

Innovative Strategies for the Utilization of Agro-Industrial Residues: Towards a Sustainable Circular Economy

Estrategias innovadoras para el aprovechamiento de residuos agroindustriales:
Hacia una economía circular sostenible

Betzabe Ebenhezer López-Corona^{1*}, Francisco Rodríguez-Félix¹, Carlos Gregorio Barreras-Urbina¹, María de Jesús Moreno-Vásquez², Idania Emedith Quintero-Reyes³, Bernardo Murillo-Amador⁴, Ramón Jaime Holguín-Peña⁴, Edgar Omar Rueda-Puente⁵, José Agustín Tapia-Hernández¹

¹ Departamento de Investigación y Posgrado en Alimentos (DIPA), Universidad de Sonora, Blvd. Luis Encinas y Rosales, S/N, Colonia Centro, 83000, Hermosillo, Sonora, México.

² Departamento de Ciencias Químico Biológicas (DCQB), Universidad de Sonora, Blvd. Luis Encinas y Rosales, S/N, Colonia Centro, 83000, Hermosillo, Sonora, México.

³ Departamento de Ciencias de la Salud, Universidad de Sonora, Blvd. Bordo Nuevo s/n, antiguo Ejido Providencia, 85010, Cd. Obregón, Sonora, México.

⁴ Centro de Investigaciones Biológicas del Noroeste, Km. 1 Carretera a San Juan de La Costa, 23205, La Paz, Baja California Sur, México.

⁵ Departamento de Agricultura y Ganadería (DAGUS), Universidad de Sonora, Blvd. Luis Encinas y Rosales, S/N, Colonia Centro, 83000, Hermosillo, Sonora, México.

ABSTRACT

The proper management of waste generated during agro-industrial activities is currently one of the greatest challenges for achieving a circular economy. The considerable increase in population, along with technological and industrial advances, has negatively affected optimal waste management, posing environmental, social, and economic challenges. The circular economy emerges as an alternative to promote the reduction and impact of agro-industrial waste, encouraging its valorization with a more innovative and sustainable approach. The objective of this study was to analyze the current state of waste generation and propose sustainable strategies through the circular economy. To this end, a review of scientific literature published between 2020 and 2025 was conducted, consulting databases such as Scopus, Web of Science, and ScienceDirect. The main findings indicate that the most relevant strategies focus on bioenergy production and the development of value-added bioproducts. Composting, anaerobic digestion, and biotechnology were identified as emerging technologies with the greatest application. Finally, technical, economic, and regulatory barriers limiting the implementation of these strategies were recognized. These findings provide a basis for improving the management of agro-industrial waste and contribute to mitigating its environmental impact.

Keywords: By-products, circular economy, recycling, sustainability, valorization.

RESUMEN

El correcto manejo de los residuos que son generados durante las actividades agroindustriales es actualmente uno de los mayores retos hacia la economía circular. El aumento

considerable en la población y los avances tecnológicos e industriales han afectado negativamente su óptimo manejo planteando desafíos ambientales, sociales y económicos. La economía circular surge como alternativa para fomentar la reducción e impacto de los residuos agroindustriales, promoviendo la valorización de estos con un enfoque más innovador y sustentable. El objetivo del presente estudio fue analizar el estado actual en la generación de residuos y proponer estrategias sostenibles a través de la economía circular, para ello, se realizó una revisión de literatura científica publicada entre 2020 y 2025 consultando bases de datos como Scopus, Web of Science y ScienceDirect. Los principales hallazgos indican que las estrategias más relevantes se enfocan en la producción de bioenergía y la obtención de bioproductos de valor agregado. Se identifican como tecnologías emergentes con mayor aplicación el compostaje, la digestión anaerobia y la biotecnología. Finalmente, se reconocen barreras técnicas, económicas y regulatorias que limitan la implementación de estas estrategias. Estos datos permiten garantizar un mejor manejo de los residuos agroindustriales y ayudará a mitigar sus efectos sobre el medio ambiente.

Palabras clave: Economía circular, reciclaje, sostenibilidad, subproductos, valorización.

INTRODUCTION

The agroindustry, which encompasses everything from the initial acquisition of raw materials to food processing, generates large amounts of both organic and inorganic waste. When these wastes are not properly managed, they can cause negative environmental impacts such as the deterioration of water and soil quality, the release of gases, and the spread of diseases through vectors (Jiménez-Robles *et al.*, 2025;

*Author for correspondence: Ebenhezer López-Corona
e-mail: betzabe.lopez@unison.mx

Received: October 2, 2025

Accepted: January 27, 2026

Published: February 25, 2026

Vicente-Zurdo *et al.*, 2025; Llanes and Pérez, 2024; Anaconda and Piamba, 2023; Alcántara-Revilla *et al.*, 2022; Marchan-Solier *et al.*, 2021). However, many of these residues contain high-value compounds such as proteins, fiber, antioxidants, vitamins, and minerals (Jiménez-Robles *et al.*, 2025; Salazar-López *et al.*, 2023; Arun *et al.*, 2020), which could be used in the production of functional foods, nutritional supplements, and other value-added products. Despite their potential, the lack of infrastructure, appropriate technologies, and effective waste management policies limits their use, resulting in both environmental and economic losses.

The circular economy proposes a production and consumption system focused on extending the use of resources, optimizing their utilization, and recovering materials once they have completed their life cycle (Tseng *et al.*, 2020). Specifically, in the agroindustrial sector, this perspective allows for the transformation of waste into valuable inputs, promoting both the economic and ecological sustainability of the sector.

Processes such as composting, anaerobic digestion, or the extraction of bioactive compounds make it possible to reduce the use of non-renewable resources and decrease pollutant emissions. This approach also drives innovation, fosters cooperation among different stakeholders in the value chain, and strengthens the sector's ability to face climate change and economic instability.

In addition to reducing the volume of waste, circular strategies enable the production of high value-added products. One example is the reuse of residues such as peels, bagasse, and plant residues to develop ingredients with functional, antioxidant, and antimicrobial properties applicable to food, cosmetic, and pharmaceutical industries (Minjarez *et al.*, 2025; Narvaez *et al.*, 2024; Campos-Rodríguez *et al.*, 2023; Chel *et al.*, 2022; Jideani *et al.*, 2021; Nieto, 2020). Likewise, this model significantly contributes to combating climate change by reducing greenhouse gas emissions.

Current technologies such as anaerobic digestion make it possible to convert waste into biogas (a renewable energy source) and produce biofertilizers, thereby reducing the use of fossil fuels and synthetic fertilizers, while also lowering pollutant emissions (Balakrishnan, 2024). It also encourages a more rational use of water and energy, which is crucial in agricultural areas facing water scarcity.

From an economic standpoint, circularity opens new business opportunities by transforming residues previously considered "waste" into useful materials. This stimulates the rural economy, creates green jobs, and strengthens local production networks. Examples such as the development of materials from agroindustrial residues, demonstrate how technological innovation can become a competitive advantage (Hussain *et al.*, 2025; Pagliuso *et al.*, 2025; Orozco *et al.*, 2024).

Finally, the circular economy promotes intersectoral and interdisciplinary cooperation, encouraging collaborative innovation and the development of joint solutions. It is essential for universities, public institutions, and companies

to foster strategic alliances to research and scale up circular models that are sustainable from economic, ecological, and social perspectives. Such collaboration is key to structurally transform the agroindustrial sector and advance toward the fulfillment of the Sustainable Development Goals (SDGs) of the 2030 Agenda.

The implementation of circular approaches in the agro-industrial sector not only helps to address environmental challenges, but also represents an opportunity to foster sustainable growth, enhance competitiveness, and contribute to food security and the global economy. Therefore, the objective of this review was to analyze innovative strategies for the valorization of agro-industrial residues from a circular economy perspective, highlighting their potential to mitigate environmental challenges, promote sustainable growth, improve the competitiveness of the agro-industrial sector, and contribute to food security and global economic development. The study was conducted as a thematic literature review, with the aim of analyzing the environmental and socioeconomic impacts of plant- and animal-based agro-industrial residues, as well as innovative strategies for their valorization within the framework of a circular economy. The search was carried out using databases such as Scopus, Web of Science, and ScienceDirect, employing keywords in Spanish and English related to agro-industrial residues, circular economy, by-product valorization, nanotechnology, and sustainability. Scientific articles, reviews, and technical documents published between 2020 and 2025 were included, prioritizing those addressing innovative, technological, and environmentally applicable approaches in the agro-industrial sector. Out of approximately 245 documents initially identified, 100 were selected for the final analysis after applying criteria of relevance, currency, and thematic pertinence. The information was organized into categories such as environmental and socioeconomic impacts of residues, circular economy principles (reduction, reuse, and recycling), innovative valorization strategies, and emerging technologies such as nanotechnology. The synthesis allowed the identification of promising approaches for waste reduction, value-added generation, and sustainability in the agro-industrial sector, as well as limitations related to study heterogeneity and the uneven availability of information across regions and types of residues.

