ORIGINAL RESEARCH ARTICLE

Sustainable utilization of agro-industrial fruit and vegetable waste in industry: potential to produce bioactives and biomaterials

Aprovechamiento sostenible de residuos agroindustriales de frutas y vegetales en la industria: potencial para producir bioactivos y biomateriales

Aproveitamento sustentável de resíduos agroindustriais de frutas e vegetais na indústria: potencial para produção de bioativos e biomateriais

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Abstract

Background: Sustainable utilization of agro-industrial waste has been established as a key strategy for addressing environmental and economic challenges. **Objective:** This study is focused on identifying how agro-industrial waste from fruits and vegetables is utilized globally. **Methods:** To achieve this, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) method was employed, which facilitates the conduct of systematic reviews and meta-analysis. This approach allows for a comprehensive and structured literature search, ensuring transparency and reproducibility in the review process. **Results:** The study's results revealed that 29.9% of the waste is used through fermentation processes, while 16% is utilized via supercritical fluid extraction (SFE). **Conclusions:** These findings conclude that sustainable utilization of agro-industrial waste, through innovative methods such as fermentation and supercritical fluid extraction, provides effective solutions to environmental and economic challenges. These methods not only enable the conversion of waste into high-value products but also contribute to waste reduction and the promotion of a circular economy, aligning with global goals of waste reduction and resource optimization.

Keywords: *agro-industrial waste; bioactive; compounds; fermentation; supercritical fluid extraction.*

Resumen

Antecedentes: El aprovechamiento sostenible de residuos agroindustriales se ha establecido como una estrategia clave para enfrentar problemas ambientales y económicos. **Objetivo:** Este estudio se centró en identificar cómo se utilizan los residuos agroindustriales de frutas

y hortalizas a nivel global. **Métodos:** Para lograrlo, se empleó el método PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), que facilita la realización de revisiones sistemáticas y metaanálisis. Este enfoque permite llevar a cabo una búsqueda exhaustiva y estructurada de la literatura, garantizando la transparencia y reproducibilidad del proceso de revisión bibliográfica. **Resultados:** Los resultados del estudio revelaron que el 29.9% de los residuos se optimizan mediante procesos fermentativos, mientras que el 16% se aprovecha mediante la extracción con fluidos supercríticos (SFE). **Conclusiones:** El aprovechamiento sostenible de residuos agroindustriales, a través de métodos innovadores como la fermentación y la extracción con fluidos supercríticos, ofrece soluciones efectivas para los desafíos ambientales y económicos. Estos métodos no solo permiten la conversión de residuos en productos de alto valor, sino que también contribuyen a la reducción de desechos y al fomento de una economía circular, alineándose con los objetivos globales de reducción de residuos y optimización de recursos.

Palabras clave: *bioactivos; compuestos; extracción con fluidos supercríticos; fermentación; residuos agroindustriales.*

Resumo

Antecedentes: O aproveitamento sustentável de resíduos agroindustriais tem se consolidado como uma estratégia chave para enfrentar problemas ambientais e econômicos. **Objetivo:** Este estudo concentrou-se em identificar como os resíduos agroindustriais de frutas e hortaliças são utilizados em nível global. **Métodos:** Para isso, foi empregado o método PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), que facilita a realização de revisões sistemáticas e meta-análises. Essa abordagem permite uma busca exaustiva e estruturada da literatura, garantindo a transparência e a reprodutibilidade do processo de revisão bibliográfica. **Resultados:** Os resultados do estudo revelaram que 29,9% dos resíduos são otimizados por meio de processos fermentativos, enquanto 16% são aproveitados por meio da extração com fluidos supercríticos (SFE). **Conclusões:** Essas descobertas concluem que o aproveitamento sustentável de resíduos agroindustriais, por meio de métodos inovadores como a fermentação e a extração com fluidos supercríticos,

oferece soluções eficazes para os desafios ambientais e econômicos. Esses métodos não apenas permitem a conversão de resíduos em produtos de alto valor, mas também contribuem para a redução de desperdícios e para o incentivo a uma economia circular, alinhando-se aos objetivos globais de redução de resíduos e otimização de recursos.
Palavras-chave: *bioativos; compostos; extração com fluidos supercríticos; fermentação; resíduos agroindustriais.*

Introduction

The growing generation of agro-industrial waste from fruit and vegetable processing presents significant environmental and economic challenges. These residues contain valuable bioactive compounds, such as polyphenols and dietary fibers, which can be transformed into high-value products, including bioactives, biomaterials, biofuels, and bioplastics (Mirabella et al., 2014). The valorization of these by-products contributes to reducing environmental impact, fostering a circular economy, and minimizing dependency on fossil resources (Haque et al., 2023). However, a more holistic approach to utilization is needed, integrating technical efficiency with long-term economic and environmental sustainability (Rosen, 2012).

