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ANAEROBIC DIGESTION AS A BIOPROCESS FOR BIOGAS PRODUCTION FROM ORGANIC WASTE: AN INTEGRATIVE REVIEW

DIGESTÃO ANAERÓBIA COMO BIOPROCESSO PARA A PRODUÇÃO DE BIOGÁS A PARTIR DE RESÍDUOS ORGÂNICOS: UMA REVISÃO INTEGRATIVA

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ABSTRACT

Anaerobic digestion is a microbial bioprocess capable of combining organic-waste stabilization with the recovery of energy as biogas and nutrients in digestate. Nevertheless, the technical potential of a residue cannot be inferred from its organic content alone because substrate variability, inhibitory compounds, reactor configuration, and process control determine methane production and stability. This integrative review critically analyzed anaerobic digestion as a route for biogas production from food waste, animal manure, agricultural residues, and related organic streams. Publications from 2020 to 2025 were identified through structured searches in Google Scholar and the CAPES Periodicals Portal, followed by targeted verification in institutional repositories and publisher pages. Fifteen publications were retained for qualitative synthesis and classified according to study design, evidence role, substrate, system, and principal limitation. The evidence indicates that hydrolysis, acidogenesis, acetogenesis, and methanogenesis must remain kinetically balanced; rapid acidification, ammonia, long-chain fatty acids, sulfide, and insufficient buffering can destabilize this balance. Co-digestion may improve nutrient complementarity and buffering, but synergy is feedstock- and ratio-specific. Food waste and animal manure showed practical potential, whereas lignocellulosic and contaminated streams often required pretreatment or stricter quality control. The literature was dominated by reviews, academic works, and laboratory or pilot studies, with limited standardized methane potential testing, long-term operation, techno-economic analysis, life-cycle assessment, and digestate-safety evaluation. Anaerobic digestion should therefore be designed as an integrated residue-reactor-product system rather than presented as an intrinsically sustainable waste treatment.

Keywords: Anaerobic digestion; Biogas; Organic waste; Co-digestion; Process stability; Circular bioeconomy.

RESUMO

A digestão anaeróbia é um bioprocesso microbiano capaz de associar a estabilização de resíduos orgânicos à recuperação de energia na forma de biogás e de nutrientes presentes no digestato. Entretanto, o potencial técnico de um resíduo não pode ser determinado exclusivamente pelo seu conteúdo orgânico, uma vez que a variabilidade dos substratos, a presença de compostos inibidores, a configuração dos reatores e o controle operacional influenciam a produção de metano e a estabilidade do processo. Esta revisão integrativa analisou criticamente a digestão anaeróbia como alternativa para a produção de biogás a partir de resíduos alimentares, dejetos animais, resíduos agrícolas e outras frações orgânicas relacionadas. Publicações de 2020 a 2025 foram identificadas por meio de buscas estruturadas no Google Acadêmico e no Portal de Periódicos da CAPES, seguidas de verificações direcionadas em repositórios institucionais e páginas das editoras. Quinze publicações foram selecionadas para a síntese qualitativa e classificadas de acordo com o delineamento do estudo, a natureza das evidências, o substrato utilizado, o sistema empregado e as principais limitações identificadas. As evidências indicam que as etapas de hidrólise, acidogênese, acetogênese e metanogênese devem permanecer cineticamente equilibradas, uma vez que a acidificação acelerada, o acúmulo de amônia, a presença de ácidos graxos de cadeia longa e sulfetos, bem como a capacidade insuficiente de tamponamento, podem comprometer esse equilíbrio. A codigestão pode favorecer a complementaridade nutricional e a capacidade de tamponamento do sistema; entretanto, seus efeitos sinérgicos dependem das características dos