Current Outlook on Agroindustrial Waste of Plant and Animal Origin

The latest UN figures (2023) indicate an annual production of more than 11,000 tons of solid waste worldwide, a scenario expected to increase by up to 70 % by 2050. The variability of the sources of this type of waste in agroindustry prevents the existence of accurate statistical data on how much agroindustrial waste is produced globally. However, products such as sugarcane generate more than 30% waste for every 100 tons of milled cane. This figure represents a considerable amount of waste that, if mismanaged, will have negative effects on the environment due to its ability to produce high emissions

of gases such as CO₂ and particulate matter from combustion, as well as direct contamination of water deposits in rivers and aquifers, in addition to generating unpleasant odors and pests such as rodents and insects (SEMARNAT, 2023).

In Mexico, agriculture and livestock are the most important economic activities due to their capacity to generate employment and are among the main sources of food supply for millions of Mexicans (Acosta *et al.*, 2020). In the country, agriculture represents 4 % of the annual GDP, with 13% of the national territory dedicated to this industry, producing harvests of approximately 200 products (FAO, 2023). In 2022 alone, the agricultural sector was responsible for generating 91% of Mexico's total food volume, with 271 million tons (SIAP, 2023a). That same year, in Northwestern Mexico, 31.9 tons of food were produced from this activity, equivalent to approximately 162.2 million pesos (SIAP, 2022). Meanwhile, the animal-based industry, specifically the meat sector, represents one of the main production and consumption industries in Mexico, where in the last decade, the consumption of beef, pork, and poultry increased by 33% (Consejo Mexicano de la Carne, 2022b).

Due to the high demand of the agroindustrial sector, large quantities of waste are produced, with more than one billion tons of food produced worldwide ending up discarded (Ogbu and Okey, 2023). This is due to natural decomposition or treatments applied during processing, resulting in most foods not being fully utilized (Díaz Montes, 2022).

Among the main by-products of the agricultural industry are mango peel and seed, grape pomace, pineapple, apple, kiwi, potato, papaya, coffee, beans, avocado, and guava (Preciado *et al.*, 2022). Multiple studies focusing on plants and their characteristics highlight that plant-based by-products contain a wide range of bioactive compounds (Figure 1). The amount and quality of these compounds depend on several factors such as variety, genetics, maturity stage, soil composition, cultivation conditions, and the type of processing to which they are subjected (Nurzyńska-Wierdak, 2023; Leyva-López *et al.*, 2020).

Plants such as grape, coffee, apple, soy, wheat, mango, pineapple, and banana, which undergo minimal processing, produce large amounts of by-products, often exceeding the edible portion and in many cases accounting for more than 50 % of the original product (López-Escobar *et al.*, 2025; Asma *et al.*, 2023; Galanakis *et al.*, 2022; Preciado-Saldaña *et al.*, 2022). Most of the time, these by-products have equal or even higher nutritional or functional value than the edible portion itself. These by-products have been associated with biological properties of interest, such as high antioxidant and antimicrobial activity (Nieto, 2020), antiviral and antifungal potential (Coman *et al.*, 2020), anticancer activity (Jideani *et al.*, 2021), anti-inflammatory (Chel *et al.*, 2022), and antimutagenic (Chamorro *et al.*, 2022) effects, among others. On the other hand, residues such as parts, trimmings, peels, stems, seeds, husks, bran, and others produced after the extraction of juice, oil, starch, and sugar from various plant products are a considerable source of compounds such as phenols,

carotenoids, vitamins, polysaccharides, and dietary fibers. Furthermore, they are usually a rich natural source of carbohydrates, polysaccharides, proteins, vitamins, minerals, and antioxidants (Mateus *et al.*, 2022).

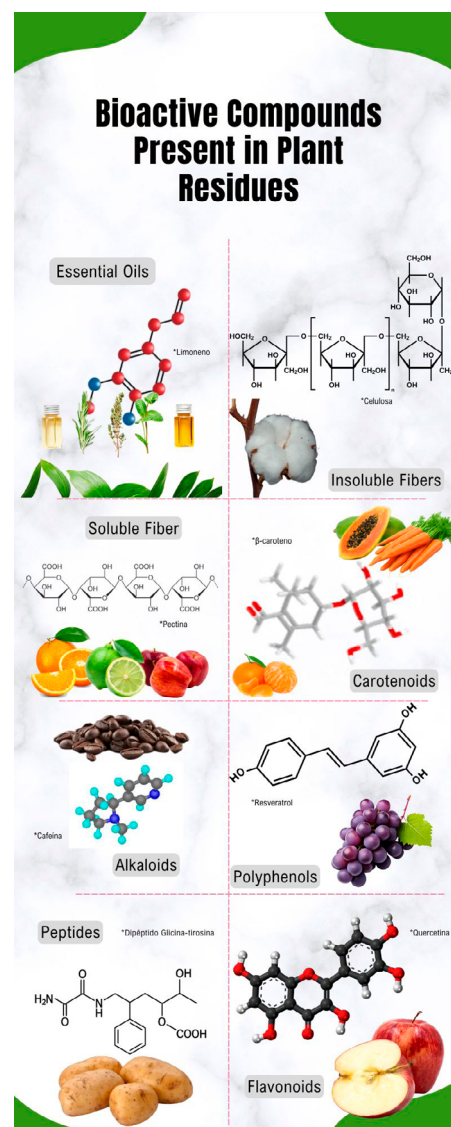


Figure 1. Bioactive compounds reported in plant residues. Source: As reported in Sánchez, 2024; Urrialde *et al.*, 2022; Stegmayer *et al.*, 2021.

Figura 1. Compuestos bioactivos reportados en residuos vegetales. Según lo reportado en Sánchez, 2024; Urrialde *et al.*, 2022; Stegmayer *et al.*, 2021.

In Mexico, beef production ranks as the leading activity within the livestock sector, representing 27.9 % of the total national livestock production value in 2022, equivalent to approximately 164 billion pesos. This marked a 7.9 % increase compared to the previous year. According to preliminary data from SIAP-SADER, in 2023 a historic production of 2.21 million tons of beef was achieved, setting the highest level recorded to date. The states leading this production nationwide are Veracruz, Jalisco, Durango, San Luis Potosí, and Chiapas, which together account for 64 % of the national total (FIRA, 2024a). Regarding pork, its production has shown sustained growth,

increasing from 1.2 to 1.7 million tons, driven by a per capita demand that reaches 18 kilograms (SADER, 2022a). This product is currently the second most consumed type of meat in the country, after chicken. Over the last decade, pork production has recorded an average annual growth rate of 3.6 %, reaching a new historic high of 1.77 million tons in 2023, representing a 2.2% increase compared to the previous year (FIRA, 2024b).

Meanwhile, the poultry industry, which includes the breeding, reproduction and use of domestic birds, is one of the most important branches of livestock farming in Mexico, both for its nutritional and economic value (Delgado *et al.*, 2025; Romero-López, 2021). Between 2010 and 2020, poultry product exports from Mexico increased from 2.8 to 3.7 million tons, while per capita consumption rose from 29 to 35 kg in the same period. More recently, in 2023, national production reached a historic record of 3.89 million tons, with an annual growth of 2.8 %, demonstrating greater dynamism than other livestock sectors such as beef and pork (FIRA, 2024).