Sustainable utilization of agro-industrial residues has gained relevance as a solution to reduce waste and create value-added products. For example, potato starch can be thermally treated to produce flour, enhancing its application in animal feed, while banana peels, with a protein content of 16%, have been successfully incorporated into broiler chicken feed (Enriquez & Ojeda, 2020). Other notable applications include the conversion of sugarcane, coffee, and citrus residues into bioethanol, biogas, and essential oils, with the latter showing potential in pharmaceutical and cosmetic industries (Krzyżostan et al., 2024).

The intensification in the generation of agro-industrial waste derived from the processing of fruits and vegetables constitutes a critical environmental and economic challenge (Diaconeasa, 2022). Nevertheless, these wastes represent a significant source of bioactive compounds with high functional value, which can be transformed into bioproducts with industrial applications, favoring the implementation of circular economy models. In this framework, a systemic approach is required that integrates the technical efficiency of

recovery processes with long-term environmental and economic sustainability criteria. Eco-efficient extraction technologies, such as microwave-assisted extraction and the use of supercritical fluids, have demonstrated high effectiveness in obtaining antioxidant compounds with beneficial properties for human health and potential preventive effects against chronic diseases, while contributing to the mitigation of environmental impact (Sagar et al., 2018). Likewise, technological innovations such as the development of biodegradable packaging and the use of bioreactors for waste valorization reinforce the efficiency of agro-industrial by-product management systems and promote innovation in various productive sectors (Mirabella et al., 2014). This review emphasizes the importance of adopting sustainable practices for waste management, highlighting their environmental and economic benefits, and explores the potential of these residues to support global sustainability goals (Das et al., 2019). In this context, the present review aims to answer the following research question: What types of bioactive compounds can be recovered from agro-industrial waste of fruits and vegetables through eco-efficient extraction methods, and how can these bioproducts contribute to sustainable industrial applications and the reduction of environmental impact? To this end, the following specific objectives are proposed: i) to identify the most common types of agro-industrial waste derived from fruits and vegetables with potential for the recovery of bioactive compounds; ii) to analyze the main eco-efficient extraction techniques used in the valorization of these wastes; and iii) to evaluate the industrial applications of the obtained bioproducts and their contribution to environmental sustainability and the circular economy. This study provides a comprehensive view of the potential of agro-industrial residues, emphasizing the importance of their valorization to enhance sustainability and efficiency in industry (Galanakis, 2012). Against this background, the objective of this review is to identify and analyze global methods for the valorization of agro-industrial residues derived from fruits and vegetables, with particular emphasis on fermentation and supercritical fluid extraction (SFE) as the most prominent techniques.

Materials and methods

Figure 1 presents the methodological framework of this systematic review, which follows the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-

Analyses), an internationally recognized standard that ensures transparency, rigor, and reproducibility in systematic literature reviews. This methodology was structured into four key stages: identification, selection, eligibility, and inclusion, each designed to refine the search and focus specifically on global strategies for the valorization of agro-industrial residues from fruits and vegetables, with a particular emphasis on fermentation and supercritical fluid extraction (SFE) as leading techniques.

Identification: For the identification of relevant scientific literature, a systematic search was conducted in recognized academic databases, including Scopus, Web of Science, ScienceDirect, and SpringerLink, during the period from 2013 to 2024. The following search terms were used, combined using Boolean operators: ("agro-industrial waste" OR "fruit and vegetable residues") AND ("bioactive compounds" OR "antioxidants") AND ("eco-efficient extraction" OR "green technologies" OR "microwave-assisted extraction" OR "supercritical fluid extraction") AND ("bioproducts" OR "sustainable applications" OR "circular economy

Selection: The identified records were imported into EndNote and Microsoft Excel for data cleaning. Duplicate records were removed, and studies were screened based on preliminary criteria such as topic relevance, methodological quality, and direct connection to the valorization of agro-industrial waste. Articles not aligned with the focus on fermentation or SFE were excluded. The reasons for exclusion were documented to maintain methodological transparency.