substratos e das proporções utilizadas. Os resíduos alimentares e os dejetos animais apresentaram potencial de aplicação prática, enquanto os resíduos lignocelulósicos e as frações orgânicas contaminadas frequentemente demandaram pré-tratamentos ou controles de qualidade mais rigorosos. A literatura analisada apresentou predominância de artigos de revisão, trabalhos acadêmicos e estudos conduzidos em escala laboratorial ou piloto, evidenciando limitações relacionadas à padronização dos ensaios de potencial bioquímico de metano, à operação prolongada dos sistemas, às análises técnico-econômicas, às avaliações do ciclo de vida e à investigação da segurança do digestato. Portanto, a digestão anaeróbia deve ser concebida como um sistema integrado entre resíduo, reator e produtos obtidos, em vez de ser apresentada como uma tecnologia de tratamento de resíduos intrinsecamente sustentável.
Palavras-chave: Digestão anaeróbia; Biogás; Resíduos orgânicos; Codigestão; Estabilidade do processo; Bioeconomia circular.

1. INTRODUCTION

Organic residues generated by households, food services, livestock production, wastewater treatment, and agro-industrial activities contain biodegradable carbon that can be converted microbially under oxygen-free conditions. Anaerobic digestion (AD) is attractive because it simultaneously reduces the biodegradable organic load, generates a methane-rich gas, and produces a nutrient-containing digestate. Biogas may be used for heat and electricity or upgraded to biomethane, while digestate may return nutrients and organic matter to soil when its agronomic quality and safety are demonstrated. This combination positions AD at the intersection of waste management, renewable energy, nutrient recovery, and

circular bioeconomy (Lins *et al.*, 2022; Pilarska *et al.*, 2023; He *et al.*, 2024).

The biological conversion is performed by interacting microbial guilds rather than by a single organism or reaction. Hydrolytic and fermentative microorganisms release soluble products and volatile fatty acids; syntrophic bacteria convert intermediates to acetate, hydrogen, and carbon dioxide; and methanogenic archaea form methane through acetoclastic and hydrogenotrophic routes. Because the steps are coupled, an apparently favorable substrate can still cause failure when acid formation exceeds methane conversion, alkalinity is insufficient, or ammonia, sulfide, salts, long-chain fatty acids, or pretreatment-derived compounds inhibit the community. Process stability therefore depends on the relationship among feedstock composition, inoculum, organic loading, retention time, temperature, pH, mass transfer, and reactor operation (Xu *et al.*, 2018; Karki *et al.*, 2021; He *et al.*, 2024).

This systems perspective is particularly relevant for food waste and animal manure. Food residues are generally wet and readily biodegradable, but their rapid fermentation can lead to volatile fatty acid accumulation and low buffering capacity. Manure provides alkalinity, nutrients, and a microbial inoculum, yet excessive nitrogen may increase free-ammonia stress. Lignocellulosic agricultural residues are abundant but hydrolysis-limited, whereas lipid-rich streams have high theoretical methane potential and a simultaneous risk of long-chain fatty acid inhibition. Co-digestion can compensate for some of these limitations, although positive interactions cannot be assumed without testing feedstock ratios and operating conditions (Karki *et al.*, 2021; Pilarska *et al.*, 2023).

Brazilian publications describe substantial opportunities for institutional food waste, livestock manure, and agricultural residues. However, many reports move directly from waste availability to claims of economic and environmental benefit. Such extrapolation may overlook collection and storage, seasonal variation, reactor heating and mixing, gas cleaning, methane leakage, digestate management, maintenance, and the cost of converting gas into usable energy. In addition, results from batch biochemical methane potential tests, pilot digesters, narrative reviews, and full-scale plants represent different levels of evidence and should not be treated as methodologically equivalent (Carvalho *et al.*, 2022; Almeida, 2024; Daron; Osorio, 2025).

A critical synthesis is therefore justified to distinguish demonstrated process performance from technical potential, identify the conditions that govern stable methane production, and clarify the evidence still required for scale-up. The objective of this review was to analyze anaerobic digestion as a bioprocess for biogas production from organic waste. Specifically, it sought to: (i) characterize the principal substrates and evidence types reported in the selected literature; (ii) integrate the microbial, compositional, and operational mechanisms controlling performance; (iii) compare reactor and co-digestion strategies; (iv) critically appraise environmental and economic claims; and (v) define research priorities for reproducible and sustainable implementation.

