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Harnessing Agro-Industrial waste for biogas production via anaerobic co-digestion: A systematic review

Aprovechamiento de residuos agroindustriales para la obtención de biogás mediante co-digestión anaerobia: Una revisión sistematica

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RESUMEN

El incremento de residuos agroindustriales y la demanda de energía sostenible representan un doble desafío ambiental y energético. A pesar de su alto contenido orgánico, su manejo inadecuado agrava el daño ecológico y desperdicia su potencial energético. La codigestión anaerobia surge como alternativa eficiente, transformando estos residuos en biogás y permitiendo una gestión sostenible de la biomasa. Este artículo analiza sistemáticamente la producción de biogás a partir de residuos agroindustriales mediante codigestión anaerobia, evaluando tipos de residuos, condiciones operativas, pretratamientos y rendimiento metanogénico. Los resultados demuestran que la combinación adecuada de sustratos mejora la estabilidad del proceso y maximiza la producción de biogás. Factores como la relación carbono-nitrógeno, el pretratamiento de materiales lignocelulósicos y el uso de aditivos (como biocarbón) influyen notablemente en la eficiencia.No obstante, persisten barreras técnicas y logísticas, especialmente en zonas rurales, que limitan su implementación a gran escala. Se concluye que la codigestión anaerobia no solo es una solución viable para generar energía renovable, sino también un avance hacia una economía circular con beneficios ambientales y sociales concretos.

Palabras clave: *Ambiental, fuentes energéticas, residuos, metano, carbono.*

ABSTRACT

The increase in agro-industrial waste and the growing demand for sustainable energy represent a dual environmental and energy challenge. Despite their high organic content, the inadequate management of these residues exacerbates ecological damage and wastes their energy potential. Anaerobic co-digestion emerges as an efficient alternative, transforming these wastes into biogas and enabling the sustainable management of biomass. This article systematically analyzes biogas production from agro-industrial residues through anaerobic co-digestion, evaluating types of waste, operational conditions, pretreatment methods, and methanogenic performance. The results show that the appropriate combination of substrates enhances process stability and maximizes biogas production. Factors such as the carbon-to-nitrogen ratio, the pretreatment of lignocellulosic materials, and the use of additives (such as biochar) significantly influence system efficiency. However, technical and logistical barriers persist, particularly in rural areas, limiting large-scale implementation. It is concluded that anaerobic co-digestion is not only a viable solution for renewable energy generation but also a step forward toward a circular economy with tangible environmental and social benefits.

Key words: *Environmental, energy sources, waste, methane, carbon.*

INTRODUCTION

In recent years, the urgency to develop sustainable energy systems has driven research into methods capable of converting organic waste into renewable energy sources. This growing interest stems not only from the environmental pressure exerted by current production models but also from the need to reduce dependence on fossil fuels. Within this context, anaerobic digestion has gained prominence as a promising technology, as it enables the controlled degradation of organic matter by microorganisms under anaerobic conditions, producing biogas a renewable energy resource with a reduced environmental impact (Parra, 2015; Weiland, 2010).

Agro-industrial residues, which include peels, pulps, bagasse, manure, and plant remains, represent a significant proportion of residual biomass worldwide. Despite their high carbon content and energy value, many of these materials pose technical challenges, such as the presence of lignin, unfavorable carbon-to-nitrogen (C/N) ratios, or complex polymeric structures that hinder their biological degradation. To overcome these barriers, anaerobic co-digestion has emerged as an effective strategy, allowing the combination of various residues with complementary properties that enhance metabolic synergy and optimize the process (Flotats, 2008; Rodríguez-Verde et al., 2014).

Anaerobic co-digestion (AcoD) has been evaluated in numerous studies as an efficient alternative for maximizing biogas and methane production through the combination of substrates with complementary characteristics. For example, mixtures of fruit and vegetable waste such as tomato pulp, apple pulp, or olive cake have demonstrated high biogas production rates when their carbon and nitrogen contents are adequately balanced. These blends have achieved yields of up to 1096 mL/L of biogas with a methane content of 70%, highlighting the optimization potential through synergistic substrate formulations (Hernández et al., 2024).