Eligibility: In this phase, the remaining articles underwent detailed abstract and full-text analysis to verify their scientific contribution to the valorization of fruit and vegetable residues. Special attention was given to those exploring the extraction of bioactive compounds or bioproduct development via fermentation or SFE. Only studies presenting experimental or systematic data with clear methodologies and outcomes related to these processes were retained.

Inclusion: A total of 32 articles, published between 2010 and 2024, were finally included in the review. These met all inclusion criteria and offered high-quality evidence regarding the

application of fermentation and SFE in the context of agro-industrial residue valorization. The selected studies span diverse geographic regions and food systems, providing a global perspective aligned with the review's objective.

Data Processing and Analysis: The selected literature was organized and analyzed using EndNote to manage references and facilitate structured coding of relevant information. Data extraction focused on categorizing each study by country, source of agro-industrial waste, type of residue, extraction method (with emphasis on fermentation and SFE), type of bioproduct obtained, application, and recovery efficiency. This allowed for a comparative and thematic synthesis of global practices in fruit and vegetable residue valorization.

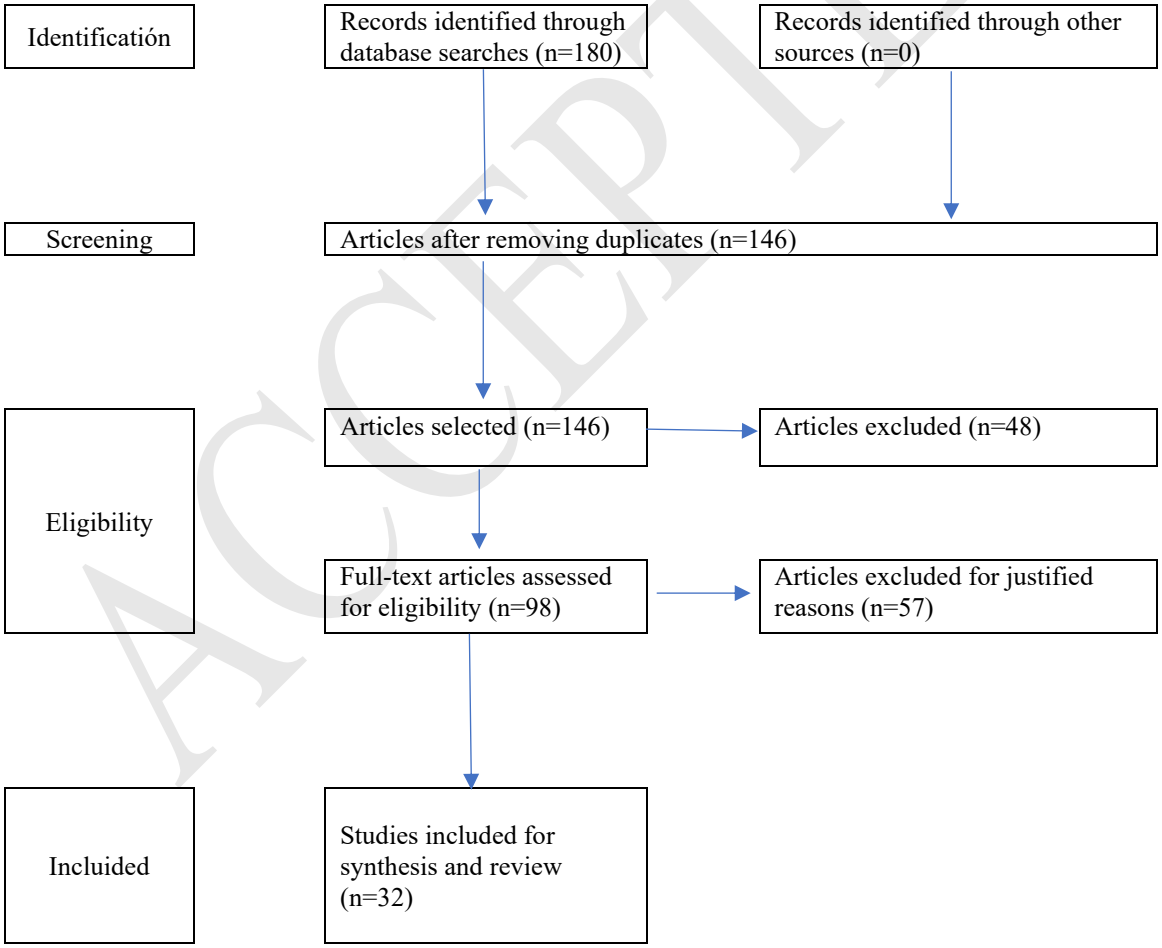

Figure 1. PRISMA Method Procedure.

Characterization of Variables

Table 1 organizes and describes the elements of the study on the utilization of agro-industrial fruit and vegetable waste in a structured manner. This characterization aims to facilitate the understanding of the technical and scientific approach of the study, as well as to guide the development of sustainable strategies for the valorization of agro-industrial by-products.

Table 1. Characterization of Key Variables in the Sustainable Valorization of Agro-Industrial Fruit and Vegetable Waste

Category	Variable	Characteristic	Applications
Agro-industrial Residues	Tipe of residues	By-products generated from the processing of fruits and vegetables.	Sugarcane bagasse, banana peels, citrus waste.