The animal-based industry plays an essential role in both the economy and food security worldwide by providing essential products such as meat, milk, eggs, leather, and other derivatives. This industry not only meets the nutritional demand of millions of people but also generates employment in rural and urban areas, fosters national and international trade, and contributes to the development of multiple productive sectors. However, despite its benefits, this industry is also one of the main generators of organic and inorganic waste. Inadequate management of manure, effluents, animal remains, and packaging can cause severe consequences, including the alteration of terrestrial and aquatic ecosystems, along with the emission of compounds responsible for climate change and the spread of diseases. Therefore, although the animal-based industry is important and necessary, it also implies a significant environmental responsibility that requires sustainable practices to reduce and properly manage the waste it produces.

The main animal-origin residues are generated primarily by three industries: dairy, poultry, and meat. It has been noted that, according to their composition, these residues are rich in high-quality protein and are an important source of zinc, iron, B-complex vitamins, and essential amino acids (Shah *et al.*, 2025). However, they are most often discarded for aesthetic reasons. Most of the proteins contained in animal residues can be easily extracted and are frequently used in the production of hydrolysates, which are later incorporated as ingredients in various foods (Rojas *et al.*, 2022). However, for optimal utilization of agroindustrial by-products, it must be considered that they contain significant amounts of fat, which increases susceptibility to oxidation and rancidity. Therefore, proper processing and storage are necessary to avoid microbial growth and/or contamination. It is also important to note that, compared to plant-based by-products, those of animal origin represent higher costs but also greater profitability (Ordaz *et al.*, 2022).

In the meat industry, the largest proportion of residues

is generated during slaughter (Trujillo Echeverría, 2023). These are parts of the animal that cannot be marketed as meat or used in meat products, and they vary by geographic area due to differences in dietary habits and in what is considered edible or inedible. These residues typically include organs, fat or lard, skin, ears, feet, lungs, tripe, abdominal and intestinal contents, bones, and blood from various animals such as cattle, pigs, and sheep. They usually represent approximately 66.52 % to 68 % of the live weight (Abdulla, 2020).

According to 2021 data, poultry accounted for 28.5 % of national livestock production, with per capita annual consumption of 34.2 kg of chicken, 23 kg of eggs, and 1.3 kg of turkey (SADER, 2021). In that same year, poultry farming represented 0.75 % of Mexico's GDP, while within the livestock GDP it accounted for 36.8% (Unión Nacional de Avicultores, 2021). Sonora recorded a production of 35.5 million tons of poultry meat in 2022, equivalent to 1,163.4 million pesos (SENASICA, 2022).

The poultry industry also generates large amounts of by-products such as blood, bones, meat scraps, skin, fatty tissues, feet, skulls, and viscera. These have been shown to contain high amounts of proteins, fats, carbohydrates, minerals, vitamins, and other nutrients, making them a valuable option for obtaining different functional compounds and ingredients (Romero *et al.*, 2022). Furthermore, previous studies have shown that peptides derived from poultry by-products exhibit biological activity, including antihypertensive and anticancer effects (Bravo *et al.*, 2023; Romero-Garay *et al.*, 2022).

Environmental and Socioeconomic Impacts

Agroindustry, by encompassing the stages of cultivation, processing, and marketing of agricultural and livestock products, has become an essential component of economic development in various regions of the world. However, its expansion has been accompanied by a parallel increase in the generation of both organic and inorganic waste. When not properly managed, these wastes can cause serious environmental and socioeconomic repercussions. In this context, the sustainable management of such waste has become a priority challenge in achieving more responsible and sustainable models of rural and agricultural development.

From an environmental perspective, the accumulation and inadequate disposal of agro-industrial waste can lead to the deterioration of soils and both surface and groundwater, as well as contribute significantly to greenhouse gas emissions (Mohanta *et al.*, 2025; Nair *et al.*, 2022). Wastes such as manure, bagasse, pulp, husks, and wastewater with high organic matter and nutrient content, when untreated, can increase nitrogen and phosphorus levels in water bodies, fostering eutrophication processes (Tiwari and Pal, 2022). Likewise, the anaerobic decomposition of these residues in landfills generates methane (CH₄), a gas with a climate impact 28 times greater than that of carbon dioxide (CO₂) (Villegas-Henao *et al.*, 2024). Recent research indicates that agroindustry contributes approximately 10 – 12 % of global

greenhouse gas emissions, mainly due to the inadequate management of its waste (FAO, 2023).

In addition to environmental effects, the improper accumulation of agro-industrial waste also poses a public health problem, as it fosters the appearance of pests, the presence of disease-transmitting vectors, and the spread of pathogenic microorganisms. For example, in tropical regions, wet and easily fermentable organic waste can become hotspots of microbiological contamination, affecting both the sanitary quality of food and the health of nearby populations. Added to this is the intensive use of agrochemicals, whose toxic residues can harm ecosystems and endanger human health by accumulating in living organisms and amplifying along food chains (Gupta and Gupta, 2020).

On the socioeconomic level, the lack of effective policies for waste valorization represents a substantial loss of economic opportunities. Residues that could be transformed into high-value-added products such as biofertilizers, biogas, functional foods, industrial enzymes, or construction materials are discarded due to the lack of appropriate technologies, investments, or technical knowledge. This inefficiency particularly affects small and medium-sized producers, who could greatly benefit from circular economy initiatives that reduce production costs, diversify income, and increase competitiveness. According to Gupta and Gupta (2020), agro-industrial residues may contain up to 50 % reusable bioactive compounds, highlighting the enormous potential wasted under the current disposal-oriented model.

Moreover, the impacts of agro-industrial waste are unevenly distributed among different social groups. Rural communities, especially those with low levels of infrastructure and public services, face the most severe consequences of environmental pollution generated by agro-industrial activities (Senthilkumar *et al.*, 2020). Exposure to poorly managed waste not only degrades the natural environment and public health but also perpetuates conditions of poverty, exclusion, and vulnerability. This socio-environmental inequality underscores the need to integrate environmental justice approaches into waste management strategies. In light of this scenario, it is essential to redesign public policies and production models that incorporate principles of sustainability, circularity, and social inclusion. Promoting environmental education, encouraging applied research, facilitating access to valorization technologies, and creating economic incentives for responsible practices, are key actions to transform agro-industrial waste management. Likewise, the role of consumers is increasingly relevant: informed purchasing decisions can encourage agro-industrial companies to adopt more sustainable practices.

Principles of the Circular Economy Applied to the Agro-Industrial Sector: Reduction, Reuse, and Recycling

The circular economy has emerged as an essential paradigm for redesigning production and consumption systems toward sustainability, particularly in resource-intensive and waste-generating sectors such as agroindustry (Melendez,

2023). Unlike the traditional linear model, which is based on extraction, transformation, consumption, and disposal, the circular economy promotes closed material cycles in which waste becomes an input, thereby extending the product life cycle and reducing environmental impact (Imberno and Souto, 2023). In this context, the principles of reduction, reuse, and recycling represent a strategic pillar for transforming agro-industrial processes into more efficient, resilient, and regenerative systems.

One of the key principles of the circular economy is reduction, which constitutes a highly effective strategy within the circular approach (Morsetto, 2022). It involves preventing waste generation from the very design and logistics of agro-industrial processes. In practice, this means optimizing the use of inputs, water resources, and energy sources throughout all stages of the production cycle. For example, through the implementation of precision technologies, smart sensors, and sustainable agricultural practices, it is possible to significantly reduce the use of agrochemicals and fertilizers, thereby avoiding hazardous waste and secondary pollution (Palacios *et al.*, 2025; Muhie, 2022).

Likewise, in the processing phase, the application of engineering techniques to minimize losses during product transformation can reduce the volume of discarded by-products. Efficient logistics planning also helps minimize post-harvest and cold-chain losses, which is particularly important for perishable products such as fruits, vegetables, and meat products. This preventive perspective not only reduces environmental pressure but also represents a clear and profitable pathway for the sector.

In the second principle, reuse, the aim is to extend the useful life of materials, equipment, and agro-industrial by-products before they become waste. In rural settings, traditional practices such as reusing wastewater in crops or animal manure, are examples of circular economy approaches that can now be integrated into more advanced systems. In addition, solid residues such as containers, packaging structures, or metallic components can be refurbished and reused multiple times if designed with durability and disassembly in mind. From a more industrial perspective, reuse can also involve the recirculation of by-products within the same agro-food system. For example, whey, a bulky by-product of the cheese industry, can be reused as an input for the production of fermented beverages or nutritional supplements instead of being discarded as a polluting waste (Jiménez-Robles *et al.*, 2025). Such solutions require process redesign and the establishment of closed material loops, often through partnerships among different links in the value chain.