Moreover, studies conducted under mesophilic conditions show that the co-digestion of fruit and vegetable residues stabilized with crude glycerol maintains stable pH conditions, achieving specific methane production of up to 681 L CH_4/kg VS and chemical oxygen demand (COD) removal efficiencies close to 77.6% (Muñoz-Martínez et al., 2025). These results underscore the importance of using co-substrates with high availability of easily degradable compounds, as well as the need to control critical parameters such as pH and organic loading rate.

In the Latin American context, the management of organic waste from the agro-industrial sector presents a significant challenge. Although the region generates large volumes of agricultural and livestock by-products, the lack of adequate infrastructure for their valorization, coupled with limited access to decentralized energy technologies, has hindered the exploitation of this resource. This situation not only represents a loss of energy potential but also contributes to the pollution of soils, water bodies, and the atmosphere due to inefficient waste management (Bustamante, 2016; García, 2016). Nevertheless, various studies have demonstrated that the implementation of co-digestion schemes can transform this problem into a viable energy opportunity (Castañeda, 2019; González & Pérez, 2021).

The key to successful co-digestion processes lies in the ability to combine residues with complementary nutritional profiles. Mixtures including residues rich in simple sugars with others containing higher nitrogen content allow for the correction of imbalances, reduction of inhibition risks from volatile fatty acids or ammonia, and increased methane production in a stable and sustained manner (Ward et al., 2008). Furthermore, the application of pretreatments such as thermal hydrolysis, milling, or the use of alkaline reagents has been shown to significantly enhance the availability of organic matter for microorganisms, thereby increasing system performance (Agbor et al., 2011; Barua & Kalamdhad, 2018).

A crucial factor in the study of organic residues is their biochemical methane potential (BMP), a key parameter for estimating their viability as an energy source. The specialized literature reveals notable variability in these values, influenced by multiple factors: substrate characteristics, volatile solids content, process conditions, and the type of microbial culture used (Gunaseelan, 2004; González-Sánchez et al., 2015). These findings highlight the need to develop specific characterization protocols and customized formulations based on regionally available resources.

Despite significant progress in the field, several challenges remain. Among the most prominent are the lack of standardized methodologies, limited comparability between different waste mixtures, and the need to validate findings under real operational conditions. Recently, pioneering studies have demonstrated the positive impact of additives such as biochar, which enhances methanogenic activity, mitigates toxic effects, and increases system stability under environmental fluctuations (García & Posadas, 2022; Montenegro, 2023).

The purpose of this work is to critically analyze the current body of knowledge on biogas production through anaerobic co-digestion of agro-industrial residues. The study focuses on research that evaluates types of waste, operational conditions, pretreatment methods, and methane production performance. The resulting synthesis seeks to establish a solid scientific basis for future technological innovations and support decision-making processes in regions with an urgent need to valorize their organic waste.

The methodology employed was based on a rigorous search protocol in specialized academic platforms (Scopus, Web of Science, ScienceDirect, SpringerLink, Latindex, and Scielo), prioritizing recent studies ranging from laboratory-scale research to full-scale applications. This approach ensures an up to date and representative perspective of the state of the art.

Beyond its energy potential, anaerobic co-digestion emerges as a solution aligned with the principles of sustainability and the circular economy. Its strategic implementation in areas with high organic waste generation could deliver multidimensional benefits, provided effective synergies are established among the scientific community, policymakers, and local stakeholders directly involved.

METHODOLOGY

This work was conducted in accordance with the highest standards of scientific research, aiming to provide a critical and reproducible assessment of recent advances in anaerobic co-digestion applied to agro-industrial residues. The methodological design employed not only enables the identification of significant patterns in the literature but also allows the establishment of relationships between operational variables, substrate-specific synergies, and technical limitations that condition the sustainable implementation of this technology.