	Origin	Source of the residues.	Agro-industrial processing.
Extractions Methods	Fermentation	Conversion of lignocellulosic biomass to obtain enzymes or valuable metabolites.	Enzyme production, bioethanol.
	Supercritical Fluid Extraction (SFE)	Use of carbon dioxide in a supercritical state to extract bioactive compounds.	Polyphenols, antioxidants.
	Ultrasound-Assisted Extraction (UAE)	Use of ultrasonic waves to enhance the extraction of compounds.	Flavonoids, polyphenols
	Microwave-Assisted Extraction	Application of microwaves to release compounds from biomass	Carotenoids, dietary fibers.
Bioactive Compounds	Polyphenols	Phenolic compounds with antioxidant properties.	Found in fruit residues; used in supplements and preservatives.
	Flavonoids	Subclass of polyphenols with antioxidant, antifungal, and anti-inflammatory activities.	Extracted from peels and vegetable waste.
	Carotenoids	Liposoluble pigments with antioxidant and coloring properties.	Applications in functional foods and cosmetics.
Derived products	Bioethanol	Alcohol produced through the fermentation of biomass.	Substitute for fossil fuels.
	Bioplastics	Biodegradable polymers obtained from plant biomass.	Sustainable alternative to conventional plastics.
	Biofertilizers	Natural fertilizers produced from organic waste.	Used in sustainable agriculture; improve soil quality.

Results

Principal Agroindustrial Wastes in the Extraction of Bioactive Compounds

This table 2 provides a comprehensive overview of various countries and their respective sources of agro-industrial waste from fruits and vegetables. It highlights the types of residues, extraction methods employed, bioproducts obtained, and their applications. The references cited offer valuable insights into the optimization and effectiveness of these processes, demonstrating the potential for sustainable industrial applications and the promotion of a circular economy. The data underscores the importance of eco-efficient technologies in recovering bioactive compounds, which contribute to health improvement, disease prevention, and environmental impact mitigation.