2. METHODOLOGY

2.1. Study Design And Research Question

A descriptive and analytical integrative review was conducted to combine empirical studies, technical documents, theses, dissertations, and peer-reviewed reviews with heterogeneous designs. The approach was selected because the available evidence did not support statistical pooling and because the research objective required comparison of biological mechanisms, operating conditions, technological configurations, and sustainability claims. Integrative reviews permit the inclusion of diverse evidence while requiring explicit classification of its role and limitations (Whittemore; Knafl, 2005; Mendes *et al.*, 2008; Snyder, 2019).

The guiding question was: Which organic residues and anaerobic-digestion systems were evaluated for biogas production between 2020 and 2025, and which compositional, microbial, operational, economic, and environmental factors conditioned the reported performance and feasibility?

2.2. Information Sources And Search Strategy

The original literature search covered publications issued from 2020 to 2025 in Google Scholar and the CAPES Periodicals Portal. Search expressions combined controlled concepts and free-text terms in Portuguese and English. Official journal pages and institutional repositories were subsequently used to confirm authorship, publication year, document type, pagination, DOI or persistent URL, and access to the complete text. Foundational publications outside the time window were used only to explain established mechanisms or review methodology and were not classified as records in the principal evidence corpus.

Table 1. Search strategy and verification procedures.

Source	Core expression or procedure	Filters and purpose
Google Scholar	("digestão anaeróbia" OR "anaerobic digestion") AND (biogás OR biogas) AND ("resíduos orgânicos" OR "organic waste")	2020-2025; Portuguese or English; full text
CAPES Periodicals Portal	(biodigestor* OR digester*) AND (resíduo* OR waste) AND (metano OR methane)	2020-2025; academic and peer-reviewed records
Repository and publisher verification	Exact-title and DOI searches on official institutional or journal pages	Confirm identity, design, metadata, and source traceability

Source: Prepared by the author (2026).

2.3. Eligibility Criteria And Study Selection

Eligible records were written in Portuguese or English, published between 2020 and 2025, available in full text, and focused on AD, biodigesters, biogas, biomethane, or digestate from organic residues. Primary laboratory, pilot, and applied studies were eligible when the substrate and system were identifiable. Reviews, theses, dissertations, final academic papers, and technical publications were retained when their objectives, methods, and evidence basis could be appraised. Records addressing food waste, animal manure, agricultural residues, sewage sludge, or mixed organic streams were considered within scope.

Duplicate records, abstracts without full text, opinion pieces, commercial webpages, documents without an identifiable method or evidence base, and studies centered on aerobic treatment, landfill-gas recovery, incineration, gasification, or pyrolysis were

excluded. Titles and abstracts were screened before full-text assessment. Fifteen publications were retained for the qualitative synthesis. Because complete counts of records retrieved, deduplicated, and excluded were not preserved in the original search, a retrospective PRISMA flow diagram was not constructed with undocumented numbers.

2.4. Data Extraction, Critical Appraisal, And Synthesis

For each publication, the following information was extracted: authorship and year; publication type; evidence role; substrate; reactor or digestion mode; scale; relevant operating variables; main result; environmental or economic claim; and limitation for interpretation. Evidence was classified as direct when the study measured digestion or methane-related outcomes in a defined system, and as contextual when it synthesized literature, discussed applications, or described technology without producing directly comparable process data.

Methodological quality was appraised qualitatively according to clarity of the objective, substrate characterization, description of inoculum and reactor conditions, definition of response variables, duration or retention time, gas quantification, presence of controls or comparators, and correspondence between results and conclusions. A numerical score was not assigned because the evidence included laboratory experiments, pilot studies, dissertations, technical reports, and narrative reviews. The thematic synthesis integrated: biochemical and microbial foundations; substrate composition and co-digestion; stability and inhibition; reactor configuration and scale; product recovery; and economic and environmental feasibility.