Selection and Analysis of Scientific Literature

The collection of scientific evidence followed a structured protocol covering indexed publications from the past five years. The sources consulted included prestigious academic platforms such as Scopus, Web of Science, and ScienceDirect, complemented by specialized regional repositories (SpringerLink, Latindex, Scielo). The search strategy incorporated combinations of key terms in both English and Spanish, including: "anaerobic co-digestion," "agro-industrial waste," "biogas yield," "process optimization," and "substrate synergy." The selection criteria ensured the inclusion of studies meeting fundamental requirements of methodological quality and thematic relevance. Special attention was given to:

- Experimental studies involving at least two types of agro-industrial residues
- Applications at laboratory, pilot, or industrial scale
- Quantitative reports on biogas/methane production, organic matter removal efficiency, or kinetic parameters

Duplicated reviews, reports lacking verifiable experimental data, and documents with low academic impact were excluded.

Classification and Extraction of Key Parameters

Relevant information was systematically organized into the following thematic axes:
a) Types of agro-industrial residues used: origin, physicochemical composition, seasonal availability.
b) Pretreatments and additives: physical (grinding, screening), chemical (alkaline, acidic), biological (enzymatic), or energy co-substrates (lipids, glycerol, sugars).

c) Performance indicators: biogas production (m^3/kg VS), methane content (% CH_4), COD/BOD removal efficiency, kinetic modeling (Gompertz, Logistic, Transient models).

This classification allowed for cross-comparison among studies, highlighting common patterns and critical variables affecting co-digestion system efficiency.

Critical evaluation and comparative synthesis

Each study was evaluated based on the consistency between materials used, experimental conditions, and results obtained. Scientific quality criteria, as proposed by Li et al. (2022) and Kant et al. (2021), were applied, prioritizing studies with robust experimental design and validated replicability. Points of consensus and controversy were identified, particularly regarding the impact of lipid-rich substrates, the use of additives, and the effects of chemical pretreatments.

The final synthesis was presented in the form of comparative matrices and narrative analysis, integrating empirical trends and theoretical principles related to anaerobic microbiology, biochemical kinetics, and energy efficiency.

Ethical Standards and Data Quality

Only peer-reviewed sources with verifiable data traceability were included. All references were cited in compliance with academic integrity standards, avoiding unnecessary redundancies. The methodological quality of all included articles was assessed following PRISMA guidelines adapted for thematic reviews.

RESULTS

The systematic analysis of the selected scientific articles allowed for the identification of several consolidated trends regarding the use of agro-industrial waste as feedstock for biogas production through anaerobic co-digestion (AcoD). Empirical evidence was organized into four main analytical axes: types of residues used, operational conditions and critical parameters, pretreatments and use of additives, as well as energy performance and methane production. Collectively, these findings consolidate AcoD as an integrated strategy for waste valorization, renewable energy generation, and the strengthening of circular economy models in both rural and industrial contexts.

1. Types of Agro-Industrial waste used

Most of the studies reviewed agree that the residues most commonly used in anaerobic co-digestion processes are by-products from the processing of fruits, sugarcane, coffee, cereals, and tubers. Specifically, sugarcane bagasse (*Saccharum officinarum*), banana peel (*Musa paradisiaca*), coffee pulp, and potato and carrot residues have been widely evaluated as primary substrates (Alengebawy et al., 2024; Muñoz-Martínez et al., 2025; Hernández et al., 2024).

These residues exhibit high seasonal and geographic availability, particularly in agricultural regions of Latin America, making them ideal candidates for energy valorization projects. However, when used individually, many of these residues present technical limitations related to low biodegradability or unbalanced carbon-to-nitrogen (C/N) ratios, which can lead to process inhibition (Gunaseelan, 2004; Barua & Kalamdhad, 2018). To mitigate these limitations, numerous studies have proposed formulating mixtures with animal manure, kitchen waste, or nitrogen-rich industrial by-products, which improve methanogenesis efficiency and system stability (Alengebawy et al., 2024; Parra, 2015).

