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Factors maximizing biogas yield in anaerobic digestion of agro-industrial wastes: A systematic review (2015-2025)

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Abstract. Agro-industrial waste has significant potential as a feedstock for biogas production, contributing to both energy generation and waste recovery. This study aimed to analyze the scientific literature published between 2015 and 2025 on biogas production from agro-industrial waste, identifying which co-substrate combinations, mixture proportions, and pretreatment strategies are associated with the highest biogas yields. A systematic literature review was conducted using the Science Direct, Scopus, and Web of Science databases, accessed through the Capes Journal Portal, applying boolean search operators and explicit eligibility criteria; after screening 351 records, 130 articles were retained for analysis. Results show an exponential growth in publications over the period, led by Brazil, India, and Italy. Anaerobic co-digestion of easily degradable substrates with more recalcitrant lignocellulosic residues produced the largest relative gains over mono-digestion, while a carbon-to-nitrogen ratio between 20:1 and 30:1 was consistently associated with the best performance. Physical, thermochemical, and biological pretreatments increased methane yield by 16% to 222%. It is concluded that, although anaerobic digestion is a technically mature process, critical gaps remain regarding standardization of yield units, comparability among studies, and economic feasibility indicators.
Keywords: co-digestion, pretreatment, methane, biomass

Introduction

The contemporary dependence on fossil fuels for global development imposes challenges that extend beyond the economic sphere, reaching environmental, social, and political dimensions. The combustion of these non-renewable sources is one of the main contributors to greenhouse gas (GHG) emissions, which accelerate climate change (Pirmoghani et al., 2025). At the same time, population growth and the intensification of agricultural and industrial production increase the generation of solid waste and effluents, posing an environmental challenge with consequences for land use and water resource quality (Alengebawy et al., 2024). Given this scenario, it is necessary to seek and develop alternative ways of supplying global energy demand while ensuring a lower environmental impact.

In this context, biofuels, particularly biogas, emerge as a sustainable and renewable alternative to supply energy in place of fossil fuels such as coal and petroleum (Sharma et al., 2025). Biogas, composed mainly of methane (CH4) and carbon dioxide (CO2), is a clean energy source produced via anaerobic digestion. This technology enables the conversion of the environmental liability represented by waste and effluents into a high-value energy asset. It should be noted that the absence of adequate systems for collecting and using these gases results in the release of methane into the atmosphere, a greenhouse gas considered 23 times more harmful than carbon dioxide (Nair et al., 2022).

The efficiency of anaerobic biodigestion is intrinsically linked to the type of biomass used and the chemical composition of the organic matter (Boro et al., 2022). In the agro-industrial sector, residues such as vinasse, molasses, and animal manure present high methanogenic potential, allowing energy recovery to occur within the industrial plant itself, reducing operational costs and the carbon footprint (Almeida and Rizzato, 2022). However, the microbiological stability of these systems is frequently challenged by recalcitrant biomass and fluctuations in organic loading. The literature indicates that the presence of adapted methanogenic microorganisms and the use of strategies such as co-digestion, pretreatment, and mixture proportioning are essential to ensure methane productivity and reduce the pollutant load (Correa et al., 2025; Kasinath et al., 2021).

Despite the maturity of anaerobic digestion, the diversity of substrates and the need for operational optimization point to persistent gaps, especially regarding the energy balance of pretreatments and economic feasibility at full scale (Cremonez et al., 2021). Thus, a literature survey that systematizes the advances achieved over the past decade is warranted, allowing the identification of consolidated trends and areas that require further scientific investigation.

Given the diversity of approaches reported in the literature, this review addresses three specific research questions: which co-substrate combinations show the greatest success in biogas/methane production; which mixture proportions between substrates are associated with the highest yields; and which pretreatment methods result in the highest yield for each substrate type. The objective was to synthesize, from the scientific literature published between 2015 and 2025, the co-substrate combinations, mixture proportions, and pretreatment strategies associated with the highest biogas yields in the anaerobic digestion of agro-industrial waste.

Contextualization and analysis

This section presents the search strategy, eligibility criteria, and data extraction procedure adopted for this systematic review, given the absence of a primary experimental component.

This research was developed based on a systematic literature review. Guidelines were adopted to define the articles analyzed, including database, language, keywords, publication year, and publication type. The literature search was conducted in the Science Direct, Scopus, and Web of Science databases, through the Journal Portal of the Coordination for the Improvement of Higher Education Personnel (Capes).

Research and review articles published between 2015 and 2025 were considered, in order to ensure the inclusion of up-to-date publications. The literature search in the databases was carried out using boolean operators and the following keywords: ("biogas production" OR "produção de biogás") AND ("anaerobic digestion" OR "digestão anaeróbia") AND ("agro-industrial waste" OR "agroindustrial waste" OR "agroindustrial residues" OR "agricultural waste" OR "food processing waste" OR "resíduos agroindustriais" OR "resíduos agrícolas"). The retrieved results were then filtered according to the eligibility criteria.