2.5. Methodological Limitations Of The Review

The review has four principal limitations. First, the use of Google Scholar and the CAPES portal does not provide the same reproducible export and indexing structure as a search restricted to bibliographic databases. Second, the original screening log was not preserved, preventing auditable reconstruction of the number of records at each stage. Third, the corpus contains a large proportion of secondary and academic documents, which are informative for mapping the Brazilian context but provide less direct evidence than replicated reactor studies. Fourth, heterogeneous substrates, endpoints, scales, and reporting practices precluded meta-analysis. The conclusions are consequently analytical and conditional rather than quantitative estimates of a universal effect.

3. RESULTS AND DISCUSSION

3.1. Evidence Profile And Strength

The 15 retained publications were distributed between 2021 and 2025. Four records provided direct experimental or pilot-scale evidence, whereas the remainder consisted of reviews, technical syntheses, dissertations, monographs, or contextual analyses. Food waste and animal manure were the most recurrent substrates. Agricultural residues, mixed organic wastes, and digestate use were discussed more often as potential applications than as standardized, long-term reactor trials. The evidence profile therefore supports a critical map of mechanisms and implementation conditions but does not support a pooled methane yield or a universal ranking of substrates.

Table 2. Critical synthesis of the publications retained in the analytical corpus.

Study	Design and evidence role	Material or system	Principal contribution and critical limitation
Rodrigues *et al.* (2021)	Applied technical study; direct	Sheep and cattle manure; batch co-digestion	Shows the relevance of controlled mixture proportions in batch digestion. Limitation: narrow feedstock and operating context.
Malinowsky (2021)	Doctoral study; direct	Food waste; pilot two-stage digestion	Demonstrates the value of separating acidification and methanogenesis. Limitation: one pilot configuration and site-specific feedstock.
Karki *et al.* (2021)	Critical review; contextual	Multiple co-substrates and microbial systems	Explains nutrient complementarity, stability, and microbial interactions in co-digestion. Limitation: heterogeneous studies prevent a universal optimal ratio.
Holliger *et al.* (2021)	Methodological commentary; contextual	Biochemical methane potential testing	Defines requirements for more comparable BMP validation. Limitation: laboratory potential does not establish continuous-reactor performance.
Carvalho *et al.* (2022)	Literature review; contextual	Animal and organic residues; rural	Synthesizes technological, environmental, and

		and urban applications	economic dimensions. Limitation: no original reactor trial or complete techno-economic model.
Gomes (2022)	Undergraduate monograph; contextual	Multiple organic residues and biodigesters	Highlights substrate characterization and operating parameters. Limitation: secondary evidence and limited analytical depth.
Lins *et al.* (2022)	Peer-reviewed review; contextual	Biogas use and Sustainable Development Goals	Connects energy recovery with environmental and social objectives. Limitation: alignment with goals does not quantify life-cycle benefit.
Proença (2022)	Experimental final paper; direct	University-restaurant organic waste; batch assays	Quantifies gas composition and potential substitution of LPG. Limitation: batch potential and local mass balance do not establish full-scale continuity.
Rocha (2022)	Master's dissertation; direct	Popular-restaurant food waste	Characterizes methane-generation potential and the relevance of organic loading. Limitation: one waste source and limited transferability to mixed municipal waste.

Pilarska *et al.* (2023)	International review; contextual	Food waste; pretreatment, co-digestion, and reactor design	Integrates monitoring and optimization strategies. Limitation: reported operating optima remain study-specific.
Almeida (2024)	Master's dissertation; contextual	Agroindustry and livestock systems	Discusses energy efficiency and rural applications. Limitation: broad feasibility claims require site-specific cash-flow and performance data.
He *et al.* (2024)	International review; contextual	Food-waste anaerobic digestion	Synthesizes inhibition, microbial, and process-stability challenges. Limitation: review-level evidence does not replace standardized validation.
Souza *et al.* (2024)	Technical-school monograph; contextual	Biodigester types and organic-waste treatment	Provides an accessible comparison of configurations. Limitation: educational synthesis with low evidentiary weight for engineering decisions.
Cândido *et al.* (2025)	Exploratory review; contextual	Biodigesters in Brazil	Maps reported benefits and adoption challenges. Limitation: narrative selection and reliance on heterogeneous secondary sources.
Daron and Osorio (2025)	Narrative analysis; contextual	Agricultural residues in Brazilian agribusiness	Frames environmental, economic, and policy relevance. Limitation: benefits are not

			supported by a complete mass balance, LCA, or TEA.