Table 2. Agro-industrial residues and their utilization

Country	Source (Fruit/Vegetable)	Type of Residue	Extraction Method	Bioproduct Obtained	Application	Reference
Australia	Fruits/vegetables	Residual lignocellulosic biomass (60% optimization)	Fermentation	Lignocellulolytic enzymes (cellulases, xylanase) – 50% conversion	Bioethanol production, nutritional improvement of animal feed, biocontrol agents	Chukwuma et al., 2020
Chile	Cherimoya	Peels, pulp, processing residues (70% optimization)	Pressurized liquid extraction (PLE), supercritical fluid extraction (SFE)	Bioactive compounds such as polyphenols, flavonoids, carotenoids, tocopherols, and sterols – 80% recovery	Food industry (functional foods), health industry (pharmaceuticals and medicines), textile industry	Bustos, 2019
China	*Astragalus membranaceus* (stems and leaves)	Stems and leaves (50% optimization)	Ultrasound-assisted extraction (UAE)	Flavonoids with antioxidant and antifungal activity – 60% recovery	Natural antioxidant source for food applications	Gou et al, 2023
Ecuador	Various fruits and vegetables	Bagasse, rice molasses, corn stover, whey, citrus by-products, banana peels, horticultural waste (50% optimization)	Chemical-biological methods, bioenergetic processes, environmental treatment, pyrolysis, gasification, combustion, synthesis, hydrolysis, fermentation, product separation	Functional biofuels, bioplastics, cellulosic structures, biodegradable materials – 40% conversion	Biofuels, applications in food, cosmetic, pharmaceutical industries, bioplastics and biofuels production	Aguiar et al., 2022
USA	Various fruits and vegetables	Various organic residues (65% optimization)	Arrested anaerobic digestion (ADA)	Volatile fatty acids (VFAs) including acetic, propionic, and butyric acid – 55% yield	Sustainable production of biofuels and other high-value bioproducts	Zubairi et al., 2016
India	Various fruits	Peels, seeds, pulp (60% optimization)	Microwave-assisted extraction, enzymatic extraction, high hydrostatic pressure extraction	Phenolic compounds, antioxidants, dietary fibers – 75% recovery	Development of nutraceuticals, functional foods	Kainat et al., 2022

Country	Source (Fruit/Vegetable)	Type of Residue	Extraction Method	Bioproduct Obtained	Application	Reference
Malaysia	Apples, strawberries, tomatoes, onions	Peels, seeds, unwanted pulp (55% optimization)	Maceration, distillation, microwave-assisted extraction, supercritical fluid extraction	Polysaccharides, proteins, antioxidants, natural colorants – 65% yield	Edible films and coatings, natural food colorants, adsorbents	Aqilah et al., 2023
Mexico	*Agave tequilana*	Leaves (50% optimization)	Fermentation	Lactic acid – 60% conversion	Enzyme, bioplastics, and biofuel production	Martínez-Hernández et al., 2024
Portugal	Various fruits and vegetables	Seeds, peels (65% optimization)	Supercritical fluid extraction (SFE)	Bioactive compounds such as antioxidants and essential nutrients – 70% recovery	Dietary use, nutraceutical and cosmetic applications	Da Silva et al., 2016
Tunisia	*Citrus aurantium* L. var. *amara* Engl. (bitter orange)	Fruit peel (60% optimization)	Ultrasound-assisted extraction (UAE)	Extract rich in polyphenols (33.76 mg GAE/g DM) and flavonoids (75.50 mg NE/g DM) – 50% yield	Food industry, nutraceuticals, cosmetics	Abdallah et al., 2024

Predominance of Eco-efficient Techniques with High Recovery Efficiency

Among the methods applied for the utilization of agro-industrial waste, two techniques stand out with the highest usage percentage (20% each): fermentation and ultrasound-assisted extraction (UAE). Fermentation, used in countries such as Australia and Mexico, allows the biological conversion of lignocellulosic biomass and other organic residues into high-value products such as ethanol, enzymes, and lactic acid. This technique offers multiple advantages, including low cost, adaptability, and compatibility with biorefinery schemes, making it particularly useful in the transformation of residues rich in structural carbohydrates. On the other hand, UAE, employed in China and Tunisia, has demonstrated high efficacy in extracting bioactive compounds such as flavonoids and polyphenols. Its mechanism, based on cell disruption by cavitation, enables efficient extraction with low solvent consumption, reduced times, and optimal results in obtaining natural antioxidants relevant to the food and pharmaceutical industries.

Integration of Combined Methods

There is a marked trend towards the implementation of technological combinations, represented by three groups that integrate different extraction methods to optimize the yield and quality of the obtained compounds. In India, microwave-assisted extraction (MAE), enzymatic extraction, and high hydrostatic pressure (HHP) are combined, allowing efficient recovery of phenolic compounds and dietary fiber without compromising the functionality of bioactives. In Malaysia, maceration, distillation, MAE, and supercritical fluid extraction (SFE) are jointly employed to extract a wide range of compounds, including natural colorants, proteins, and antioxidants, supporting the development of products such as edible packaging and food colorants. In Chile, the combination of pressurized liquid extraction (PLE) with SFE maximizes the recovery of polyphenols and carotenoids with high selectivity and without degrading thermolabile compounds, which is key for applications in high-value industries.

Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction, implemented in Chile, Portugal, and Malaysia, is an advanced technique for obtaining high-purity bioactive compounds. Using primarily carbon dioxide (CO_2) in a supercritical state, this method allows clean extractions free of toxic residues. Its ability to operate at low temperatures and high selectivity makes SFE particularly suitable for heat-sensitive compounds, making it a preferred option in sectors such as pharmaceuticals, nutraceuticals, and cosmetics.

Non-conventional Methods for Energy Production

In the United States, the technique of arrested anaerobic digestion (ADA) has been developed and applied, a non-conventional method that allows the accumulation of volatile fatty acids (VFAs). These intermediate compounds have high value as precursors in the synthesis of bioplastics, biofuels, and other energy bioproducts, significantly expanding the energy valorization potential of agro-industrial waste.

Use of Multiple Methods in Integrated Processes

Ecuador stands out for the simultaneous application of chemical, biological, and thermochemical methods such as fermentation, pyrolysis, and gasification. This integral approach allows the valorization of different fractions of agro-industrial waste and the production of diverse products such as bioplastics, bioethanol, and cellulosic structures. The combination of techniques favors a circular economy strategy by reducing waste, increasing biomass utilization, and diversifying production lines with sustainability criteria.

The presented chart 2 illustrates the percentage distribution of various extraction methods employed in the analyzed studies on the valorization of agro-industrial residues. It is observed that fermentation and ultrasound-assisted extraction (UAE) are the most frequently used techniques, each accounting for 20% of the total. This highlights their high efficiency and adaptability in biomass valorization processes. Other relevant approaches include technological combinations such as PLE + SFE and Microwave + Enzymatic + HHP, as well

as advanced methods like supercritical fluid extraction (SFE) and arrested anaerobic digestion (ADA). This distribution reflects a clear trend toward the adoption of eco-efficient and multifunctional technologies that optimize the recovery of bioactive compounds with applications in the food, pharmaceutical, and energy industries.