Eligibility criteria

Subsequently, for each article, titles, abstracts, and keywords were analyzed to identify their relation to the research theme.

Table 1. Inclusion and exclusion criteria for the articles

Criterion	Inclusion	Exclusion
Substrate type	Agro-industrial residue (agricultural, livestock, agri-food)	Only urban/municipal organic waste
Data type	Quantitative biogas/methane yield data	Studies without quantitative yield data
Intervention type	Co-digestion, mixture proportion, and/or pretreatment reported	Mono-digestion without comparison
Document type	Original or peer-reviewed review article	Conference abstracts, book chapters, editorials
Language	Portuguese and English	Other languages
Accessibility	Full text available	Article without institutional access

Source: prepared by the authors.

Table 1 presents the selection and exclusion criteria applied to the articles included in the review. Duplicate documents and those outside the thematic scope were also excluded, as shown in the flowchart in Figure 1. Data processing and analysis were performed using R Studio software and Microsoft Excel spreadsheets.

Data extraction and synthesis

From each selected article, the following information was extracted: country of origin, article type (research or review), type of agro-industrial waste, inoculum type, mixture proportion, type of pretreatment applied, reactor operating condition (mesophilic or thermophilic), and biogas or methane yield.

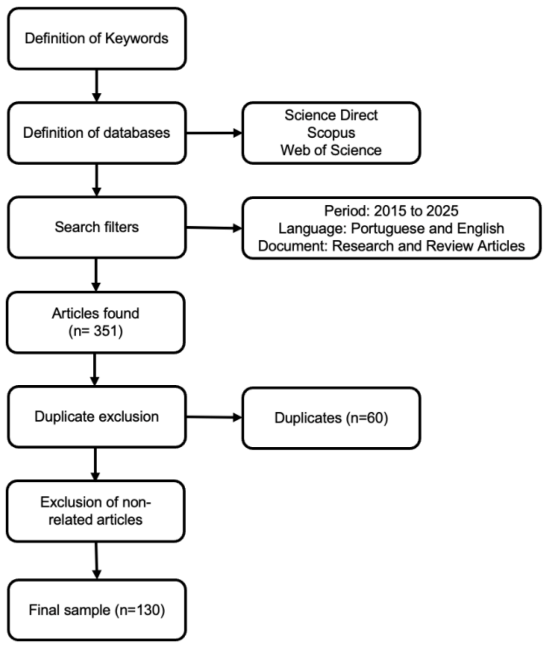

Figure 1. Methodological flowchart of the systematic literature review

Results and discussion

The literature search resulted in 351 research and review articles published between 2015 and 2025 across the three databases used. After exclusion for duplication, accessibility, and thematic relevance, 130 final articles were retained. The filtered articles were analyzed regarding bibliometric parameters and content.

Bibliometric overview

The field of energy recovery from agro-industrial waste is relatively recent, with relevant scientific output beginning in the late 2000s (Segundo et al., 2024). Regarding the temporal distribution of the selected articles, as illustrated in Figure 2, an exponential growth in scientific publications related to the field was observed. This growth was particularly pronounced in the most recent years investigated, especially in 2021 and 2025.

Before 2015, biogas was regarded merely as a by-product of effluent treatment, applied in a decentralized manner in industries and rural areas. Research during this period focused on identifying effluents and residues to be treated in reactors, without considering biogas as having significant energy and sustainability potential (Brémond et al., 2021). A gradual increase in the number of publications was observed from 2016 onward, shortly after global milestones such as the Paris Agreement and the 2030 Agenda. The Paris Agreement, established at the end of 2015, highlighted the need to rethink the energy sources used worldwide and to pursue sustainable and economically viable solutions, such as the use of gases generated through the anaerobic digestion of waste and effluents.

The peak in article production from 2021 onward reflects the urgency of the global energy transition, mainly through the application of agricultural and industrial residues. In addition, the data suggest an increase in the complexity of published studies, such as the use of two-stage reactors (Cremonez et al., 2021), the application of additives and catalysts in the anaerobic process (Afif and Pfeifer, 2022), residue pretreatment (Alagöz et al., 2018), and co-digestion (Gao et al., 2021).