Finally, recycling constitutes an essential principle to reintegrate residual materials into the economic cycle. In agroindustry, this process often involves transforming organic waste into useful inputs through physicochemical, mechanical, or biotechnological processes. One of the most established strategies is composting, which allows the conversion of plant residues, manure, and other biodegradable waste into high-quality organic fertilizers, improving soil



Figure 2. Principles of circular economy in the material cycle.

Figura 2. Principios de la economía circular en el ciclo de los materiales.

fertility and reducing the use of synthetic fertilizers (Yin *et al.*, 2024; Ayilara *et al.*, 2020).

Another relevant example is the production of biopolymers from residues such as potato peels, sugarcane bagasse, or maize waste (Choudhary *et al.*, 2024; Ejaz *et al.*, 2023; Ebrahimian *et al.*, 2022), an alternative that not only replaces petroleum-based plastics but also promotes a closed life cycle that minimizes environmental footprints.

The incorporation of circular economy practices into the agro-industrial sector is not an automatic process but rather requires structural transformation, technological innovation, and collaborative governance. Public policies must promote regulatory frameworks and incentives for sustainable waste management, while companies need to integrate circularity into their business models. Likewise, scientific research and technology transfer should be directed toward solving frequent challenges in waste valorization and promoting context-specific solutions. The training and awareness of producers, workers, and consumers are also fundamental to accelerate this transition. A circular agroindustry will not only be more environmentally friendly but also more competitive, resilient to climate crises, and capable of meeting current demands.

Innovative Strategies for Waste Valorization

Recently, there has been increasing interest in implementing innovative strategies aimed at the valorization of agro-industrial waste, driven by the need to transform these discards into valuable resources that foster both environmental sus-

tainability and economic development. Among these alternatives, biotechnology and bioconversion stand out, as they employ controlled biological processes to transform organic residues into high value-added products. These technologies use microorganisms, enzymes, and biological systems to break down or modify residual materials, generating useful bioproducts such as biofuels, biofertilizers, bioplastics, and bioactive compounds (Almeida *et al.*, 2025; Silva *et al.*, 2025; Moisés *et al.*, 2022).

The generation of biofertilizers, bioplastics, and biofuels represents one of the most promising strategies in this field, as it integrates technologies capable of transforming waste into environmentally and economically valuable goods (Fallah and Khoshru, 2024; Chaudhary *et al.*, 2022; Daniel *et al.*, 2022). These solutions not only reduce dependence on chemical inputs and non-renewable energies but also promote a more sustainable circular economy model. By using residues as raw material, pollution and waste volumes are reduced, while providing useful alternatives for strategic sectors such as agriculture, industry, and energy.

Regarding biofertilizers, the agro-industrial sector produces large quantities of organic waste (including crop residues, manure, and food by-products) that can be transformed into natural fertilizers through processes such as fermentation and composting. These products are enriched with essential nutrients and beneficial microorganisms that enhance soil fertility, improve plant health, and optimize nutrient uptake (Fallah and Khoshru, 2024; Chaudhary *et al.*, 2022). Moreover, their use reduces the need for synthetic fertilizers, whose production and application generate significant greenhouse gas emissions that intensify climate change.

On the other hand, the production of bioplastics from agro-industrial waste constitutes an emerging pathway of valorization. Materials such as starch, cellulose, and oils extracted from agricultural by-products can be used to develop biodegradable biopolymers (Jayarathna *et al.*, 2022; Nigam *et al.*, 2022). These bioplastics represent an ecological alternative to conventional petroleum-derived plastics, whose persistence in the environment generates significant contamination and waste management issues. Using agricultural by-products for their production helps close material life cycles, reducing environmental impacts and fostering more sustainable consumption patterns.

In the case of biofuels, agroindustry provides multiple potential sources such as bagasse, shells, pulps, and manure, all rich in fermentable organic compounds. These can be converted into bioethanol, biogas, or biodiesel through different technological processes (Dave and Hebbale, 2025; Mubarak, 2024; Muñoz-Hernández *et al.*, 2023). The incorporation of these technologies into the agro-industrial environment, not only diversifies the economic sources of rural communities and sectoral enterprises but also reduces pollutant emissions and dependence on fossil fuels. Furthermore, it fosters the development of more decentralized, resilient, and sustainable local energy systems.

The synergistic combination of these three production lines (biofertilizers, bioplastics, and biofuels) can amplify the positive environmental and socioeconomic impact of agro-industrial waste valorization. For instance, residues not converted into biofertilizers can be used for biofuel production, while certain lignocellulosic wastes can serve as raw material for bioplastics (Dave and Hebbale, 2025; Mubarak, 2024; Muñoz-Hernández *et al.*, 2023). This integration maximizes resource efficiency and enables multiple products to be obtained from the same waste stream, optimizing the value chain and fostering the circular economy. Nevertheless, the large-scale adoption of these technologies faces technical, economic, and social challenges. Variability in the composition and quantity of agro-industrial residues can affect the efficiency of biotechnological processes, and the lack of adequate infrastructure limits production scalability. Additionally, it is necessary to develop public policies that encourage investment in technological innovation for the agro-industrial sector, as well as strengthen technical training and knowledge among producers and entrepreneurs.

Nanotechnology: A Promising Emerging Technology

Among the most recent technologies with promising applications in the agricultural field, nanotechnology stands out as a key tool to drive sustainability in farming. Its use in processes such as nanoformulation, nanoencapsulation, and the synthesis of nanomaterials has opened new possibilities for achieving targeted and regulated release of various active compounds in plants (Saritha *et al.*, 2022). The growing interest in updating and optimizing agricultural practices has led to the implementation of nanoscale systems, such as nanofertilizers, nanopesticides, nanoherbicides, and nanosensors. These technologies have shown a positive effect on crop productivity and establishment (Rajput *et al.*, 2021), thanks to several mechanisms of action, with improved nutrient uptake efficiency being one of the most significant.

Nanoparticle-based systems greatly enhance the absorption of essential nutrients in plants (Mittal *et al.*, 2020). Their small size increases surface area contact and facilitates penetration through roots, while also allowing greater retention within plant tissues (Chugh *et al.*, 2021). Likewise, applying fertilizers or biostimulants in nanoform improves the uptake of elements such as nitrogen and phosphorus, reducing the number of applications required and thereby decreasing the impact on natural nutrient cycles (Rani *et al.*, 2024).

In the agri-food sector, nanotechnology also plays a fundamental role, particularly in mitigating climate change. Studies such as those of Haider *et al.* (2024) and Quintarelli *et al.* (2024) have shown that these technologies can contribute to environmental protection by reducing compound leaching, toxicity, pollution, excessive use of natural resources, greenhouse gas emissions, and waste generation. One of its main benefits is the reduction of water contamination. Thanks to their physicochemical properties, nanoparticles can be incorporated into slow-release systems, minimizing

both evaporation and water source pollution. This helps maintain higher soil moisture availability for plants, reducing the need for frequent irrigation (López-Maldonado, 2023). Such a feature is especially relevant in arid or water-scarce regions, as highlighted by the UN (2024) in relation to SDG 6, which focuses on efficient water management.

Another significant contribution of nanotechnology is the more precise and effective control of pests and crop diseases. The use of nanomaterials in phytosanitary protection represents an innovative approach that specifically targets harmful organisms such as bacteria or insects, while producing fewer negative environmental impacts compared to conventional techniques. These nanoparticles can be engineered to target specific pests, penetrate their cells, disrupt metabolism, or induce mortality (López-Treviño *et al.*, 2021; Rajput *et al.*, 2021; Hernández-Díaz *et al.*, 2021). Additionally, they can stimulate plant defense responses, strengthening natural resistance (Upadhyay *et al.*, 2025; Francis *et al.*, 2024; Mishra *et al.*, 2022). Controlled-release systems also allow gradual and localized application of compounds, which significantly reduces agrochemical use and, consequently, their environmental impact. However, uncertainties remain regarding the long-term effects and safety of these technologies when used extensively.

From a technical standpoint, one of the main barriers lies in the heterogeneity and variability of agro-industrial residues, both in composition and quantity. This variability complicates the standardization of biotechnological processes and may affect the efficiency and quality of derived products such as biofertilizers, bioplastics, or biofuels. Moreover, many emerging technologies are still in experimental or pilot phases, which creates uncertainty in scalability, operational stability, and associated costs (Singh *et al.*, 2022).