Hernández et al. (2024) emphasize that combinations of fruit and vegetable residues such as tomato pulp, apple pulp, and olive cake promote favorable biochemical synergy, achieving biogas production above 1000 mL/L and methane concentrations up to 70%, without requiring physical or chemical pretreatments. These findings align with previous studies that have evaluated fruit waste for its high content of easily convertible carbohydrates and lipids (González-Sánchez et al., 2015).

2. Operational conditions and critical parameters

In operational terms, the anaerobic digesters used in the selected studies predominantly operated under mesophilic conditions, with temperatures ranging from 30 to 38 °C. These conditions favor methanogenic microbial activity and provide greater process stability compared to thermophilic systems, which while faster tend to be more sensitive to inhibitor accumulation (Muñoz-Martínez et al., 2025).

Most authors reported optimal pH values between 6.8 and 7.5, ranges that are essential for maintaining methanogenic archaea activity. To ensure this stability, natural buffers such as sodium bicarbonate were used, or the buffering capacity of manure used as inoculum was leveraged (Muñoz-Martínez et al., 2025; Alengebawy et al., 2024).

Another relevant parameter is the C/N ratio, whose optimization is critical to avoid ammonia inhibition or energy limitations due to excess carbon. Ratios between 20:1 and 30:1 were found to be the most effective in maximizing methane production, reducing the formation of undesirable intermediates, and maintaining active microbiota (Li et al., 2022; Hernández et al., 2024).

The hydraulic retention time (HRT) generally ranged between 15 and 30 days, which allows for complete degradation of residues without biomass washout or system overload. In pilot-scale studies, such as that conducted by Muñoz-Martínez et al. (2025), high levels of stability were reported during extended periods of semi-continuous operation, validating the technical sustainability of the system.

Reactor designs included both laboratory-scale batch systems and pilot-scale semi-continuous digesters. The most common configurations were completely mixed reactors and UASB (Upflow Anaerobic Sludge Blanket) systems, adapted to technological availability and local conditions (García & Posadas, 2022; Alengebawy et al., 2024).

3. Pretreatments and use of additives

The low biodegradability of certain lignocellulosic residues, such as sugarcane bagasse or water hyacinth, has prompted the development and application of various pretreatment strategies to enhance the availability of fermentable compounds. Among the most common techniques are grinding, thermal hydrolysis, alkaline treatments (NaOH, lime), and autoclaving. These technologies have significantly increased organic matter solubility, degradation rate, and methane yield (Agbor et al., 2011; Barua & Kalamdhad, 2018; Zhang et al., 2021).

Sukasema et al. (2017), for instance, reported that water hyacinth treated with lime and co-digested with pig manure achieved methane concentrations above 63% and COD removal rates of 69%, demonstrating the effectiveness of alkaline pretreatments. In the case of sugarcane bagasse, thermal hydrolysis increased the release of fermentable sugars, resulting in significant improvements in energy efficiency (Li et al., 2021).

In addition to pretreatments, some studies applied additives such as biochar, crude glycerol, or sodium bicarbonate. These compounds served as buffers, enhanced microbial activity, or acted as additional sources of easily assimilable carbon. Muñoz-Martínez et al. (2025) demonstrated that crude glycerol, a by-product of the biodiesel industry, not only increased specific methane yield but also stabilized the C/N ratio and mitigated the accumulation of volatile fatty acids.

4. Energy performance and methane production

The reviewed studies reported a wide range of biogas and methane production values, depending on the type of residue, reactor design, HRT, and pretreatments applied. In general, biogas production ranged from 300 to 500 Nm^3 per ton of treated residue, with methane content between 55% and 70% (Gunaseelan, 2004; Alengebawy et al., 2024; Hernández et al., 2024).