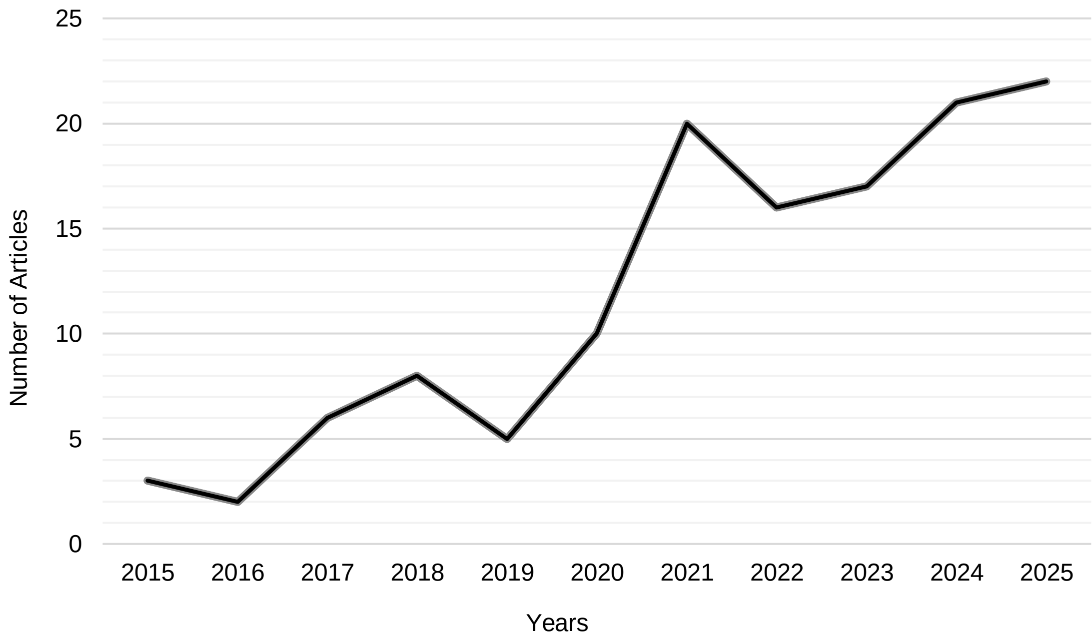

Figure 2. Number of articles per year

Regarding the origin of the publications, 49 countries with selected publications were identified. Of these, 25 countries had only one publication. Figure 3 presents the countries with two or more published articles. For classification purposes, the country considered was the one where the laboratory experiments were conducted or, in the case of literature reviews, the territory that constituted the central object of the study or the affiliation of the main author.

The geographic distribution of the analyzed publications (Figure 3) reveals the predominance of Brazil, with approximately 10.7% of the total sample (14 articles). In parallel, India and Italy follow, with nine articles each. When grouping the data by geographic blocks, it is observed that the Brazil-India-China-South Africa axis accounted for a significant share of the research conducted in developing countries, where anaerobic digestion is regarded as a solution for both sanitation and energy.

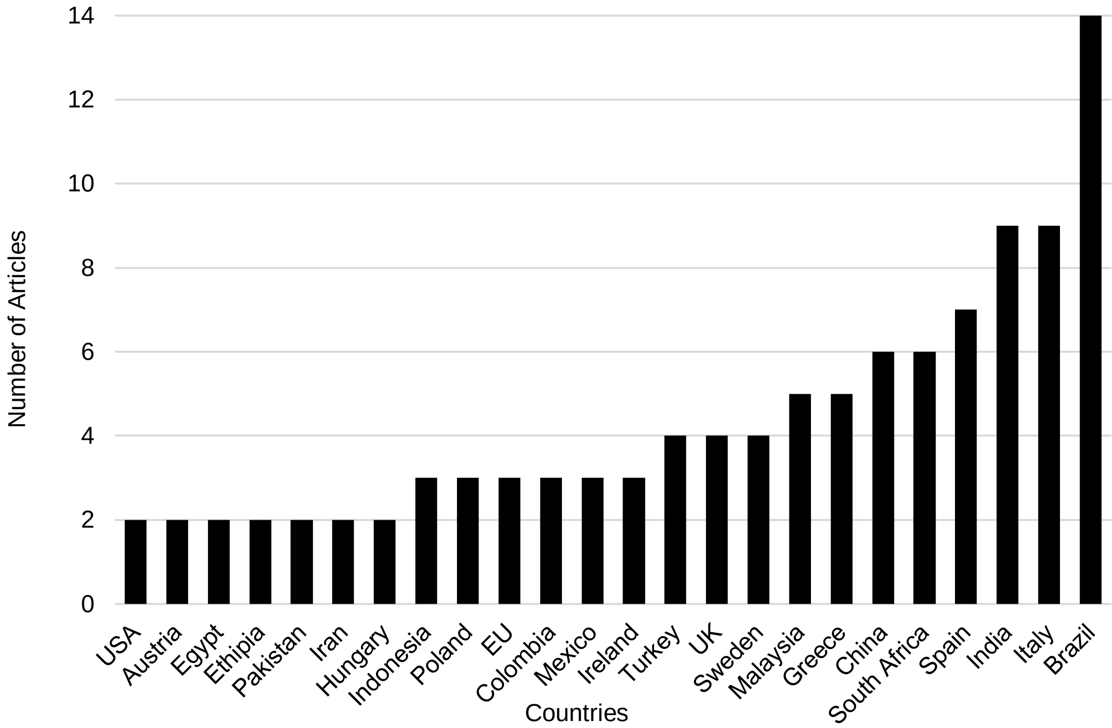

Figure 3. Number of articles per country

In Brazil, biogas production is driven by the large availability of biomass from agro-industrial activities (Porto et al., 2025), such as swine and poultry farming and the sugar-energy sector. Recent studies, such as that of Pereira et al. (2025), sought, through the anaerobic co-digestion of swine farming residues and pumpkin crop residues, to find the best methane production potential. In the same Brazilian context, the study conducted by Paranhos et al. (2020) evaluated the co-digestion of poultry litter together with lignocellulosic biomass in batch reactors. The authors concluded that the biogas generated from the anaerobic digestion of poultry waste would be able to supply half of the energy demand of a conventional farm. In addition, studies such as those by Gong and Lunelli (2024) and Rodrigues et al. (2021) sought to generate biogas from residues of the energy sector, such as sugarcane vinasse and crude glycerol, reinforcing substrate diversification in the Brazilian scenario.

