



CIRCULAR BIOGAS SYSTEMS: INTEGRATING BIOMASS VALORIZATION AND RESOURCE RECOVERY TOWARD SUSTAINABLE BIOREFINERIES

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ABSTRACT

The transition toward low-carbon and resource-efficient systems demands new strategies for waste management and energy generation. Biogas production through anaerobic digestion represents a pivotal technology connecting renewable energy, waste reduction, and nutrient recycling within the circular economy framework. This review synthesizes findings from recent literature addressing how agricultural, agro-industrial, animal, and municipal biomass streams can be valorized for energy and material recovery. Key attention is given to co-digestion, pretreatment optimization, digestate utilization, CO₂ valorization, and integration into biorefinery models. Evidence shows that coupling biogas production with by-product recovery such as biofertilizers, activated carbon, and CO₂ utilization, enhances both environmental and economic sustainability. The analysis supports that biogas systems can evolve into multi-output biorefineries that close material loops and strengthen regional circular economy strategies.

Keywords: biogas; biomethane; anaerobic digestion; circular economy; biorefinery.

1 INTRODUCTION

Growing environmental pressures, combined with the need for renewable energy expansion, have positioned biogas production as a key pillar in sustainable waste-to-energy systems. Anaerobic digestion (AD) enables the transformation of organic residues into a methane-rich gas and nutrient-dense digestate, reducing greenhouse gas emissions and diverting wastes from landfills.

Recent studies emphasize that AD is not merely an energy technology but a strategic component of the circular economy (CE). Within CE, materials and energy flow in closed loops, maximizing value extraction from biomass resources while minimizing losses. Biogas systems inherently fit this principle, as they transform residual streams from agriculture, industry, and households into renewable energy and reusable by-products [1].

Biogas generation also aligns with decarbonization targets established by the European Union, the International Energy Agency (IEA), and national programs in emerging economies. However, to unlock its full circular potential, several challenges persist: the heterogeneity of feedstocks, inefficiencies in digestion, and the underutilization of digestate and CO₂. This review explores how integrating biogas production within broader biorefinery and circular economy frameworks can enhance environmental performance and economic feasibility.