Under optimal conditions, such as in mixtures of fruit and vegetable waste with olive cake, maximum biogas yields of 1096 mL/L with 70% methane content were reported (Hernández et al., 2024). Muñoz-Martínez et al. (2025), for their part, reported a specific methane yield of 681 L CH_4/kg VS with a COD removal efficiency of 77.6%, without the need for complex pretreatments or advanced technologies.

González-Sánchez et al. (2015) and Gunaseelan (2004) confirmed that residues such as mango, banana, and onion peels achieve higher yields than pure cellulose, particularly when combined with active microbial inocula and operated under controlled pH and organic loading conditions.

Table N°01:
Main findings from relevant studies on anaerobic co-digestion of agro-industrial waste

Type of Agro-Industrial Waste	Pretreatments Applied	Inoculum/Additives	Biogas Production	Methane	Main Findings	Author
Rice Straw (RS) + Food Waste (FW)	Grinding (<1 cm)	Digestate from FW anaerobic digestion	0.616 m^3/kgVS/day (FW/RS 90:10)	58.4%	Co-digestion reduced biomethane yield by 22.1% compared to FW mono-digestion but improved economic/environmental sustainability.	Le Pera et al. (2025)
Sugarcane Bagasse (SB) + FW	Grinding (<1 cm)	Digestate from FW anaerobic digestion	0.602 m^3/kgVS/day (FW/SB 90:10)	58.5%	Co-digestion reduced biomethane yield by 23.8% but increased profit by €3.8/ton and reduced CO_2 emissions by 121 kg/ton.	Le Pera et al. (2025)
FW (mono-digestion)	None	Digestate from FW anaerobic digestion	0.793 m^3/kgVS/day	58.2%	Highest biomethane yield (0.462 m^3/kgVS) but vulnerable to feedstock shortages.	Le Pera et al. (2025)
Fruit and vegetable waste	Size reduction by liquefaction (physical method)	Swine manure (inoculum) and crude glycerol (2.5% as co-substrate)	0.576 ± 0.084 $m^3\ d^{-1}$	60–70%	Co-digestion with glycerol increased methane production by 4.6 times compared to single-substrate digestion. Achieved 77.6% COD removal efficiency and stable biogas production.	Muñoz-Martínez et al. (2025)
Orange peel waste (OPW)	None	Pretreated inoculum from UASB reactor	71.8 m^3·ton biomass^{-1}	60%	BMP of 160.5 $m^3\ CH_4$·tonVS^{-1}; D-limonene inhibition noted.	Camelo et al. (2024)
Crude glycerol (CG)	None	Pretreated inoculum from UASB reactor	461.5 m^3·ton biomass^{-1}	63%	High BMP of 344.8 $m^3\ CH_4$·tonVS^{-1}; CG enhances biogas yield.	Camelo et al. (2024)
OPW + CG (mixed)	None	Pretreated inoculum from UASB reactor	42.9 m^3·ton biomass^{-1}	46%	Synergistic effect: BMP of 501.3 $m^3\ CH_4$·tonVS^{-1} (higher than individual substrates).	Camelo et al. (2024)
Tomato pomace (TP) + Olive cake (OC)	Grinding and mixing (1:1 w/w)	Cow manure (15% w/w)	1096 mL/L	70%	Highest biogas and methane production; best fit with modified Gompertz model (R^2 = 99.7%).	Hernández et al. (2024).
Apple pomace (AP) + Olive cake (OC)	Grinding and mixing (1:1 w/w)	Cow manure (15% w/w)	885 mL/L	62%	Moderate biogas production; methane production continued beyond 12 days.	Hernández et al. (2024).
Tomato pomace (TP) + Apple pomace (AP)	Grinding and mixing (1:1 w/w)	Cow manure (15% w/w)	574 mL/L	69%	Fastest biogas production but lowest yield; process ended early due to substrate depletion.	Hernández et al. (2024).
Fish Waste (FW) and Water Hyacinth (WH)	None (co-digestion)	Cow Dung (CD)	890 CH_4 mL/g VS	53.7%	Co-digestion (1:1 ratio) yielded the highest biogas production. Synergistic effects balanced C/N ratio and improved efficiency.	Nahar et al. (2024)
Fish Waste (FW)	None (mono-digestion)	Cow Dung (CD)	610 CH_4 mL/g VS	62.9%	FW mono-digestion outperformed WH due to higher degradability. Optimal at 1:2 (CD:FW).	Nahar et al. (2024)