In India, scientific output reflects the search for agro-industrial waste management solutions that align with the demand for sustainable, low-operational-cost energy sources. According to the study by Bose et al. (2025), anaerobic digestion of agro-industrial waste is a promising alternative for waste management and renewable energy generation. The study also highlights that a two-stage reactor configuration constitutes an effective solution for treating complex, biologically recalcitrant substrates. Dey and Thomson (2023) studied sectors considered neglected in other research conducted in the country, such as agro-industries from different sectors, obtaining an estimated annual biomethane production of 3.514 million m3.

In the literature originating from Italy, emphasis is placed on optimization strategies for operational efficiency, with a focus on pretreatment and co-digestion of residues. In the study by Messineo et al. (2020), a comprehensive review was presented on methane recovery from olive residues, a critical environmental liability in the Mediterranean region due to its toxicity and low biodegradability. The authors highlighted that the use of pretreatments can induce higher methane yields. In addition, the study showed that co-digestion with animal manure reduces the dependence on chemical inputs, while digested inoculum can convert up to 89% of the organic load into methane. Finally, in the Italian context, Lenzuni et al. (2024) identified that the high concentration of phenols and substrate acidity in solid residues from olive oil extraction are significant barriers to anaerobic digestion.

The marked increase in articles published in emerging countries, as shown in Figure 3, indicates that biogas technology has become a key tool for sustainable development, particularly in the Global South. Several factors may influence the development of further research in the field, such as the predominance of agricultural activities and processing industries, as well as higher average temperatures, which facilitate the operation of anaerobic digestion units.

Regarding keyword co-occurrence, 50 main keywords from the literature database were analyzed. The purpose of the analysis presented in Figure 4 was to identify the terms most frequently used by researchers and the intrinsic relationships among them.

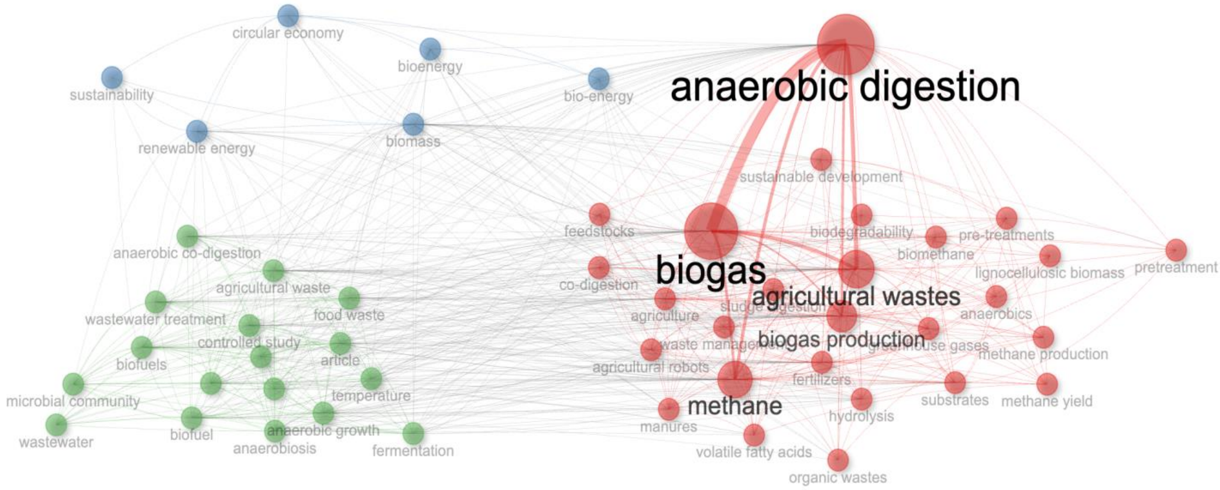

Figure 4. Keyword co-occurrence network

The co-occurrence network (Figure 4) revealed the formation of three distinct clusters, grouping terms with strong thematic correlation. The first, represented in red, is the most expressive and focuses on technical aspects and system productivity. This cluster comprises terms such as "anaerobic digestion," "biogas," "agricultural wastes," and "methane," which relate to various terms within the field of study. In addition, the presence of other terms such as "lignocellulosic," "biomass," and "pre-treatment" indicates the development of methods for treating agro-industrial waste to ensure the feasibility of biogas production.