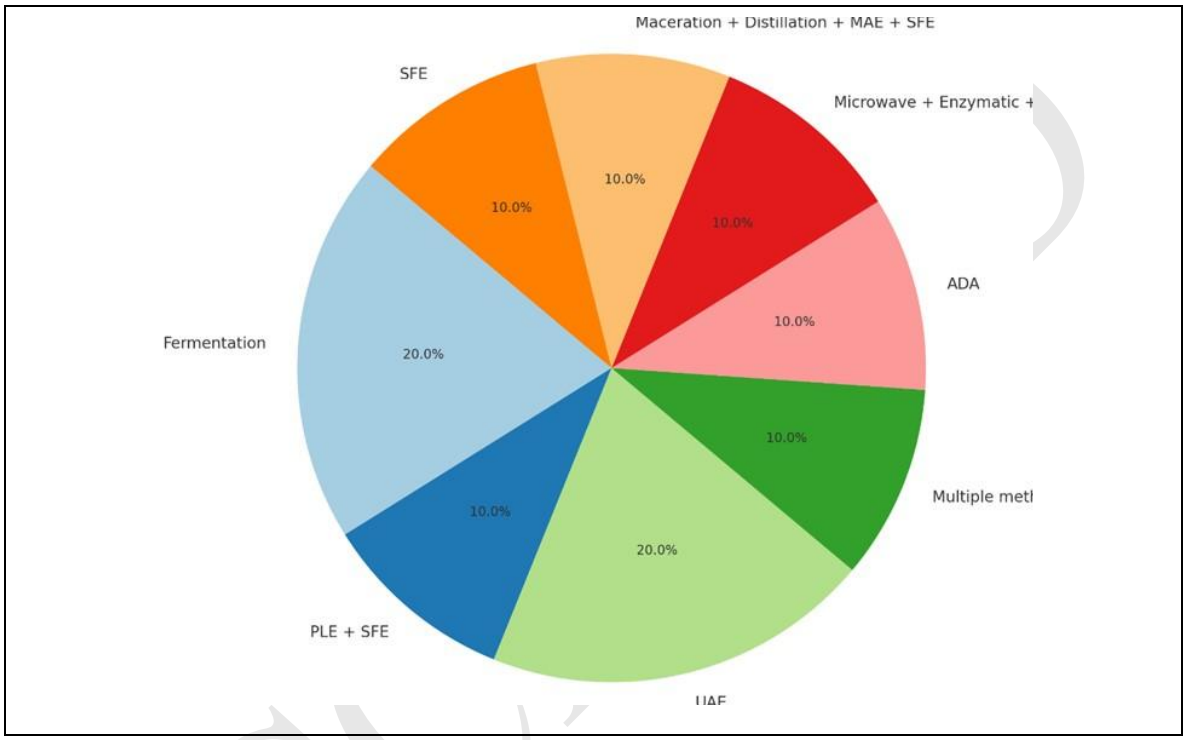

Figure 2 Distribution of Extraction Techniques Used in the Reviewed Studies.

Utilization of Agro-Industrial Residues in Animal Production

The integration of bioproducts derived from agro-industrial residues and plant biomass into animal production systems represents an innovative and sustainable strategy to enhance productive efficiency, animal health, and the quality of final products. The following table 3 summarizes various applications of these bioproducts, categorized by product type, involved bioactive compounds, target animal species, specific uses, recommended dosages, and scientific references supporting their efficacy.

Table 3 Applications of Bioproducts Derived from Agro-Industrial Residues in Animal Feeding and Production

Product	Involved Bioproducts	Species	Specific Use	Dosage	Reference
Nutritional supplements, functional flours	Polyphenols, flavonoids, carotenoids, dietary fibers	Ruminants, poultry, swine	These bioactive compounds possess antioxidant, antifungal, and anti-inflammatory properties. In poultry, they enhance intestinal integrity and reduce oxidative stress; in ruminants, they modulate ruminal microbiota; in swine, they strengthen immune response. Their mechanism includes free radical neutralization and regulation of pro-inflammatory cytokines.	200–500 mg/kg of feed (depending on compound and species)	Arrázola et al., 2008; García et al., 2013
Lignocellulosic residues	Lignocellulolytic enzymes	Ruminants (sheep, cattle)	Improves neutral detergent fiber (NDF) digestibility, increases milk production and weight gain	100–300 U/kg of DM	Villegas, 2010
		Poultry (meat, laying hens)	Reduces intestinal viscosity, improves nutrient absorption, enhances feed conversion	50–150 U/kg of feed	Llanes, 2018
		Swine	Improves digestion of non-starch polysaccharides, reduces intestinal gas	100–200 U/kg of feed	Pérez, 2019
Vegetable residues	Fatty acids	Ruminants, poultry	These fatty acids provide dense energy and improve the lipid profile of animal products. In ruminants,	Ruminants: 30–60 g/kg DM; Monogastrics:	Agnihotri et al., 2022; López et al., 2023

			their inclusion in diets with olive and tomato pomace silage improves digestibility and milk quality. In monogastrics, small doses enhance fatty acid profile in meat and eggs. Lipid oxidation control and avoidance of toxic residues are essential.	10–20 g/kg feed	
Lignocellulosic biomass	Bioethanol (as energy source)	Poultry	Bioethanol can be used as a renewable energy source for heating, lighting, or equipment operation on farms	-----	Zamora, 2019
Forage	Organic biofertilizers	Ruminants	Improve soil fertility and forage nutritional quality. Increase crude protein content and pasture digestibility, positively impacting weight gain and milk production in ruminants.	10–20 tons/ha (soil application)	Huaman et al., 2018

Discussion

The increasing value of agro-industrial waste for bioactive compound extraction has become crucial for its environmental and economic advantages. Table 2 provides a comprehensive overview of the diverse agro-industrial residues from fruits and vegetables across different countries, highlighting extraction methods, the bioactive compounds obtained, and their applications. The cited references offer a valuable understanding of how these processes can be optimized, contributing to the sustainability of industries and promoting a circular economy model.