Economically, the initial costs of implementing innovative technologies are often high, especially for small- and medium-sized agro-industrial producers (Oiganji *et al.*, 2025; Petrunenko *et al.*, 2021). Investments in infrastructure, training, maintenance, and technological adaptation may exceed their financial capacity. Likewise, the lack of economic incentives, subsidies, or specific financing mechanisms hinders the adoption of such solutions, keeping a gap between research and practical application.

On the social side, resistance to change and lack of adequate information among producers, workers, and rural communities constitute significant obstacles (Akimbekova *et al.*, 2025). Adopting new technologies requires training and a cultural shift toward sustainable practices, which are not always present. Negative perceptions or distrust toward unfamiliar innovations may hinder implementation, as does the absence of collaboration networks and technical support (Yugsi *et al.*, 2024). The regulatory and political framework also presents important barriers. In many countries, the lack of clear regulations, fiscal incentives, or specific policies for sustainable agro-industrial waste management limits the development of innovative projects (Ovalle *et al.*, 2025).

Finally, integration and collaboration among different actors in the agro-industrial value chain (producers, industry, government, academia, and civil society) remain a fundamental challenge. The lack of synergies, effective communication, and collaborative projects limits technology transfer and the joint implementation of solutions that maximize waste utilization.

CONCLUSIONS

In the face of growing challenges such as climate change, resource scarcity, and increasing pressure on production systems, this work confirms that the application of circular economy principles to the valorization of agro-industrial residues represents a key strategy for advancing toward more sustainable and resilient production models, in line with the objectives established. Throughout the analysis, it is demonstrated that the valorization of these residues not only reduces environmental impacts but also extends the life cycle of materials and generates high value-added inputs, thereby strengthening the efficiency and competitiveness of the agro-industrial sector.

Furthermore, the study highlights the role of emerging technologies, such as nanotechnology, as innovative tools for transforming residues into products with strategic applications, representing a significant contribution to the body of knowledge on sustainable technological solutions. Complementarily, the inclusion of small-scale producers in these value chains is emphasized as a central element for promoting rural development, social equity, and the local appropriation of innovation, aligning with the integrated approach proposed in the objectives of this work.

Finally, it is concluded that the consolidation of this model requires effective coordination among public policies, economic incentives, accessible financing, and technology transfer mechanisms, as well as the establishment of strong partnerships among the public, private, academic, and community sectors. In this context, the work underscores that fostering a culture of sustainability and waste valorization through education, awareness-raising, and the active participation of all stakeholders is essential to achieving a structural and lasting change capable of scaling from the local to the global level.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

REFERENCES

- Abdulla, Shefath. 2020. Study on livestock by-products & waste materials management practice at some selected slaughter houses in Dhaka City. (Doctoral dissertation, Department of animal production & management).
- Acosta, E.I., Murillo, C.A. and Ruiz, R. 2020. Factors affecting the competitiveness of agricultural enterprises in the Yaqui Valley, Sonora, Mexico. *Revista Espacios*. 41: 165–177.
- Alcántara-Revilla, A.R., Mejía-Benavides, A., Chávez-García, S.C. and Castillo-Llerena, D.E. 2022. Utilization of agro-industrial residues and their impact on the environment. *Revista Científica OGOLL*. 2: e29. <https://doi.org/10.54655/ogoll.v2i2.29>
- Almeida, B.P., Pavão, L.F.S., de Farias, M.S., Nicolodi, N.M., Petry, M.T., Leal, M.M., Coradi, P.C., de Souza, V.L., Queirós, M.S., Furtado, G.F., Tres, M.V. and Zabet, G.L. 2025. Agricultural biomass as a resource for biomaterials, biofertilizers, and bioproducts: A systematic review. *Agrochemicals*. 4(4): 23. <https://doi.org/10.3390/agrochemicals4040023>
- Akimbekova, G., Espolov, T., Baimukhanov, A., Tazhibayeva, R. and Kontselidze, N. 2025. Digital transformation in agro-industrial complex: Technological innovations for sustainable development. In *International Conference Innovation in Engineering* (pp. 412-433). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-94223-5_36
- Anacona, M.Á. and Piamba, M.E.U. 2023. Solid Waste and environmental pollution of La Yunguilla Creek at the Venecia agro-industrial technical educational institution, main Campus. *Ciencia Latina: Multidisciplinary Scientific Journal*. 7: 90–110. https://doi.org/10.37811/cl_rcm.v7i4.6850
- Arun, K.B., Madhavan, A., Sindhu, R., Binod, P., Pandey, A. and Sirohi, R. 2020. Remodeling agro-industrial and food wastes into value-added bioactives and biopolymers. *Industrial Crops and Products*. 154: 112621. <https://doi.org/10.1016/j.indcrop.2020.112621>
- Asma, U., Morozova, K., Ferrentino, G. and Scampicchio, M. 2023. Apples and apple by-products: antioxidant properties and food applications. *Antioxidants*. 12(7): 1456. <https://doi.org/10.3390/antiox12071456>
- Ayilara, M.S., Olanrewaju, O.S., Babalola, O.O. and Odeyemi, O. 2020. Waste management through composting: Challenges and potentials. *Sustainability*. 12(11): 4456. <https://doi.org/10.3390/su12114456>
- Balakrishnan, D. 2024. Exploring the potential of sugarcane vinasse for biogas and biofertilizer Production: A catalyst for advancing the bioeconomy. *Sustainable Energy Technologies and Assessments*. 61: 103474. <https://doi.org/10.1016/j.seta.2023.103474>
- Bravo, F.I., Calvo, E., López-Villalba, R.A., Torres-Fuentes, C., Muguerza, B., García-Ruiz, A. and Morales, D. 2023. Valorization of chicken slaughterhouse byproducts to obtain antihypertensive peptides. *Nutrients*. 15(2): 457. <https://doi.org/10.3390/nu15020457>
- Campos-Rodríguez, J., Acosta-Coral, K., Moreno-Rojas, C. and Paucar-Menacho, L. M. 2023. Passion fruit (*Passiflora edulis*): Nutritional composition, bioactive compounds, by-product utilization, biocontrol, and organic fertilization in cultivation. *Scientia Agropecuaria*. 14: 479–497. <http://dx.doi.org/10.17268/sci.agropecu.2023.040>
- Chaudhary, P., Singh, S., Chaudhary, A., Sharma, A. and Kumar, G. 2022. Overview of biofertilizers in crop production and stress management for sustainable agriculture. *Frontiers in Plant Science*. 13: 930340. <https://doi.org/10.3389/fpls.2022.930340>
- Chamorro, F., Carpena, M., Fraga, M., Echave, J., Rajoka, M., Barba, F., Cao, H., Xiao, J., Prieto, M.A. and Simal J. 2022. Valorization of kiwi agricultural waste and industry by-products by recovering bioactive compounds and applications as food additives: A circular economy model. *Food Chemistry*. 370: 131315.