The second cluster, identified in green, focuses on the biological dynamics related to the biodigestion process for sanitation purposes. Terms such as "wastewater treatment," "anaerobic growth," and "microbial community" reveal a central concern with microbial growth and the internal stability of anaerobic reactors. In this cluster, biogas production is approached from the perspective of biological treatment, in which microbiological efficiency is a key strategy for organic load degradation. Finally, the blue cluster represents the macroeconomic and political dimension of the field. Through terms such as "circular economy," "sustainability," and "renewable energy," it is observed that biogas acts as a strategic asset in the energy transition. The connection between "biomass" and terms from the other two clusters indicates that it is the material link between circular economy theory and the practice of methane generation through biodegradation.

Most effective co-substrate combinations

In order to identify which substrate combinations achieve the greatest success in biogas yield, Table 2 systematizes the combinations of agro-industrial residue and inoculum/co-substrate identified in the studies included in this review. The reported biogas or methane yield was associated, when available, with the relative gain over mono-digestion of the same substrate.

A total of 48 studies addressing, at some stage, the co-digestion of residues were identified. Of these, only 27 articles reported yield data relative to mono-digestion of the substrate. Table 2 presents the most significant co-digestion yield data found relative to mono-digestion. The studies with yield data from Rodrigues et al. (2021), with +464% methane yield in the co-digestion of crude glycerol and citrus vinasse relative to the glycerol-only control; Correa et al. (2025), with +434% in the co-digestion of olive pomace with pig manure; Gao et al. (2021), with +414% in the co-digestion of mushroom substrate with cattle manure; and Meier et al. (2020), with +400% hydrogen production, presented the highest percentage gains. These four studies share a common factor: the main substrate performs very poorly under mono-digestion, which inflates the relative percentage gain.

Table 2. Studies on the co-digestion of agro-industrial residues

Residue + co-substrate	Yield	Metric	References
Two-phase olive pomace + pig manure	+434% (53→283 mL CH4 g-1 VS)	CH4	Correa et al. (2025)
Crude glycerol + agro-industrial residues	+464% (vs. glycerol-only control)	CH4	Rodrigues et al. (2021)
Spent mushroom substrate + cattle manure	+414% (TS = 15%, adjusted C/N)	Cumulative CH4	Gao et al. (2021)
Cassava wastewater + crude glycerol (3%)	+400% (H2 production, not CH4)	H2	Meier et al. (2020)
Dairy residue + cattle/goat manure	+111.6% (synergistic BMP)	CH4 (BMP)	López et al. (2025)
Food waste + wheat straw + cattle manure	+130.9% (biogas) / +161.3% (CH4)	Biogas/CH4	Chaher et al. (2023)
Pumpkin residues + pig manure	+78.8% (biogas) / +86 to 113% (CH4)	Biogas/CH4	Pereira et al. (2025)
Ensiled crops + manure	+43 to 48%	CH4	Riau et al. (2021)
Corn cob + poultry litter (F/I = 0.5)	+44 to 55% (total production)	CH4	Paranhos et al. (2020)
Distillery wastewater + sludge	+72%	CH4	Ripoll et al. (2022)
Pretreated corn residue + food waste	+103% (2.03x)	Cumulative CH4	Anjum et al. (2018)
Cotton gin/winery/olive pomace + synthetic organic fraction	+88 to 119% (34-47% for juice residue)	CH4	Pellera and Gidarakos (2017)
Mezcal vinasse (75-25 mixture)	+26.7%	Cumulative CH4	Zelaya-Benavidez et al. (2022)
Poultry litter + food waste (75:25 v/v)	Mono-digestion outperformed co-digestion (0.649 vs. 0.417 L kg-1 VS)	Biogas	Naidu et al. (2024)

Source: prepared by the authors.

Considering a yield gain range between 40% and 165%, agro-industrial residues digested are frequently reported in the literature, as in the studies by Chaher et al. (2023), Pereira et al. (2025), López et al. (2025), Anjum et al. (2018), Pellera and Gidarakos (2017), Ripoll et al. (2022), Paranhos et al. (2020), and Riau et al. (2021). These studies generally present the combination of a lignocellulosic or more recalcitrant substrate (straw and bagasse) with fast-degrading substrates (manure, litter, and food waste), which corrects the C/N ratio and reduces the risk of acidification in anaerobic reactors.

However, in the study by Naidu et al. (2024), the co-digestion of poultry litter with kitchen waste did not outperform mono-digestion of the litter, although it proved more stable under operational conditions such as temperature. Similarly, Szilágyi et al. (2021) reported a 66% decrease in biogas yield during the continuous co-digestion of tomato residues with corn straw, compared to straw alone. Both the studies by Naidu et al. (2024) and Paranhos et al. (2020) concluded that a high carbon-to-nitrogen ratio can reduce biogas production, whereas a very low ratio can favor ammonia accumulation, a compound commonly present in poultry manure, thereby decreasing methane yield. It is therefore evident that an increase in biogas yield through co-digestion is not guaranteed, as it depends on the balance between substrates (C/N), the food-to-inoculum ratio (F/I), the presence of methanogenic bacteria and archaea, economic and operational feasibility, among other factors.