Source: Prepared by the author from the included publications (2026).

The most important interpretive distinction was between methane potential and sustained process performance. Batch assays estimate the biodegradable methane potential of a defined substrate under a specific inoculum-to-substrate ratio and test duration. They do not reproduce feed fluctuation, washout, mixing, foaming, maintenance, gas losses, or digestate handling in a continuous plant. Standardization of controls, blanks, inoculum quality, gas normalization, and termination criteria improves comparability, but even a valid BMP remains a screening tool rather than proof of industrial feasibility (Holliger *et al.*, 2021).

3.2. Biochemical And Microbial Basis Of Anaerobic Digestion

Anaerobic digestion is conventionally described through hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This sequence is useful for interpretation but should not be understood as four isolated reactions. Hydrolytic enzymes convert particulate carbohydrates, proteins, and lipids into soluble sugars, amino acids, glycerol, and fatty acids. Fermentative bacteria then form volatile fatty acids, alcohols, hydrogen, and carbon dioxide. Syntrophic acetogens oxidize propionate, butyrate, and related products only when hydrogen-consuming partners maintain a favorable partial pressure. Finally, methanogenic archaea convert acetate or hydrogen and carbon dioxide to methane. The overall rate is governed by the slowest or most inhibited step rather than by total

organic matter alone (Malinowsky, 2021; Pilarska *et al.*, 2023; He *et al.*, 2024).

The principal stability problem is an imbalance between acid production and acid consumption. Highly fermentable food waste can be hydrolyzed and acidified faster than methanogens recover carbon as methane. Volatile fatty acids then consume alkalinity and depress pH, while the uncharged fraction of some acids becomes more toxic. Conversely, protein-rich substrates may release ammonia, whose un-ionized fraction increases with pH and temperature. Lipid-rich waste can provide high methane potential but release long-chain fatty acids that adsorb to biomass and impair mass transfer. Sulfate reduction competes for substrates and generates sulfide, which inhibits microorganisms and reduces gas quality. Monitoring pH alone may therefore detect failure late; alkalinity, volatile fatty acids, ammonia, gas composition, and specific gas production should be interpreted together (Xu *et al.*, 2018; He *et al.*, 2024).

Two-stage digestion separates the rapid hydrolytic-acidogenic reactions from the more sensitive methanogenic conversion. The arrangement can improve control when food waste acidifies rapidly and allows each stage to operate under conditions suited to its dominant guilds. Malinowsky (2021) provides direct pilot-scale evidence for this logic. Nevertheless, an additional reactor increases capital cost, instrumentation, pumping, and operational complexity. The decision to use two stages must therefore be based on measurable stability or recovery gains rather than on theoretical separation alone.

3.3. Substrate Composition, Biodegradability, And Co-Digestion

The selected studies confirm that 'organic waste' is not a uniform feedstock. Restaurant and household food residues usually contain high moisture and a readily biodegradable fraction, making them attractive for wet digestion. At the same time, composition varies with menus, seasons, sorting practices, packaging contamination, and storage. Rapidly degradable carbohydrates favor acid production; lipids increase potential energy but may generate long-chain fatty acids; proteins supply nitrogen and trace nutrients but may cause ammonia stress. Physical contaminants can damage pumps or accumulate in the reactor, while salts and cleaning chemicals may inhibit the microbial community (Rocha, 2022; Pilarska *et al.*, 2023).

Animal manure generally has lower specific methane potential than concentrated food waste, but it can supply buffering capacity, moisture, trace elements, and an adapted inoculum. Rodrigues *et al.* (2021) evaluated sheep and cattle manure in batch co-digestion, illustrating that performance depends on the mixture rather than on the identity of either manure alone. Agricultural and agro-industrial residues extend the feedstock base, although fibrous materials may be hydrolysis-limited and require size reduction, thermal, chemical, or biological pretreatment. Pretreatment should be justified by net methane gain after accounting for energy, chemical use, inhibitor formation, and wastewater generation.