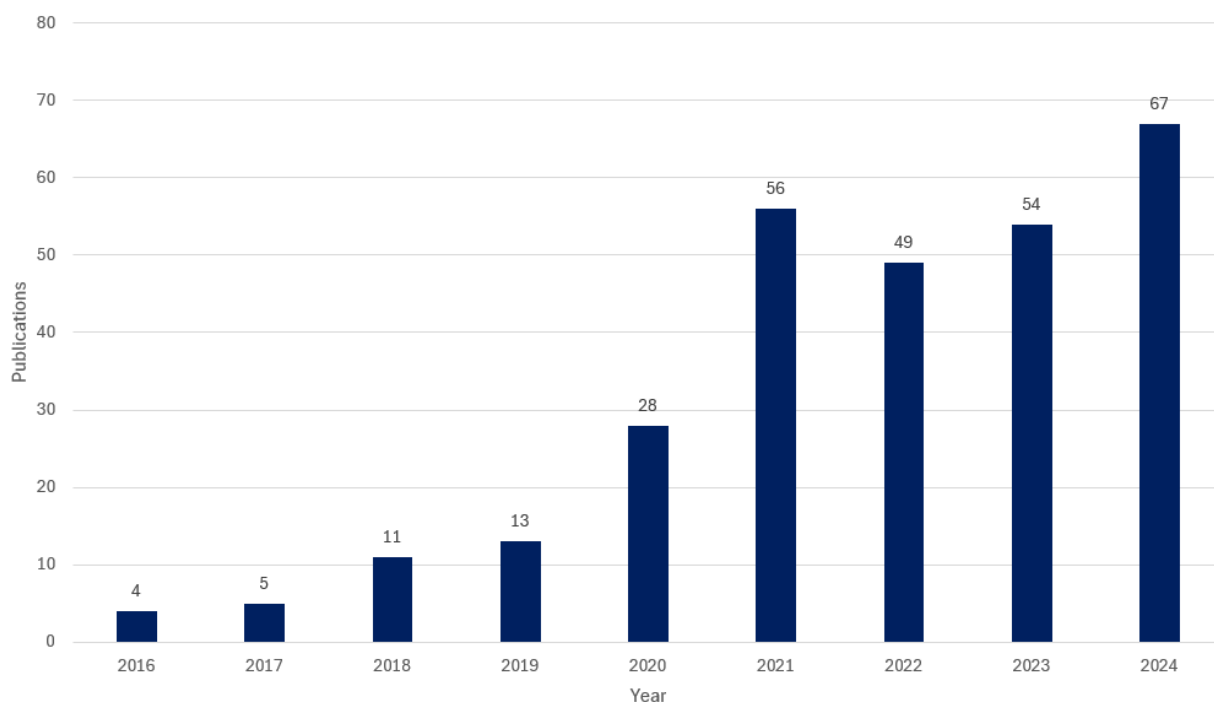


2 MATERIALS AND METHODS

An exploratory bibliometric survey was initially carried out in the Scopus and Web of Science databases with the aim of identifying the temporal evolution and geographical distribution of publications related to the topic of this review. The searches were conducted using combinations of keywords associated with biogas, biomethane, anaerobic digestion, circular economy and biorefinery. The results were analyzed descriptively for informational purposes only. They do not constitute the set of articles effectively used in the review.

Figure 1 presents the annual distribution of publications, highlighting the growing scientific interest in the topic over the years, while Figure 2 shows the distribution of publications by country, emphasizing the main research centers and their relative contributions.

Figure 1. Publications per year.



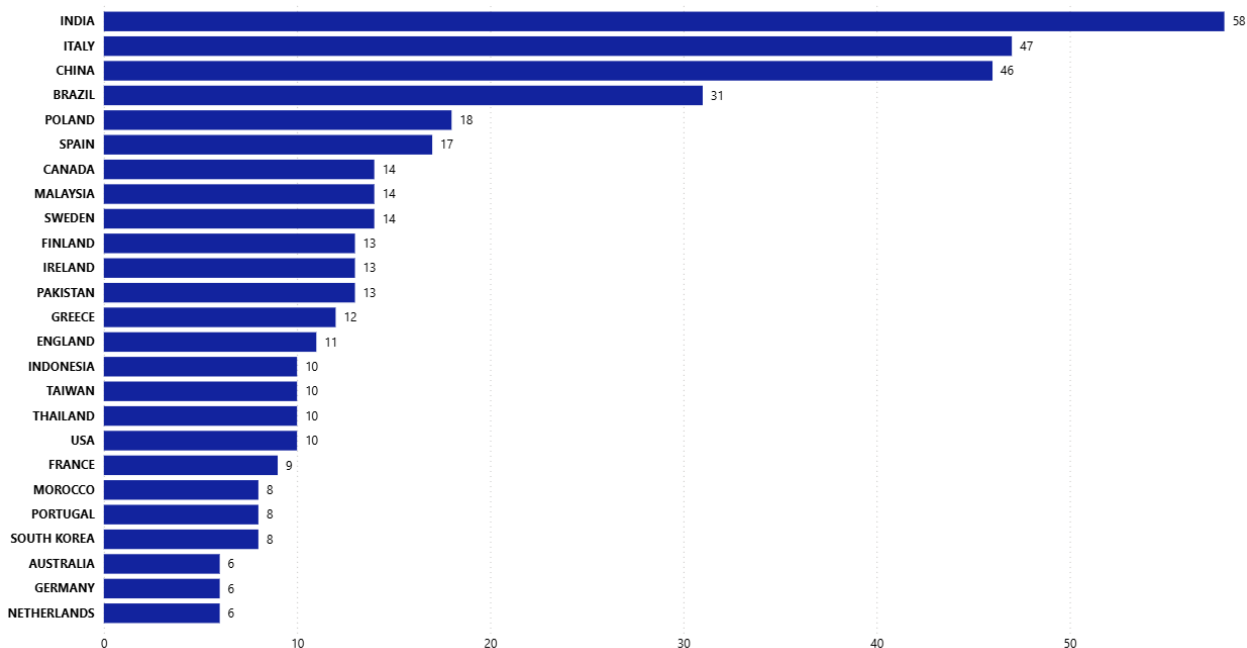
Source: Authors, based on Scopus and Web of Science data.



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Figure 2. Distribution of publications by country.



Source: Authors, based on Scopus and Web of Science data.

It is important to note that, for the actual development of this review, only the most relevant and recent articles were selected, according to criteria of thematic adherence, originality, and impact, and the entire surveyed database was not used.

A total of 10 papers published between 2019 and 2025 were analyzed, including comprehensive reviews and experimental studies covering agricultural residues, animal manure, food waste, wastewater sludge, and industrial by-products.

Papers were selected based on:

- Explicit reference to circular economy or resource recovery principles;
- Quantitative data on methane yield, substrate potential, or by-product valorization;
- Peer-reviewed status and technical completeness.
- Information was extracted on feedstock characteristics, conversion efficiency, and post-treatment pathways.

The results were organized into four thematic axes:

- a) Biomass sources and energy potential;
- b) Pretreatment and co-digestion optimization;
- c) By-product valorization (digestate, CO₂, biochar, ashes);
- d) Integration of AD into circular biorefineries.