Among the extraction techniques, fermentation and supercritical fluid extraction (SFE) are two key processes. Fermentation, which is employed in countries such as Australia and

Mexico, accounts for 17.39% of the methods used and is widely applied to convert lignocellulosic biomass and other organic residues into bioethanol, enzymes, and lactic acid. The benefits of fermentation are well-established, offering a low-cost, scalable, and adaptable method that is compatible with biorefinery schemes. In the case of Ecuador, fermentation is used in combination with pyrolysis and gasification to valorize different agro-industrial residues, such as rice molasses and corn stover, into bioplastics, biofuels, and cellulosic structures. This integrated approach not only maximizes the potential of agro-industrial waste but also aligns with sustainable production practices.

Similarly, supercritical fluid extraction (SFE), utilized in countries like Chile, Portugal, and Malaysia, ranks second in application frequency, contributing 13.04% to the extraction methods in agro-industrial waste valorization. SFE is highly effective for extracting bioactive compounds such as antioxidants and polyphenols, particularly from heat-sensitive fruits and vegetables. This technique, which typically uses carbon dioxide (CO_2) in a supercritical state, is advantageous due to its high purity and non-toxic byproducts, making it ideal for applications in the pharmaceutical, nutraceutical, and cosmetic industries.

Another technique that has garnered attention is ultrasound-assisted extraction (UAE), which is employed in countries like China and Tunisia. UAE is particularly efficient in extracting antioxidants such as flavonoids and polyphenols, contributing to the growing demand for natural antioxidants in food and pharmaceutical applications. The method's efficiency is largely attributed to the cavitation process, which disrupts plant cell walls, enhancing the extraction yield while reducing solvent use and extraction time.

In addition to individual techniques, there is a clear trend toward combining extraction methods to improve the yield and quality of bioactive compounds. For example, in India, a combination of microwave-assisted extraction (MAE), enzymatic extraction, and high hydrostatic pressure (HHP) enables the effective recovery of phenolic compounds and dietary fibers, which are integral to the development of nutraceuticals and functional foods. In Malaysia, the integration of maceration, distillation, MAE, and SFE optimizes the

extraction of a wide range of bioactive compounds, including proteins, polysaccharides, and antioxidants, which are used in the production of edible films and natural food colorants (Enriquez et al., 2023).

The integration of these advanced extraction methods supports the development of biofuels, bioplastics, and other valuable products, thereby reducing waste and enhancing the circular economy. For instance, the application of anaerobic digestion in the United States enables the conversion of organic residues into volatile fatty acids (VFAs), which are precursors for bioplastics and biofuels, expanding the energy valorization potential of agro-industrial waste. This non-conventional method highlights the versatility of agro-industrial waste as a source of energy and high-value bioproducts.

Conclusions

The analysis of the valorization of agro-industrial waste derived from fruits and vegetables underscores the significance of eco-efficient and multifunctional techniques for recovering bioactive compounds. Among the most utilized methods are fermentation and ultrasound-assisted extraction (UAE), both noted for their efficiency. Fermentation converts organic residues into valuable products such as bioethanol and enzymes, while UAE enhances the extraction of bioactive compounds. Supercritical fluid extraction (SFE) stands out for its ability to obtain high-purity bioactive compounds without toxic residues, making it particularly useful in pharmaceutical, nutraceutical, and cosmetic sectors. Additionally, there is a trend towards integrating multiple extraction techniques, such as microwave-assisted extraction (MAE) and high hydrostatic pressure (HHP), to optimize the recovery of phenolic compounds and dietary fiber.

Ecuador exemplifies an integral approach by combining chemical, biological, and thermochemical methods, enabling the valorization of waste and the production of bioplastics and bioethanol, thus promoting a circular economy. Non-conventional methods like arrested anaerobic digestion (ADA) in the USA show potential for producing biofuels and bioplastics, expanding the energy utilization of agro-industrial waste. Overall, the use of eco-efficient

technologies not only reduces waste but also fosters sustainability and the development of a circular economy, transforming agro-industrial waste into valuable products.

Declarations

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Conflicts of interest

The authors declare that they have no conflicts of interest regarding the work presented.

Author contributions

Miguel Enriquez carried out most of the work and is the lead author. Luis Arboleda handled the writing, Paul Ricaurte reviewed the bibliographic citations and review sources, Ahmed El Salous focused on the translation, and Maria Jose Andrade conducted the reviews of the sources and methods used.

Use of artificial intelligence (AI)

No AI or AI-assisted technologies were used during the preparation of this work.

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