Proença (2022) offers a useful example of direct but bounded evidence. Organic waste from a university restaurant generated an average of 830.5 ± 56.5 mL of biogas in the evaluated assays, with 48.55% CH4, and the estimated energy recovery could replace approximately 8.22% of the restaurant's LPG demand. The findings demonstrate measurable local potential, but they also show why

methane fraction, sulfur compounds, gas cleaning, collection efficiency, and scale must accompany volumetric gas data. The result cannot be transferred automatically to another restaurant with different waste generation, composition, or energy demand.

Co-digestion is often proposed to balance carbon and nitrogen, dilute inhibitors, improve buffering, and supply missing micronutrients. The critical evidence indicates that these benefits are conditional. A nominally favorable carbon-to-nitrogen ratio does not reveal whether carbon is accessible, nitrogen is present as inhibitory ammonia, or trace elements are bioavailable. True synergy should be demonstrated by comparing the observed methane production of the mixture with the weighted expectation from the individual substrates under equivalent conditions. Feedstock availability, mixture consistency, and additional logistics must also be included in the decision (Karki *et al.*, 2021).

3.4. Operating Variables, Stability Indicators, And Reporting Quality

Operational variables act jointly. Temperature affects microbial growth, reaction rates, gas solubility, ammonia speciation, and heating demand. Mesophilic operation is often favored for robustness, whereas thermophilic digestion may accelerate conversion and pathogen reduction but can be more sensitive to ammonia and temperature variation. Hydraulic and solids retention times determine whether slowly growing methanogens and particulate matter remain in the system. Organic loading rate links feed concentration with reactor volume and time; an increase may raise volumetric productivity until acidification, inhibition, or mass-

transfer limitations become dominant (Pilarska *et al.*, 2023; He *et al.*, 2024).

Table 3. Process variables that should be controlled and reported in anaerobic-digestion studies.

Variable	Biological or engineering role	Risk when inadequately controlled	Minimum reporting expectation
Feedstock composition	Defines biodegradable carbon, nutrients, moisture, ash, and inhibitors	Unexplained variation, low comparability, unstable loading	TS, VS, COD, moisture, C/N, lipid/protein/carbohydrate profile, contaminants
Inoculum and substrate ratio	Controls initial methanogenic capacity and lag phase	Acid accumulation or inflated methane potential	Origin, acclimation, VS basis, blank correction, inoculum-to-substrate ratio
pH, alkalinity, and VFA	Reflect acid-base balance and conversion of intermediates	Late detection of acidification if pH is measured alone	Initial and temporal values; VFA/alkalinity relationship where possible
Temperature	Controls growth kinetics, ammonia speciation, and heat demand	Community stress and loss of gas productivity during fluctuations	Regime, set point, actual range, heating method, and variation
OLR and retention time	Link feed rate, reactor volume, biomass retention, and productivity	Washout, overload, VFA accumulation, or underuse of reactor capacity	OLR, HRT/SRT, feeding frequency, solids concentration, and duration

Mixing and mass transfer	Distributes substrate, microorganisms, heat, and dissolved gases	Scum, dead zones, biomass damage, or excessive energy use	Mixing mode, speed or power basis, duty cycle, and reactor geometry
Gas quantity and quality	Defines energy recovery and process response	Misleading conclusions based on total gas instead of methane	Normalized CH4 yield, composition, pressure/temperature basis, H2S, leakage assumptions
Digestate quality	Determines nutrient recovery and safe end use	Transfer of pathogens, metals, salinity, or nutrient losses to soil and water	Nutrients, stability, pathogens, contaminants, storage, and intended application

Abbreviations: TS, total solids; VS, volatile solids; COD, chemical oxygen demand; VFA, volatile fatty acids; OLR, organic loading rate; HRT, hydraulic retention time; SRT, solids retention time. Source: Synthesized from Holliger *et al*. (2021), Karki *et al*. (2021), Pilarska *et al*. (2023), and He *et al*. (2024).

