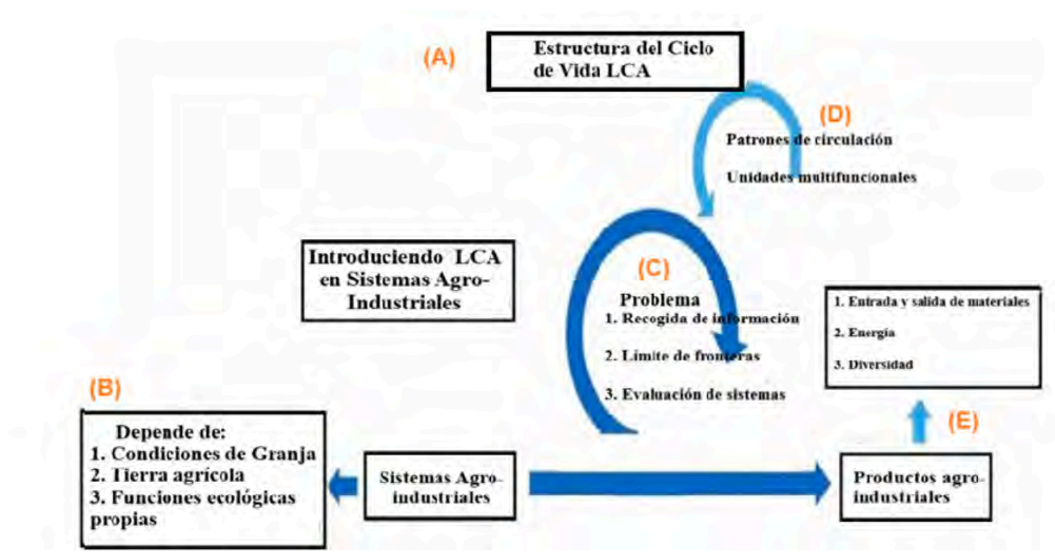
Conclusions of the authors in section IV

Effective waste management is essential for sustainable agriculture, agro-industrial processes, and the protection of the environment and human, animal, and climate health. Circular and bioeconomic agricultural production models for agro-industrial waste management are essential to reduce, reuse, and recycle waste. Continued research and innovation will help achieve the goal of transforming waste into resources and creating a zero-waste farming system.

Section V: Valorization of agro-industrial waste for biorefinery processes and circular bioeconomy: a critical review (Yaashikaa *et al*., 2022)

Results such Yaashikaa *et al*. (2022) analyze the valorization of agro-industrial waste in the context of biorefinery and the circular bioeconomy. The life cycle impact assessment (LCA) consists of three phases: categorization, characterization, and standardization, which allow ecological effects to be assessed. Categorization organizes data, characterization measures the magnitude of impacts, and standardization compares results to get a complete picture. This approach is critical to managing waste and maximizing the production of energy and valuable products, such as fuels, chemicals, and electricity. The use of agro-industrial waste as a raw material in the biorefinery not only generates energy, but also contributes to environmental sustainability by adding value to the waste. The cascading use of biomass drives economic development through the generation of renewable products (Vargas-Canales *et al*., 2023). LCA applied to agro-industrial systems assesses performance, facing challenges such as material diversity, energy consumption, and data collection. This analysis is key to addressing ecological degradation, food security, and energy crises, highlighting the differences between the agricultural and industrial sectors. Figure 6 represents a framework that integrates life cycle analysis (LCA) that serves as the basis for assessing the environmental impact of an agro-industrial system.

Figure 6. Life cycle analysis (Yaashikaa et al., 2022).



LCA allows the flow of materials, energy, and environmental loads to be assessed throughout the life cycle of agricultural products, from agricultural production to the final product.

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Interpretation of Figure 6

A) LCA framework where steps B to E are shown; B) Introduction of LCA into the agro-industrial system: this involves applying LCA to study various aspects of the agro-industrial system, which depends on three main factors: farm conditions (size, location, and resources), agricultural land (such as fertility, quality, and land use); ecological functions provided by the farm or land (biodiversity, nutrient cycling, etc.). C) Problems in the implementation of LCA: data collection: collection of information, which can be complicated due to the variability of production methods. Boundary boundaries: setting system boundaries to decide which processes should be included (from resource extraction to waste management). Systems assessment: development of criteria (they are technological) to assess the environmental, social, and economic impacts of the system. (D) central aspects of LCA applied to agro-industrial systems. Circulation pattern analysis: evaluation of how water, nutrient, and energy resources are recycled within the system. Multifunctional units: many agro-industrial systems provide more than just food production, such as carbon sequestration or soil improvement. The LCA must consider these multifunctional functions. E) Agro-industrial product: at the end of the process, the system produces an agro-industrial product that is influenced by input and output of materials; that is flow of raw materials and products. Energy: that required for production and processing. Diversity: the biological or production diversity present within the system. In conclusion, the framework visually illustrates how LCA can be incorporated into an agro-industrial system by addressing various challenges such as data collection and system boundaries and focusing on the analysis of resource circulation and multifunctionality to produce sustainable agricultural products.

Conclusions of the authors in section VI

The LCA framework for agro-industrial systems includes five key steps: A) general structure of the LCA; B) its introduction into the agro-industrial system considering farm, land, and ecological functions; C) challenges in its application such as data collection, system boundaries, and impact assessment; D) core aspects such as resource circulation and multifunctionality and E) the final product, influenced by material flows, energy, and diversity. Together, this approach allows LCA to be integrated to optimize agro-industrial sustainability.

Conclusions

Circular and bioeconomic models are essential to reduce, reuse, and recycle agro-industrial waste. Research and innovation have contributed to achieving the goal of transforming waste into resources and creating a zero-waste agricultural system. There is a need for an approach to optimizing the collection of waste (from the field, processes, and industry) with the support of agricultural collectors installing reservoirs close to biomass sources to meet quality specifications. The agricultural circular economy seeks to maximize ecological and economic benefits through the efficient use of energy and materials, minimizing ecological degradation, improving food security, and reducing the energy crisis. In the same way, by integrating the life cycle analysis, carried out in this work, it serves as a basis for evaluating the environmental impact of an agro-industrial system. Life cycle analysis makes it possible to assess the flow of materials, energy, and environmental loads throughout the life cycle of agricultural products, from agricultural production to the final product. It is a key issue that will contribute to improving the use of agro-industrial waste.

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