Water Hyacinth (WH)	None (mono-digestion)	Cow Dung (CD)	440 CH_4 mL/g VS	47.6%	WH required longer lag phases. Lower methane yield compared to FW.	Nahar et al. (2024)
WH + FW (Co-digestion)	None	Cow Dung (CD)	775 CH_4 mL/g VS	55.4%	Co-digestion ratios (1:1, 1:2) significantly enhanced biogas yield over mono-digestion. COD reduction >80%.	Nahar *et al.* (2024)
Food waste (FW) + Garden waste (GW)	Sequential hybrid (thermal + extrusion)	Anaerobic digester sludge (ADS)	430 mL/g VS (co-digestion)	Not specified	Sequential hybrid pretreatment increased biogas production by 1.19–2.47 times compared to conventional methods.	Cherukuri & Parthasarathy (2023)
Food waste (FW)	Thermal (100°C, 30 min)	Anaerobic digester sludge (ADS)	217 mL/g VS (mono-digestion)	Not specified	Thermal pretreatment enhanced biogas yield due to disintegration of complex organic matter.	Cherukuri & Parthasarathy (2023)
Food waste (FW)	Extrusion (mechanical)	Anaerobic digester sludge (ADS)	177 mL/g VS (mono-digestion)	Not specified	Extrusion increased surface area but showed minimal biogas improvement.	Cherukuri & Parthasarathy (2023)
Food waste (FW) + Garden waste (GW)	None (conventional)	Anaerobic digester sludge (ADS)	410 (co-digestion)	Not specified	Co-digestion with GW improved biogas yield but required longer digestion time.	Cherukuri & Parthasarathy (2023)
Mixed pineapple pulp and peel	None (high reducing sugar content eliminated need for pretreatment)	Anaerobic pond inoculum (10 g VSS/L)	0.39 v/v-d (highest at HRT7)	52.38% (max at HRT15)	Two-stage system (CSTR + AHR) improved biogas yield (0.43 m³/kg COD removed) and COD removal (67.05%). Higher TS (4%) and longer HRT enhanced stability.	Jitpupakdee *et al.* (2023)
Cashew nut hull	Crushing and sieving (0.5 mm)	Pig manure (PM)	189.16 L/kg VS	69.2%	Highest biogas and methane yields achieved with PM as inoculum. Acidic pH (5.86–6.44) adjusted to neutral for optimal digestion.	Sawadogo et al. (2023)
Cashew almond skin	Crushing and sieving (0.5 mm)	Cow dung (CD)	159.85 L/kg VS	62.3%	CD yielded the second-highest biogas and methane. High C/N ratio (31.94–37.79) required nitrogen supplementation.	Sawadogo et al. (2023)
Wheat Straw (WS), Rice Straw (RS), Sugarcane Bagasse (BA)	Mechanical pretreatment (grinding to 0.1 mm)	Cow manure effluent	393.08 (WSRS), 177.96 (BAWS), 188.30 (BARS), 337.90 (BAWSRS)	70.63% (WSRS), 64.5% (BAWS), 65% (BARS), 69% (BAWSRS)	Highest methane yield from WSRS at S/I ratio 1.5. Mechanical pretreatment improved hydrolysis. Logistic function model best fit the data	Meraj et al. (2021)
Agricultural solid wastes (ASWs: clover, grass, wheat straw) and cow dung (CD)	Alkalinity treatment with $NaHCO_3$ (1.0 g/gVS)	Cow dung as inoculum	297.99 NL/kgVS (untreated); 386.3 NL/kgVS (treated)	66–77% (untreated); 56–73% (treated)	Co-digestion at 60:40 (ASWs:CD) optimized biogas production. $NaHCO_3$ pretreatment increased methane yield by 29.7% and reduced lignin, cellulose, and hemicellulose content.	Almomani & Bhosale (2020)
Kitchen waste (FW)	Thermal (134 °C, 320,000 Pa)	Anaerobic digester sludge	392 mL/g VS	Not specified	Thermal pretreatment slightly reduced biogas yield compared to untreated samples.	Gallipoli et al. (2020)
Food waste (FW) + Yard waste (YW)	Thermal pretreatment	Sewage sludge (SS)	332 mL/g VS	Not specified	Co-digestion with YW and SS doubled methane production compared to mono-digestion.	Mu et al. (2020)
Cashew nut shells	Thermal and biological treatments	Not specified	16.55–40.04 L/kg VS	28.76–77.40 %	Low biogas yield compared to theoretical estimates; pretreatments improved degradation.	Nikiema et al. (2020)