In the scenario of residues from the sugar-and-ethanol sector, sugarcane bagasse and vinasse stand out as residues with low biodegradability and limited applicability (Go et al., 2019; Zelaya-Benavidez et al., 2022). When vinasse is degraded together with effluent or granular sludge in a reactor, it shows expressive production potential of 302 NL kg-1 VS or 229.08 mmol CH4 L-1 (Ripoll et al., 2022; Rodrigues et al., 2021). Sugarcane bagasse is characterized as a residue from the sugar-energy sector with a high solids concentration, which can reach up to 21,000 mg COD L-1, according to the study by Liu et al. (2020).

Among the various residues generated by the agricultural sector, straws and grain husks, such as rice and wheat, are still underutilized in the production process and are frequently incinerated, even though they present high methane production potential (Nessem et al., 2025). These materials may present a high chemical oxygen demand due to their cellulosic compounds, but low nutrient availability for microbial degradation, especially nitrogen (Ahmed et al., 2024). In this scenario, methanogenic activity can be favored by degrading or co-digesting straws and husks with high-nitrogen-load effluent or sludge, such as swine farming effluent. Liu and Pan (2023) reported an initial COD of 12,027.52 mg L-1, demonstrating that combining straw and husk substrate with swine effluent can favor the use of organic matter and microbial activity during biodigestion.

In summary, the combinations with the highest percentage gains are concentrated in pairs that associate easily degradable substrates with a low C/N ratio (crude glycerol, pig manure, animal manure) with more recalcitrant substrates (lignocellulosic residues, bagasse, cobs). Meanwhile, co-digestion performance itself requires prior analysis to ensure a percentage increase in biogas yield from the digestion of agro-industrial substrates.

Most effective mixture proportions and parameters

With the objective of improving biogas production yield, this section sought to identify the ideal substrate mixture proportions. The carbon-to-nitrogen (C/N) ratio is the parameter most frequently associated with mixture performance among the studies that explicitly report this data. Table 3 systematizes the studies found that report a mixture proportion or parameter, expressed as a percentage of volatile solids, a biomass ratio, or C/N ratio.

Table 3. Mixture proportions found in the literature

Substrate	Proportion or C/N ratio reported	Reference
Sugarcane straw	C/N = 20.4:1	Devi et al. (2022)
General recommendation for agro-industrial anaerobic digestion (review)	Optimal C/N = 26:1; substrate/inoculum ratio (S/I) > 2.0	Bose et al. (2025)
Olive pomace + cattle manure (2POMW:CM)	60:40, optimal C/N of 20-30	Rubio et al. (2022)
Distillery residue + textile residue (CoS)	7:3 (VS and C/N basis)	Szilágyi et al. (2021)
Corn straw + cattle manure + vegetable residue	40:10:0.5 (dry basis)	Su et al. (2020)
Coffee pulp + chicken feathers + cow manure	25% TS; C/N = 25 (g/g); ratio 2:1:1	Sumardiono et al. (2021)
Poultry litter + kitchen waste/newspaper waste	75:25 (v/v) or 90:10 (v/v)	Naidu et al. (2024)
Food waste + poultry litter	1:1	Akinsola et al. (2025)
Corn cob + poultry litter	F/I ratio = 0.5 g VS g-1 VS (most favorable to yield)	Paranhos et al. (2020)

Source: prepared by the authors.

The data in Table 3 confirm the optimal C/N range between 20:1 and 30:1 already established in the consolidated literature, with systematic deviations in both directions: C/N ratios above 30:1 (e.g., newspaper waste, C/N = 43, in Naidu et al., 2024) impair performance due to an excess of lignocellulosic carbon that is difficult to degrade; ratios below 20:1 favor the accumulation of free ammonia, especially in protein-rich substrates such as poultry manure. Regarding the substrate/inoculum ratio (F/I or S/I), Paranhos et al. (2020) and Pellera and Gidarakos (2017) converge in indicating that lower ratios (F/I ≈ 0.5) favor yield by reducing the risk of volatile fatty acid accumulation, although at the cost of lower volumetric treatment capacity.

While Rubio et al. (2022) and Naidu et al. (2024) report direct mass or volumetric ratios between the two substrates (60:40 w/w; 75:25 or 90:10 v/v), Bose et al. (2025) expresses the same idea through the substrate/inoculum (S/I) ratio, and Sumardiono et al. (2021) combines total solids percentage with the C/N ratio and a three-component mass proportion simultaneously (2:1:1). This absence of a standard parameter hinders direct comparison between studies, even though all result in the same optimal C/N range. It is also worth noting that only two of the nine studies in Table 3, Su et al. (2020) and Sumardiono et al. (2021), go beyond binary co-digestion, testing three-substrate mixtures simultaneously, suggesting that mixture optimization remains underexplored in the literature.