- Choudhary, P., Pathak, A., Kumar, P., S, C. and Sharma, N. 2024. Commercial production of bioplastic from organic waste-derived biopolymers viz-a-viz waste treatment: A minireview. *Biomass Conversion and Biorefinery*. 14(10): 10817–10827. <https://doi.org/10.1007/s13399-022-03145-1>
- Chugh, G., Siddique, K.H. and Solaiman, Z.M. 2021. Nanobiotechnology for agriculture: Smart technology for combating nutrient deficiencies with nanotoxicity challenges. *Sustainability*. 13(4): 1781. <https://doi.org/10.3390/su13041781>
- Daniel, A.I., Fadaka, A.O., Gokul, A., Bakare, O.O., Aina, O., Fisher, S., Burt A.F., Mavumengwana V., Keyster M. and Klein, A. 2022. Biofertilizer: the future of food security and food safety. *Microorganisms*. 10(6): 1220. <https://doi.org/10.3390/microorganisms10061220>
- Dave, N. and Hebbale, D. 2025. The prospect of bamboo and non-fodder rice husk for sustainable bioethanol production. *Environmental Science and Pollution Research*. 32(14): 9236–9249. <https://doi.org/10.1007/s11356-025-36271-0>
- Delgado, R.A.G., Muñoz, J.S.I. and Dávila, W.E.C. 2025. Poultry farming and technical training in rural areas. *University and Society*. 17(4): e5298–e5298.
- Díaz Montes, E. 2022. Agro-food waste: What is it? who generates it? and why is it valuable?. *Frontera Biotecnológica*. 23. <https://www.revistafronterabiotecnologica.cibatlaxcala.ipn.mx/volumen/vol23/pdf/vol-23-2.pdf>
- Ebrahimian, F., Denayer, J.F. and Karimi, K. 2022. Potato peel waste biorefinery for the sustainable production of biofuels, bioplastics, and biosorbents. *Bioresource Technology*. 360: 127609. <https://doi.org/10.1016/j.biortech.2022.127609>
- Ejaz, U., Rashid, R., Ahmed, S., Narejo, K.K., Qasim, A., Sohail, M., Ali S.T., Althakafy, J.T., Alanazi, A.K., Abo-Dief, H.M. and Moin, S.F. 2023. Synthesis of methylcellulose-polyvinyl alcohol composite, biopolymer film and thermostable enzymes from sugarcane bagasse. *International Journal of Biological Macromolecules*. 235: 123903. <https://doi.org/10.1016/j.ijbiomac.2023.123903>
- FAO, Food and Agriculture Organization of the United Nations. 2023. Livestock Accounts for 12% of Greenhouse Gas Emissions. Rome, Italy. Accessed June 25, 2025. Available at: <https://www.fao.org/republica-dominicana/noticias/detail-events/es/c/1675383/#:~:text=La%20ganader%C3%ADa%20representa%2012%25%20de%20las%20emisiones%20de%20gases%20con%20efecto%20invernadero,-08%2F12%2F2023&text=08%2F12%2F2023-,La%20ganader%C3%ADa%20representa%2012%25%20de%20las%20emisiones%20de%20gases%20con,advirti%C3%B3%20el%20viernes%20la%20FAO.>
- Fallah Nosratabad, A. and Khoshru, B. 2024. Potentials and challenges of biofertilizers in sustainable agriculture. *Journal of Sol Biology*. 12(1): 19–63. <https://doi.org/10.22092/sbj.2024.366090.265>
- FIRA, Trust Funds Established in Relation to Agriculture. 2024. Agri-Food Outlook 2024, Chicken Meat. Directorate of Economic and Sectoral Research and Evaluation. Sector Analysis Subdirectorato. Government of Mexico, Mexico.
- FIRA, Trust Funds Established in Relation to Agriculture. 2024a. Agri-Food Outlook 2024, Beef. Directorate of Economic and Sectoral Research and Evaluation. Sector Analysis Subdirectorato. Government of Mexico, Mexico.
- FIRA, Trust Funds Established in Relation to Agriculture. 2024b. Agri-Food Outlook 2024, Pork. Directorate of Economic and Sectoral Research and Evaluation. Sector Analysis Subdirectorato. Government of Mexico, Mexico.
- Francis, D.V., Asif, A. and Ahmed, Z.F.R. 2024. Nanoparticle-enhanced plant defense mechanisms harnessed by nanotechnology for sustainable crop protection. *Nanoparticles in Plant Biotic Stress Management*. 451–491. https://doi.org/10.1007/978-981-97-0851-2_19
- Galanakis, C.M. 2022. Sustainable applications for the valorization of cereal processing by-products. *Foods*. 11(2): 241. <https://doi.org/10.3390/foods11020241>
- Gupta, S. and Gupta, K. 2020. Bioaccumulation of pesticides and its impact on biological systems. *Pesticides in crop production: physiological and biochemical action*, 55–67. <https://doi.org/10.1002/9781119432241.ch4>
- Haider, H. U., Arshad, E., Amir, M. A., Zafar, N., Akhtar, I., Ahmad, M. T., Saeed K., Khan M. J. and Ali, M. Integrating nanotechnology and bacteria-based remediation: A synergistic approach to mitigating climate change and soil degradation in agriculture.
- Hernández-Díaz, J.A., Garza-García, J.J., Zamudio-Ojeda, A., León-Morales, J.M., López-Velázquez, J.C. and García-Morales, S. 2021. Plant-mediated synthesis of nanoparticles and their antimicrobial activity against phytopathogens. *Journal of the Science of Food and Agriculture*. 101(4): 1270–1287. <https://doi.org/10.1002/jsfa.10767>
- Hussain, R., Aziz, A., Amin, R. and Khurshid, A. 2025. Development and characterization of polymeric-based biomaterial from agro-food waste: A sustainable and eco-friendly approach towards plastic pollution. *Current Pharmaceutical Biotechnology*. 26(4): 550–563. <https://doi.org/10.2174/0113892010304507240528064315>
- Imbernó Díaz, A.L. and Souto Anido, L. 2023. Innovation and circular economy, a perfect pair. *Economía y Desarrollo*. 167(2). Disponible en: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0252-85842023000200007&lng=es&nrm=iso
- Jayarathna, S. Andersson, M. and Andersson, R. 2022. Recent advances in starch-based blends and composites for bioplastics applications. *Polymers*. 14(21): 4557. <https://doi.org/10.3390/polym14214557>
- Jiménez-Robles, B.D., Mendoza-Sánchez, M., Abadía-García, L., Hernández-López, M.S., Cruz, D.A. and Huerta-Manzanilla, E.L. 2025. Sustainability and innovation: Harnessing the potential of agroindustrial whey and grape pomace residues in the rise of sports beverages. *Agroindustrial Science*. 15(2): 183–193. <https://doi.org/10.17268/agroind.sci.2025.02.10>
- Leyva-López, N., Lizárraga-Velázquez, C.E., Hernández, C. and Sánchez-Gutiérrez, E.Y. 2020. Exploitation of agro-industrial waste as potential source of bioactive compounds for aquaculture. *Foods*. 9(7): 843. <https://doi.org/10.3390/foods9070843>
- López-Escobar, L.A., Olivo-Alanís, D.S. and Nava-Valente, N. 2025. Coffee (Coffea) byproducts: environmental challenges and opportunities for the bioeconomy. *Trends in Renewable Energy and Sustainability*. 4(1): 45–49. <https://doi.org/10.56845/terys.v4i1.422>
- López-Maldonado, V. 2023. Use of nanotechnology in different production systems. *Milenaria, Ciencia y Arte*. 22: 19–22. Accessed January 22, 2025. Available at: <https://www.milenaria.umich.mx/ojs/index.php/milenaria/article/view/410/201>