Food waste (FW) + Grass	Microwaving (140 °C, 2 min)	Anaerobic digester sludge	270 mL/g VS	Not specified	Thermal pretreatment improved methane yield compared to untreated samples.	Panigrahi et al. (2020)

Overall, the findings support the conclusion that anaerobic co-digestion represents a robust, adaptable, and efficient technological alternative for the valorization of agro-industrial waste. The strategic combination of substrates, the selective use of pretreatments, and the application of natural additives reinforce the technical and environmental feasibility of the process, even in contexts with technological or economic limitations (Table 1). Despite practical barriers such as the lack of parameter standardization, logistical challenges in waste collection, and the need for locally adapted technologies the available evidence supports the hypothesis that AcoD not only enhances energy performance but also improves the stability, resilience, and sustainability of anaerobic digestion systems in heterogeneous agro-industrial settings (Alengebawy et al., 2024; Ma et al., 2022; Kumar et al., 2022).

DISCUSSION

The findings gathered in this systematic review confirm the fundamental role of anaerobic co-digestion (AcoD) in the integrated management of agro-industrial waste. As noted by Alengebawy et al. (2024) and Muñoz-Martínez et al. (2025), this technology has transcended its purely experimental character to become a practical solution that combines environmental, energy, and socioeconomic benefits.

From a technical standpoint, the accumulated evidence clearly demonstrates the superiority of AcoD over mono-substrate digestion systems. Li et al. (2022) and Gunaseelan (2004) have documented how the strategic combination of substrates with complementary biochemical profiles allows optimization of key parameters such as the C/N ratio while mitigating inhibitory effects on microbial consortia. These findings corroborate the pioneering observations of Flotats (2008), who highlighted the capacity of co-digestion systems to enhance both yields and operational stability.

An important trend identified in the literature is the growing application of pretreatment strategies and the use of functional additives. Recent studies, such as those by Agbor et al. (2011) and Barua & Kalamdhad (2018), demonstrate that physical, chemical, and thermal pretreatments improve the degradability of lignocellulosic compounds by facilitating the release of fermentable sugars and increasing methane production. In parallel, the use of additives such as biochar or crude glycerol has shown positive effects in mitigating the accumulation of inhibitors like volatile fatty acids or ammonia (Muñoz-Martínez et al., 2025; Montenegro, 2023).

From an environmental perspective, AcoD enables the comprehensive valorization of agro-industrial residues, transforming them into renewable energy sources while simultaneously reducing the pollution burden associated with landfill disposal. This dual function of waste treatment and energy generation strengthens AcoD's role within circular economy strategies. As Weiland (2010) points out, anaerobic digestion reduces greenhouse gas emissions and produces a valuable by-product digestate which can be used as a biofertilizer.

However, despite the demonstrated benefits, there are operational and structural limitations that hinder the large-scale deployment of this technology. The heterogeneity of residues, seasonal variations in waste generation, and logistical challenges related to their collection, transport, and storage represent significant technical barriers. These are compounded by the lack of adequate infrastructure in rural areas or regions with low technological investment. Bustamante (2016) had already warned of the need for public policies that promote the adoption of biodigesters tailored to local conditions.