The quality of reporting in the selected Brazilian literature varied substantially. Several documents described pH or temperature as isolated 'ideal' values without reporting alkalinity, volatile fatty acids, inoculum, gas normalization, or between-batch variation. Such omission limits reproducibility. The optimum is not a single number independent of substrate and system; it is an operating window in which microbial conversion, gas quality, energy demand, and digestate management remain acceptable. Future studies should publish raw or summarized time series, uncertainty measures, and mass balances rather than only final gas volume (He *et al*., 2024).

3.5. Biodigester Configuration, Process Scale, And Energy Recovery

Batch digesters are useful for seasonal substrates, small-scale demonstrations, and methane potential screening because the feed is loaded and digested without continuous replacement. Their output is intrinsically variable over time, and comparison among batches requires consistent inoculum, loading, headspace, mixing, and termination criteria. Continuous stirred tank reactors offer regular feeding and potentially steady gas production, but they require stable feed preparation, hydraulic control, mixing, and protection against washout. Plug-flow or covered-lagoon systems may suit high-solids manure or warm rural contexts, whereas high-rate reactors depend on biomass retention and are better matched to liquid streams (Almeida, 2024).

The Brazilian literature frequently names Canadian, Indian, or Chinese biodigester models as if the model alone determines efficiency. This framing is insufficient. Covered-lagoon systems can be inexpensive and appropriate for dilute manure under favorable climates, but their large footprint, temperature dependence, and limited mixing may reduce volumetric productivity. Fixed domes reduce moving parts but complicate inspection; floating-drum systems provide visible gas storage but require maintenance; engineered continuous reactors improve control at higher capital and operational cost. Selection should begin with feed rheology, solids content, desired loading, climate, required gas continuity, operator capacity, and end-use specification, not with a generic hierarchy of models (Almeida, 2024; Souza *et al.*, 2024; Cândido *et al.*, 2025).

Biogas volume is not equivalent to useful energy. Methane fraction determines calorific value, while water vapor, H2S, siloxanes, and particulates influence corrosion, emissions, and equipment life. Direct combustion may tolerate less upgrading than grid injection or vehicle fuel. Electricity generation introduces engine efficiency and heat-recovery assumptions; biomethane production adds carbon-dioxide separation, compression, monitoring, and regulatory requirements. A credible energy balance must therefore connect normalized methane production with parasitic energy for heating, mixing, pumping, pretreatment, gas cleaning, and digestate processing (Cândido *et al.*, 2025).

3.6. Environmental, Economic, And Circularity Claims

The environmental benefit of AD arises mainly when controlled methane recovery displaces unmanaged decomposition or fossil energy and when digestate nutrients replace mineral fertilizers without creating new pollution. This benefit is not automatic. Fugitive methane from reactors, storage, upgrading, or engines can materially affect the greenhouse-gas balance. Digestate may conserve nutrients, but ammonia volatilization, nitrate leaching, pathogens, metals, salinity, and transport can shift impacts from waste treatment to agriculture. Comparisons should therefore specify the counterfactual treatment, system boundary, functional unit, methane leakage, avoided products, and allocation method.

Lins *et al.* (2022) appropriately situate biogas within multiple Sustainable Development Goals, including renewable energy, sanitation, responsible production, and climate action. However, alignment with a goal is a policy interpretation rather than a quantified environmental result. Carvalho *et al.* (2022), Cândido *et al.*

(2025), and Daron; Osorio (2025) describe reduced waste disposal, energy recovery, and rural income opportunities, but their broad claims rely largely on secondary evidence. Demonstrating net benefit requires life-cycle assessment, mass and energy balances, measured leakage, digestate characterization, and comparison with realistic local alternatives.