- López-Treviño, E.A., Sandoval-Rangel, A., Mendoza, A.B., Ortiz, H.O., Pliego, G.C. and de la Fuente, M.C. 2021. Selenium nanoparticles absorbed in chitosan-polyvinyl alcohol hydrogels in the production of grafted cucumber. *Revista Mexicana de Ciencias Agrícolas*. 26: 159–169. <https://doi.org/10.29312/remexca.v0i26.2946>
- Llanes, E.E.D. and Pérez, A.A.F. 2024. Agroindustrial residues as sources of antioxidant compounds. *Revista de Ingeniería en Industrias Alimentarias*. 1: 26–34.
- Marchan-Solier, C.E., Zorrilla-Crespo, V.A., Cardenas-Quispe, M.A. and Pacheco, A. 2021. Pollution from urban solid waste: case of the Occochaca community, Huanta, Peru, 2021. *Scientific Research Journal CIDI*. 1(1): 1–14. <https://doi.org/10.53942/srjcid.v1i1.39>
- Mateus R., Kawata S., Sivieri K. and Maróstica J. 2022. Agro-industrial by-products: Valuable sources of bioactive compounds, *Food Research International*: 152: 110871, <https://doi.org/10.1016/j.foodres.2021.110871>
- Melendez, J.R. 2023. Circular agro-food economy: Managerial trends for the sustainability of production systems. *Revista Venezolana de Gerencia: RVG*. 28(9): 664–684. <https://doi.org/10.52080/rvgluz.28.e941>
- Mexican Meat Council. 2022a. Meat Production in Mexico in 2022. Mexican Meat Council. Accessed May 16, 2025. Available at: <https://comecarne.org/produccion-carnica-de-mexico-en-2022/>
- Minjarez, J.M.Á.C., León, E.A.V., Lua, Y.E., Valdez, F.J.M. and Sancén, G.C. 2025. Free radical scavenging capacity of phenolic compounds recovered from agroindustrial residues. *Investigación y Ciencia: de la Universidad Autónoma de Aguascalientes*. 94: 4.
- Mishra, P., Kumari, S., Saini, P. and Meena, R.K. 2022. Role of nanotechnology in management of plant viral diseases. *Materials Today: Proceedings*. 69: 1–10. <https://doi.org/10.1016/j.matpr.2022.06.355>
- Mittal, D., Kaur, G., Singh, P., Yadav, K. and Ali, S.A. 2020. Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*. 2: 579954. <https://doi.org/10.3389/fnano.2020.579954>
- Mohanta, Y.K., Mishra, A.K., Lakshmayya, N.S.V., Panda, J., Thatoi, H., Sarma, H., Sarvesh R., Kwang-Hyun B. and Mishra, B. 2025. Agro-waste-derived bioplastics: Sustainable innovations for a circular economy. *Waste and Biomass Valorization*. 1–25. <https://doi.org/10.1007/s12649-025-03070-0>
- Moisés, J., Martínez, J.M., Duval, M.E. and Galantini, J.A. 2022. Chemical and spectrometric characterization of agro-industrial residues for their potential use as organic amendments. *Soil Science*. 40(2): 227–236.
- Morseletto, P. 2022. Environmental principles for modern sustainable economic frameworks including the circular economy. *Sustainability Science*. 17(5): 2165–2171. <https://doi.org/10.1007/s11625-022-01208-w>
- Mubarak Alqahtani, A. 2024. Sweet sorghum and bagasse: a comprehensive review of feedstock traits, conversion processes, and economic viability for bioethanol and biogas production. *Biofuels*. 15(5): 575–585. <https://doi.org/10.1080/17597269.2023.2261789>
- Muhie, S.H. 2022. Novel approaches and practices to sustainable agriculture. *Journal of Agriculture and Food Research*. 100446: 10. <https://doi.org/10.1016/j.jafr.2022.100446>
- Muñoz-Henández, J.A., Sánchez-Jiménez, C.A., Roa-Acosta, D.F., Bravo-Gómez, J.E., Solanilla-Duque, J.F. and Muñoz-Henández, H. 2023. Waste processes to obtain biogas and bioethanol. In *Microbial Biodiversity, Biotechnology and Ecosystem Sustainability*. 483–531. Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-4336-2_21
- Nair, L.G., Agrawal, K. and Verma, P. 2022. An overview of sustainable approaches for bioenergy production from agro-industrial wastes. *Energy Nexus*. 6: 100086. <https://doi.org/10.1016/j.nexus.2022.100086>
- Narvaez, A.J.B., García, A.V., Rodríguez, I. and Muñoz, J.E. 2024. The potential of bioactive compounds from fruit and vegetable residues in the food industry: A review. *Revista de Ciencias*. 27(2): 14046–14046. <https://doi.org/10.25100/rc.v27i2.14046>
- National Poultry Union. 2021. Industry – National Poultry Union. Available at: <https://una.org.mx/industria/#:~:text=La%20industria%20av%C3%ADcola%20mexicana%20es,particip%C3%B3%20con%2036.8%20por%20ciento>
- Nigam, S., Das, A.K., Matkawala, F. and Patidar, M.K. 2022. An insight overview of bioplastics produced from cellulose extracted from plant material, its applications and degradation. *Environmental Sustainability*. 5(4): 423–441. <https://doi.org/10.1007/s42398-022-00248-3>
- Nurzyńska-Wierdak, R. 2023. Phenolic compounds from new natural sources—Plant genotype and ontogenetic variation. *Molecules*. 28(4): 1731. <https://doi.org/10.3390/molecules28041731>
- Ogbu, C.C. and Okey, S.N. 2023. Agro-industrial waste management: the circular and bioeconomic perspective. *Agricultural Waste-New Insights*. <https://doi.org/10.5772/intechopen.109181>
- Oigani, E., Igbadun, H., Amaza, P.S. and Lenka, R.Z. 2025. Innovative technologies for improved water productivity and climate change mitigation, adaptation, and resilience: a review. *Journal of Applied Sciences and Environmental Management*. 29(1): 123–136. <https://doi.org/10.4314/jasem.v29i1.17>
- Ordaz, S., Abadía, G., Femat, D. and Mendoza, S. 2022. Learning to revalorize by-products and their application in meat products. *EPISTEMUS*. 16: 33.
- Orozco, S., Espino, J. and Rivero, M. 2024. Materials from avocado agroindustrial residues for contaminant removal in water. *Materiales Avanzados*. 40: 79–83. <https://doi.org/10.22201/iim.rma.2024.40.35>
- Ovalle Másmela, J.C., Zambrano, M.A., Gómez, C.L., Acevedo, W.F., Salazar, G.A., Flórez, M.D. and Uribe, G.C. 2025. First Bulletin: Emerging technologies in the agricultural sector. Observatory of Science, Technology, and Innovation of the Colombian Agricultural Sector (OCTIAGRO). Unit of Rural Agricultural Planning (UPRA). Colombian Corporation for Agricultural Research (AGROSAVIA), 1–37. <https://doi.org/10.21930/agrosavia.boletin.2025.3>
- Pagliuso, D., Grandis, A., de Castro Juraski, A., Azzoni, A.R., Maria de Lourdes, T.M., Villanueva, H.H., Krieger, F.G. and Buckeridge, M.S. 2025. Fingerprinting agro-industrial waste: Using polysaccharides from cell walls to biomaterials. Preprints. 2025051825 <https://doi.org/10.20944/preprints202505.1825.v1>