A critical issue identified in this review is the scarcity of studies conducted at industrial scale or under real operational conditions. While laboratory and pilot studies provide valuable insights, extrapolating these data to productive scenarios raises uncertainties related to system stability, long-term efficiency, and social acceptance. This finding underscores the need for research designs that include techno-economic analyses, life cycle assessments, and studies on social acceptability (Alengebawy et al., 2024).

The critical examination of the specialized literature reveals a marked disparity in the methods used to quantify the biochemical methane potential (BMP) and other key performance indicators. As emphasized by Ward et al. (2008) and González-Sánchez et al. (2015), this methodological inconsistency poses serious challenges for making valid comparisons between studies and for developing reliable databases, highlighting the urgent need to standardize evaluation protocols.

A particularly concerning issue that emerged from the analysis is the evident publication bias in this field. According to Muñoz-Martínez et al. (2025), the tendency to report predominantly successful cases with high biogas yields while omitting negative or failed results can generate a distorted perception of the technology's true potential, hindering the objective identification of its practical limitations.

Despite these challenges, recent research shows significant progress in the diversification of usable feedstocks. Hernández et al. (2024) and González & Pérez (2021) have demonstrated the potential of non-conventional residues such as dairy by-products, coffee processing waste, and tropical fruit peels, evidencing a more comprehensive approach to circular economy in the agro-industrial sector.

Simultaneously, several studies are exploring promising synergies by integrating anaerobic co-digestion with other valorization technologies. Ma et al. (2022) and Luo et al. (2021) highlight the benefits of combining this process with carbon capture systems, biohydrogen production, and nutrient recovery, which could multiply the environmental and economic benefits of these solutions.

For regions with a strong agro-industrial base such as Latin America, the evidence compiled by Alengebawy et al. (2024) and Kumar et al. (2022) suggests that successful implementation of these technologies will require effective coordination between academic, productive, and governmental sectors, alongside the development of appropriate regulatory frameworks and the strengthening of local technical capacities. As various experts have pointed out, anaerobic co-digestion should not be understood as a standalone solution, but as a fundamental component of integrated waste management systems and decentralized renewable energy production. This holistic perspective combined with an interdisciplinary and long-term approach is essential to maximize its contribution to the sustainability of the agro-industrial sector.

CONCLUSIONS

The continuous increase in agro-industrial waste generation, coupled with the urgent need to develop sustainable energy alternatives, has led to growing interest in valorization technologies such as anaerobic co-digestion. This comprehensive analysis of the scientific literature examines the current state of knowledge regarding the combined use of various organic wastes in anaerobic processes, assessing their technical feasibility, operational efficiency, and environmental benefits. The findings reveal consistent patterns in substrate selection, operating conditions, application of pretreatments, and use of additives. It has been demonstrated that the formulation of mixtures with complementary waste characteristics not only enhances process stability but also significantly increases methane production. Particularly noteworthy is the positive effect of pretreatments and the addition of coadjuvants such as biochar, which help to overcome obstacles such as low biodegradability or the presence of inhibitory compounds.

However, the study also identifies critical limitations that must be addressed. These include the lack of standardization in evaluation methods, technical challenges associated with large-scale implementation, and the scarcity of studies conducted under real operating conditions. These barriers represent significant challenges to the widespread adoption of the technology.

As the main conclusion, anaerobic co-digestion is positioned as a key tool within integrated waste management strategies, with considerable potential to advance circular economy models in regions with significant agro-industrial activity. Nevertheless, there is a clear need to continue research focused on adapting these systems to specific local contexts, as well as on the development of regulatory frameworks that facilitate their implementation in the productive sector. The success of this technology will largely depend on its ability to be harmoniously integrated into existing production systems, offering solutions that are both environmentally and energetically sustainable.

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