Some studies did not report C/N values but tested ideal residue percentages; for example, in fruit residues, tested proportions ranged from 20% to 50% substrate (4.65 to 14.50 g L-1 VS), corresponding to yields of 4.6 to 202.6 L CH4 kg-1 VS, reaching up to 301.7 L CH4 kg-1 VS at the extremes of the range (Chubur et al., 2024; Husein et al., 2025). This range reflects the high biodegradability of soluble fruit sugars, such as fructose and glucose; however, the excess of easily digestible carbohydrates can trigger accelerated acidogenesis, requiring inocula with greater pH buffering capacity. For olive residues, the volatile solids fraction ranged from 15.7% to 75% VS, associated with a relatively stable specific methane yield, between 154.1 and 183.2 mL CH4 g-1 VS (Pellera and Gidarakos, 2018; Rubio et al., 2022).

Most effective pretreatments

Pretreatment applied to agro-industrial residues promotes the degradation of sugars and proteins and improves the effective adsorption and transmembrane transfer of microorganisms to the substrates, thereby ensuring the efficient conversion of biomass into biogas (Zou et al., 2024). Some studies sought to apply different pretreatment methods relative to the yield of the untreated substrate. Table 4 organizes a selection of articles by mechanism, showing that pretreatment effectiveness is strongly dependent on the type of substrate and the technique employed.

Table 4. Pretreatment applied to residues and reported yield gain

Method	Pretreatment and substrate	Reported gain	Reference
Physical	Ultrasound in cheese whey (251-694 Wh kg-1 VS)	+16%	Sar et al. (2022)
Physical	Ultrasound in corn residue (110 W, 3 min)	+41%	Rahimi-Ajdadi and Esmaili (2020)
Physical/thermal	Hot water extraction (HWE) in rice/wheat straw	+20% to +222%	Ghimire et al. (2021)
Physical	Extrusion of lignocellulosic biomass	+190%	Sher et al. (2024)
Chemical	NaOH (3-7% w/v) + size reduction, empty palm bunch	+90%	Ab Aziz et al. (2025)
Chemical	H2O2 (condition B) in orange juice residue	385.6 mL CH4 g-1 VSP (mostly lower than raw; EtOH in cotton pomace: +18.7%)	Pellera and Gidarakos (2018)
Biological	Fungal delignification in rice straw	+122%	Parvathy Eswari et al. (2023)
Biological	Fungal pretreatment (Aspergillus nidulans) in corn straw	+84% to 2x	Szűcs et al. (2021)
Biological	Ensiling of agricultural residues (3-12 months)	+43 to 48%	Riau et al. (2021)
Enzymatic	Enzymes (MethaPlus + Hemicellulase) in olive residue, 55 °C	+1.3%	Afif and Pfeifer (2022)
Physical/comparison	Ultrasound vs. microwave in sludge + olive/grape pomace	Ultrasound +11-14%; microwave +30-32%	Alagöz et al. (2018)

Source: prepared by the authors.

Among physical and mechanical pretreatments, particle size reduction and increased surface area availability for enzymatic action constitute a common mechanism across different techniques. Rahimi-Ajdadi and Esmaili (2020) obtained a 41% gain in methane yield from corn residue after ultrasonication, while Sar et al. (2022) reported a more modest gain (16%) for the same type of treatment applied to cheese whey; this susceptibility of the substrate to ultrasound varies according to its original biochemical composition.

For the hot water extraction method, tested by Ghimire et al. (2021), gains between 20% (wheat straw) and 222% (rice straw) were produced, and the extrusion of lignocellulosic biomass reviewed by Sher et al. (2024) achieved a 190% increase in biomethane yield. These results reinforce that, even within a single mechanism category, the reported gain range varies according to the specific substrate and technique employed.

Chemical pretreatment, in turn, is experimentally validated by the results of Pellera and Gidarakos (2018), who demonstrated that conditions of greater chemical severity produce better results for lignocellulosic residues, confirming the premise that hydrolysis depends on the destabilization of the lignin-cellulose-hemicellulose complex (Olatunji et al., 2021). The analyses of Ab Aziz et al. (2025) obtained a gain of more than 90% with NaOH (3-7% w/v) combined with particle size reduction in empty palm bunch. However, the study by Pellera and Gidarakos (2018) itself shows that this relationship is not linear: of the eight reagent/severity combinations tested by the authors, most reduced the methane potential relative to the untreated raw substrate, and only the combination of cotton pomace with ethanol resulted in a net gain (+18.7%). This contrast reinforces that the effectiveness of chemical pretreatment is strongly dependent on the severity and reagent employed, which can also lead to the formation of by-products that inhibit methanogenic activity under more aggressive conditions.