- Palacios, L.E.S., Durazno, L.E.P. and Sandoval, B.L.R. 2025. Use of smart sensors in agriculture. *Polo del Conocimiento*, 10(9): 310–322.
- Petrunen, I., Pohrishchuk, O., Plotnikova, M., Zolotnytska, Y. and Dligach, A. 2021. Development of small farms in the agro-industrial complex. *International Journal of Computer Science & Network Security*. 21(3): 287–294. <https://doi.org/10.22937/IJCSNS.2021.21.3.37>
- Preciado-Saldaña, A.M., Ruiz, C., Villegas, O., Domínguez, A. and González, A. 2022. Utilization of by-products from the agro-food industry: An approach to circular economy. *Revista Iberoamericana de Tecnología Postcosecha*. 23(2): 92–99. <https://www.redalyc.org/journal/813/81373798002/html/>
- Quintarelli, V., Ben Hassine, M., Radicetti, E., Stazi, S.R., Bratti, A., Allevato, E., Mancinelli, R., Jamal, A., Ahsan, M., Mirzaei, M. and Borgatti, D. 2024. Advances in nanotechnology for sustainable agriculture: A review of climate change mitigation. *Sustainability*, 16(21), 9280. <https://doi.org/10.3390/su16219280>
- Rajput, V.D., Singh, A., Minkina, T.M., Shende, S.S., Kumar, P., Verma, K.K., Bauer T.V., Gorobtsova O., Deneva S. and Sindireva, A. 2021. Potential applications of nanobiotechnology in plant nutrition and protection for sustainable agriculture. *Nanotechnology in plant growth promotion and protection: recent advances and impacts*. 79–92. <https://doi.org/10.1002/9781119745884.ch5>
- Rani, D.V., Singh, A. and Jakhwal, R. 2024. Nanobiostimulants for improving plant roots regulations and nutrient uptake. *Nanobiostimulants: Emerging Strategies for Agricultural Sustainability*, 457–475. https://doi.org/10.1007/978-3-031-68138-7_20
- Rojas, L.F., Zapata, P. and Ruiz-Tirado, L. 2022. Agro-industrial waste enzymes: Perspectives in circular economy. *Current opinion in green and sustainable chemistry*. 34: 100585. <https://doi.org/10.1016/j.cogsc.2021.100585>
- Romero, G., Montalvo, G., Hernández, G., Soto, D., Becerra, V. and García, M. 2022. Bioactivity of peptides obtained from poultry by-products: A review. *Food Chemistry: X*, 13: 100181. <https://doi.org/10.1016/j.fochx.2021.100181>
- Romero-López, A.R. 2021. The roles of birds in small-scale poultry production: the case of a rural community in Hidalgo, Mexico. *Mexican Journal of Animal Sciences*. 12(1): 217–237. <https://doi.org/10.22319/rmcp.v12i1.5088>
- SADER (Secretariat of Agriculture and Rural Development). 2021. Poultry Sector, Strategic in Achieving Food Self-Sufficiency Goals in the Country: <https://www.gob.mx/agricultura/prensa/sector-avicola-estrategico-en-las-metas-de-autosuficiencia-alimentaria-en-el-pais-agricultura?idiom=es#:~:text=Este%20sector%20productivo%20brinda%20a,55%C2%B0%20Congreso%20Nacional%20de>
- SADER (Secretariat of Agriculture and Rural Development). 2022. The National Meat Sector, an Example of Productivity, Integration, and Innovation: <https://www.gob.mx/agricultura/prensa/el-sector-carnico-nacional-ejemplo-de-productividad-integracion-e-innovacion-agricultura>
- Salazar-López, N.J., Enríquez-Valencia, S.A., Zuñiga Martínez, B.S. and González-Aguilar, G.A. 2023. Agro-industrial waste as a source of nutrients and phenolic compounds. *Epistemos (Sonora)*. 17(34): 60–69. <https://doi.org/10.36790/epistemos.v17i34.265>
- Sánchez, S.P.A. 2024. Characterization of bioactive peptides derived from plant proteins and their antioxidant effect in functional foods in Ecuador. *Ibero-American Journal of Health Science Research*. 4(2): 270–277. <https://doi.org/10.56183/iberojhr.v4i2.683>
- Saritha, G.N.G., Anju, T. and Kumar, A. 2022. Nanotechnology-big impact: How nanotechnology is changing the future of agriculture?. *Journal of Agriculture and Food Research*. 10: 100457. <https://doi.org/10.1016/j.jafr.2022.100457>
- SENASICA (National Service for Health, Safety, and Agri-Food Quality). 2022. Risks in the National Poultry Sector and Economic Impacts on Poultry Production Costs due to H5N1 Avian Influenza Outbreaks in Mexico. SENASICA. https://dj.senasica.gob.mx/Contenido/files/2023/abril/RiesgosenlaaaviculuranacionalenimpactoseneconomicosenloscostosdeproduccionavicolaenlosbrotesdeIAH5N1enMéxico_6d95188b-1d2c-4c40-ac94-33f060630990.pdf
- Senthilkumar, K., Naveen Kumar, M., Chitra Devi, V., Saravanan, K. and Easwaramoorthi, S. 2020. Agro-industrial waste valorization to energy and value added products for environmental sustainability. In: Praveen Kumar, R., Bharathiraja, B., Katak, R., Moholkar, V. (eds) *Biomass Valorization to Bioenergy*. Energy, Environment, and Sustainability. Springer, Singapore. 1–9. https://doi.org/10.1007/978-981-15-0410-5_1
- SEMARNAT (Secretariat of Environment and Natural Resources). 2023. Draft Mexican official standard PROY-NOM-170-SEMARNAT-2017, air pollution. Maximum permissible emission limits from steam generators using sugarcane bagasse as fuel. Accessed June 19, 2025. Available at: https://www.dof.gob.mx/normasOficiales/6844/semarnat11_C/semarnat11_C.html
- SIAP (Agri-Food and Fisheries Information Service). 2023a. Agri-Food Expectations 2023. Available at: <https://www.gob.mx/siap/articulos/como-cerramos-el-ano-agricola-2022-y-que-esperamos>
- SIAP (Agri-Food and Fisheries Information Service). 2022. Agri-Food Overview 2022. Secretariat of Agriculture and Rural Development, 41.
- Silva, S.D.O., Mafra, A.K.C., Pelissari, F.M., Rodrigues de Lemos, L. and Molina, G. 2025. Biotechnology in agro-industry: Valorization of agricultural wastes, by-products and sustainable practices. *Microorganisms*. 13(8): 1789. <https://doi.org/10.3390/microorganisms13081789>
- Singh, R.P., Handa, R. and Manchanda, G. 2021. Nanoparticles in sustainable agriculture: An emerging opportunity. *Journal of Controlled Release*. 329: 1234–1248. <https://doi.org/10.1016/j.jconrel.2020.10.051>
- Shah, A.M., Zhang, H., Shahid, M., Ghazal, H., Shah, A.R., Niaz, M., Naz T., Ghimmire K., Goswami N., Shi W., Xia D. and Zhao, H. 2025. The vital roles of agricultural crop residues and agro-industrial by-products to support sustainable livestock productivity in subtropical regions. *Animals*. 15(8): 1184. <https://doi.org/10.3390/ani15081184>
- Stegmayer, M.I., Fernandez, L.N., Alvarez, N.H., Olivella, L., Gutiérrez, H.F., Favaro, M.A. and Derita, M.G. 2021. Essential oils from native plants for the control of phytopathogenic fungi affecting fruit trees. *Fave. Agricultural Sciences Section*. 20(1): 317–329.
- Tiwari, A.K. and Pal, D.B. 2022. Nutrients contamination and eutrophication in the river ecosystem. In *Ecological*

- significance of river ecosystems (pp. 203-216). Elsevier. <https://doi.org/10.1016/B978-0-323-85045-2.00001-7>
- Trujillo Echeverría, L. 2023. Product innovation in waste minimization and productivity improvement in a company of the meat industry (Master's thesis).
- Tseng, M.L., Chiu, A.S., Liu, G. and Jantaralolica, T. 2020. Circular economy enables sustainable consumption and production in multi-level supply chain system. *Resources, Conservation and Recycling*. 154: 104601. <https://doi.org/10.1016/j.resconrec.2019.104601>
- UNA (National Union of Poultry Farmers). 2025. Compendium of Economic Indicators of the Poultry Sector 2025. Mexico City. Accessed: January 15, 2024. Available at: <https://una.org.mx/indicadores-economicos-2/>
- United Nations (UN). 2024. Desertification and Drought Day 2024. Rome. Accessed March 17, 2025. Available at: <https://www.unccd.int/es/news-stories/press-releases/desertification-and-drought-day-2024-united-land-our-legacy-our-future>
- Upadhyay, S.K., Hidangmayum, A., Jain, D. and Dwivedi, P. 2025. Mechanisms and applicability of nanotechnology-mediated beneficial microbes in mitigation of salinity stress in plants. *Plant Physiology and Biochemistry*. 110306. <https://doi.org/10.1016/j.plaphy.2025.110306>
- Urrialde, R., Gómez-Cifuentes, A., Pintos, B., Gómez-Garay, M.A. and Cifuentes, B. 2022. Plant-derived bioactive compounds: development of new foods. *Nutrición Hospitalaria*. 39(SPE3): 8–11. <https://dx.doi.org/10.20960/nh.04302>
- Vicente-Zurdo, D., Gómez-Mejía, E., Morante-Zarcero, S., Rosales-Conrado, N. and Sierra, I. 2025. Analytical strategies for green extraction, characterization, and bioactive evaluation of polyphenols, tocopherols, carotenoids, and fatty acids in agri-food bio-residues. *Molecules*. 30(6): 1326. <https://doi.org/10.3390/molecules30061326>
- Villegas-Henao, G.A., Posada-Ochoa, S.L. and Rosero-Noguera, R. 2024. Effect of carbohydrate source on energy-nitrogen balance and methane emissions in lactating dairy cows. *Revista de Investigaciones Veterinarias del Perú*. 35: 2.
- Yin, J., Xie, M., Yu, X., Feng, H., Wang, M., Zhang, Y. and Chen, T. 2024. A review of the definition, influencing factors, and mechanisms of rapid composting of organic waste. *Environmental Pollution*. 342: 123125. <https://doi.org/10.1016/j.envpol.2023.123125>
- Yugsi, A.E.P., Tulcán, E.A.T. and Lagla, G.A.F. 2024. Emerging technologies for SMEs in the cantons of Sigchos and Latacunga. *Visionario Digital*. 8(3): 118–137. <https://doi.org/10.33262/visionariodigital.v8i3.3133>
- Zhou, J., You, M., Xu, J., Jin, Y., Li, D., Xu, Z. and Chen, C. 2024. All-cellulose bioplastics from waste wood particles. *ACS Sustainable Chemistry & Engineering*. 12: 9550–9557, 25. <https://doi.org/10.1021/acssuschemeng.4c03425>