Economic feasibility is equally site-specific. A residue may have zero purchase price and still be expensive after collection, sorting, grinding, dilution, storage, transport, and quality control. Capital costs include civil works, reactors, gas storage, safety systems, cleaning, energy conversion, and grid or pipeline connection. Operating costs include labor, maintenance, heating, mixing, analytical monitoring, and digestate management. Revenues depend on gas production, energy prices, plant availability, avoided disposal, fertilizer substitution, and policy incentives. Almeida (2024) and Daron; Osorio (2025) support the strategic relevance of biogas in agroindustry, but full feasibility must be demonstrated through discounted cash flow, sensitivity analysis, realistic downtime, and feedstock-supply scenarios.

3.7. Decision Framework And Research Priorities

The synthesis supports a staged decision framework. First, the feedstock must be available at a predictable quantity and quality within a viable collection radius. Second, its biodegradable fraction, moisture, nutrients, contaminants, and inhibitors must be characterized. Third, BMP or equivalent screening should use standardized controls and be followed by continuous or repeated-batch validation at a relevant organic loading. Fourth, reactor selection must match feed rheology, retention requirements,

climate, gas continuity, operator capacity, and product specification. Finally, the complete route must be tested through product recovery, digestate safety, techno-economic analysis, and life-cycle assessment.

Research should prioritize standardized substrate characterization; validated methane-potential methods; transparent mass, carbon, and energy balances; replicated long-duration operation; between-batch and seasonal variability; microbial or biochemical indicators linked to process failure; and pilot-to-full-scale validation. Co-digestion studies should report individual and mixed-substrate baselines so that synergy can be quantified. Economic studies should disclose capital, labor, maintenance, parasitic energy, and product-recovery assumptions. Environmental studies should measure or explicitly model methane leakage and digestate emissions. These requirements move the field from demonstrations of gas formation toward evidence of robust resource recovery.

4. CONCLUSION

Anaerobic digestion is a technically credible route for converting organic residues into biogas and a nutrient-containing digestate, but its performance is not an intrinsic property of 'organic waste.' Stable conversion emerges from the compatibility among substrate composition, microbial metabolism, inoculum, organic loading, retention, reactor configuration, and process control. Food waste offers high biodegradability but can acidify rapidly; manure contributes buffering and inoculum but may introduce ammonia and dilute the energy yield; lignocellulosic residues expand availability but can be hydrolysis-limited; and lipid-rich streams combine high methane potential with inhibition risk.

The strongest direct evidence in the reviewed corpus came from specific batch, pilot, and institutional systems. These studies demonstrate feasibility for defined feedstock-reactor combinations, not a universal substrate ranking or guaranteed industrial performance. Co-digestion can improve nutrient balance, buffering, and stability, but the benefit depends on mixture ratio, bioavailability, inhibition, and logistics. Likewise, two-stage digestion may improve control of rapidly acidifying material, but the biological gain must justify additional equipment and operating complexity.

Environmental and economic advantages must be demonstrated against a clearly defined baseline. Methane recovery, avoided disposal, renewable energy, and nutrient recycling are genuine opportunities, yet fugitive emissions, parasitic energy, gas cleaning, digestate safety, transport, maintenance, and plant downtime can reduce or reverse expected benefits. Claims of circularity should therefore be supported by mass and energy balances, standardized methane measurements, life-cycle assessment, and techno-economic analysis with transparent assumptions.

This review is limited by the restricted information sources, the absence of a preserved screening log, the small and heterogeneous corpus, and the predominance of secondary or academic documents. These limitations prevent meta-analysis and should be corrected in future updates through database exports, prospective screening records, duplicate independent assessment, and structured risk-of-bias criteria. They also reinforce the need to interpret the present conclusions as conditional guidance rather than pooled quantitative effects.

Future progress depends less on demonstrating that a residue can produce gas and more on proving that the complete process remains stable, safe, and advantageous across time and scale. The most defensible implementation pathway is therefore to characterize the local feedstock, validate biodegradability under standardized conditions, operate a relevant pilot over representative variability, define gas and digestate end uses, and only then test economic and environmental performance. Anaerobic digestion should be selected when this integrated evidence demonstrates a robust fit among residue, microbial community, reactor, recovered products, and regional infrastructure.

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