Biological pretreatment of agro-industrial residues is still underrepresented. However, the studies that applied treatment based on microorganisms obtained high yields. For example, fungal delignification of rice straw increased biogas yield by 122% (Parvathy Eswari et al., 2023), and pretreatment with the fungus Aspergillus nidulans in corn straw doubled the yield relative to the control (Szűcs et al., 2021). Ensiling of agricultural residues for periods of 3 to 12 months, addressed by Riau et al. (2021) as a low-energy-cost biological pretreatment, produced gains of 43% to 48%. These results suggest that manipulating the microbial community prior to digestion constitutes an optimization pathway with underexplored potential in the agro-industrial literature reviewed.

Alagöz et al. (2018) compared ultrasound and microwave pretreatment in the co-digestion of sewage sludge with olive and grape pomace: microwave produced the highest absolute biogas yield (+30% to +32%), but ultrasound (+11% to +14%) demonstrated approximately nine times higher energy efficiency, since the specific energy applied was substantially lower. This result illustrates a recurring tension in the pretreatment literature: the method with the highest absolute yield is not always the most economically and operationally viable.

The effectiveness of pretreatment is inseparable from substrate type and the mechanism employed: for lignocellulosic residues, overcoming the hydrolytic barrier imposed by the lignin-cellulose-hemicellulose complex is the determining factor (Olatunji et al., 2021; Pellera and Gidarakos, 2018), whereas for oleaginous residues and substrates with high organic loads, biological strategies have proven equally or more effective than traditional physicochemical disruption. This finding already pointed to the need for future research to develop new pretreatment types and test their application in large-scale reactors, in order to enable the transposition of laboratory results to industrial plants and decentralized units.

Another mechanism identified in the studies was the additive category, which is conceptually distinct from pretreatments but still acts to maximize biogas yield from the same agro-industrial residue. Additives complementary to the substrate in the digestion process include zero-valent iron (Pirmoghani et al., 2025), biochar (Nessem et al., 2025; Rowan et al., 2022), and conductive granular activated carbon (Kalantzis et al., 2023), which produced gains between 32% and 149.7%, values comparable to those of the most effective chemical and biological pretreatments in the sample.

General aspects and critical synthesis

The literature review revealed that current trends in biogas production converge toward the use of diverse substrates, including lignocellulosic residues such as vinasse, and toward the use of technologies such as physicochemical pretreatment and anaerobic co-digestion. In addition, an increase was observed in the number of studies that regard biogas as an energy alternative in the face of climate change, rather than solely as a waste disposal measure.

The heterogeneity of biogas production units, with at least 12 distinct units identified, prevents direct comparison across most of the studies and analyses. Similarly, the percentage gains in biogas yield reported for co-digestion and pretreatment use different comparison bases (versus mono-digestion of the main substrate, versus an additive-free control, versus untreated raw substrate, versus the lowest-performing scenario tested), which requires caution when comparing percentages across studies. This fragmentation of units, already noted by Cremonez et al. (2021), remains unresolved even after a decade of exponential growth in mapped publications.

From an economic standpoint, fewer than ten studies reported cost, payback, or economic feasibility indicators associated with biogas yield from agro-industrial residues. This scarcity of economic indicators is particularly critical because it compromises the transposition of laboratory findings into real-scale investment decisions. Among the few studies that report this type of data, Sar et al. (2022) estimate a 10-year payback for the co-digestion of dairy residues, and Naidu et al. (2024) project the generation of 189.46 MWh year-1 for a full-scale plant based on poultry manure. In the absence of an economic perspective, the reviewed literature is able to answer which combinations, proportions, and pretreatments maximize technical yield, but not which of these paths is the most economically viable to implement. The development of these pillars is essential for the sector to reach higher levels of scientific and technological maturity, enabling the anaerobic digestion of agro-industrial residues to transition from a technical solution to a consolidated economic pillar in the global economy.

Conclusion

Anaerobic co-digestion produced the largest relative gains in biogas or methane yield when an easily degradable, low carbon-to-nitrogen substrate (crude glycerol, swine manure, or poultry litter) was paired with a more recalcitrant substrate, such as olive pomace, spent mushroom substrate, or lignocellulosic residues.

Co-substrate selection should be guided primarily by the carbon-to-nitrogen balance between mixture components rather than by regional residue availability alone, since combinations lacking this balance did not consistently outperform mono-digestion.

A carbon-to-nitrogen ratio between 20:1 and 30:1 was the mixture parameter most consistently associated with high biogas yields; ratios above this range reduced performance due to excess recalcitrant carbon, while ratios below it favored free ammonia accumulation.

The diversity of parameters used to express mixture proportion across studies (mass ratio, volumetric ratio, substrate/inoculum ratio, volatile solids percentage) limits direct comparison and the formulation of a single, universally replicable quantitative recommendation.

Pretreatment effectiveness was strongly dependent on substrate type and technique: physical, thermal, and chemical pretreatments increased methane yield between 16% and 222%, while biological pretreatments (fungal delignification and ensiling) achieved comparable or higher gains, between 32% and 149.7%, indicating that microbial community manipulation is a relevant and still underexplored optimization pathway.

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