3 RESULTS AND DISCUSSION

3.1 Biomass Sources and Biogas Potential

Agricultural and agro-industrial residues remain the backbone of biogas production. Crop residues such as straw, bagasse, and cassava peels possess methane potentials ranging from 200–350 m³ CH₄ t⁻¹ VS, depending on lignocellulosic composition [2].

Animal manure provides more stable digestion due to its buffering capacity but lower yields (150–250 m³ CH₄ t⁻¹ VS [3]. Co-digestion of manure with plant residues improves the carbon/nitrogen balance and increases overall methane production by up to 40 %.

Municipal and food wastes exhibit high biodegradability and can generate over 350 m³ CH₄ t⁻¹ VS, yet logistics and contamination issues limit their widespread use. Industrial residues, such as those from leather, olive, or sugar industries, also show promise as feedstocks when proper pretreatments are applied [4].

Table 1 – Main biomass feedstocks and average methane yields.

Biomass type	Typical CH ₄ yield (m ³ t ⁻¹ VS)	Key notes
Agricultural residues	200–350	Straw, bagasse, cassava peels; need pretreatment
Animal manure	150–250	Stable digestion; low C/N ratio
Food and municipal waste	300–400	High biodegradability; logistic constraints
Industrial residues	250–350	Variable composition; potential pollutants

Source: Adapted from Di Mario et al. (2024) [5]; Cabrera-Codony et al. (2021) [4].

3.2 Pretreatment and Co-digestion Optimization

Lignocellulosic residues often require pretreatment to enhance hydrolysis. Physical (milling, autoclaving), chemical (alkaline, acid, or oxidative), and biological (enzymatic) approaches have been studied. Mechanical pretreatments, such as ball milling, can increase CH₄ yield by more than 100 % for corn straw [5].

Thermal pretreatments between 110 and 190 °C improve digestibility but must balance energy inputs. Integrated approaches, where valuable compounds (polyphenols, flavonoids) are first extracted before digestion, enhance both economic and environmental outcomes—an example of circular biorefinery thinking. Co-digestion, combining multiple substrates, e.g., manure, crop residues, organic waste, further stabilizes the microbial process and optimizes C/N ratio.

3.3 Valorization of By-Products

Digestate

digestate, the main residue from AD, contains nitrogen, phosphorus, and potassium that are suitable for fertilizer use. Its agronomic value depends on stabilization and pathogen reduction. Advanced treatment options—such



as composting, biochar blending, or membrane concentration—allow for safe nutrient recycling and soil improvement [6].

Incorporating digestate into soil contributes to carbon sequestration and reduces the need for synthetic fertilizers, thus closing nutrient cycles.

CO₂ and Biogas Upgrading

Biogas typically contains 25–50 % CO₂. Its upgrading to biomethane via chemical or physical scrubbing, pressure swing adsorption, or membrane separation increases energy content and grid compatibility. Captured CO₂ can be reused in methanol synthesis, algae cultivation, or greenhouse fertilization—transforming a waste gas into a marketable product [7, 8].

Ashes and Biochar

Biochar, produced from the pyrolysis of digestate, improves soil fertility and acts as a carbon sink. This thermochemical conversion pathway also generates valuable co-products, notably syngas (synthesis gas) and bio-oil. The syngas, rich in H₂, CO, and CH₄, can be internally recycled to provide the thermal energy required for drying the digestate prior to pyrolysis, significantly enhancing the process's overall energy efficiency and autonomy.

Table 2 – Circular applications of biogas by-products.

By-product	Valorization route	Benefits
Digestate	Fertilizer, compost, biochar blend	Nutrient recycling, soil carbon
CO ₂	Methanol synthesis, algae culture	Added revenue, GHG reduction
Ashes	Construction materials, fertilizer additive	Resource recovery
Heat	District heating, drying	Energy efficiency

Source: Adapted from IEA Task 37 (2025) [9].

3.4 Integration into Circular Biorefineries

The biorefinery concept expands AD beyond energy production, linking it to the extraction of chemicals, materials, and fertilizers [1]. Waste-based biorefineries recover resources through multi-stage conversion processes, integrating thermochemical and biochemical routes. Examples include:

- Food waste biorefineries: extracting volatile fatty acids, biohydrogen and medium-chain fatty acids;
- Wastewater treatment plants: evolving into energy-positive facilities via co-digestion and nutrient recovery;
- Industrial symbiosis models: where CO₂, heat, and digestate from AD are reused in nearby processes (e.g., aquaculture or horticulture).

This integration promotes economic diversification, reduces environmental footprints, and aligns with the United Nations Sustainable Development Goals (SDGs 7, 12, and 13). Furthermore, it establishes a robust model of

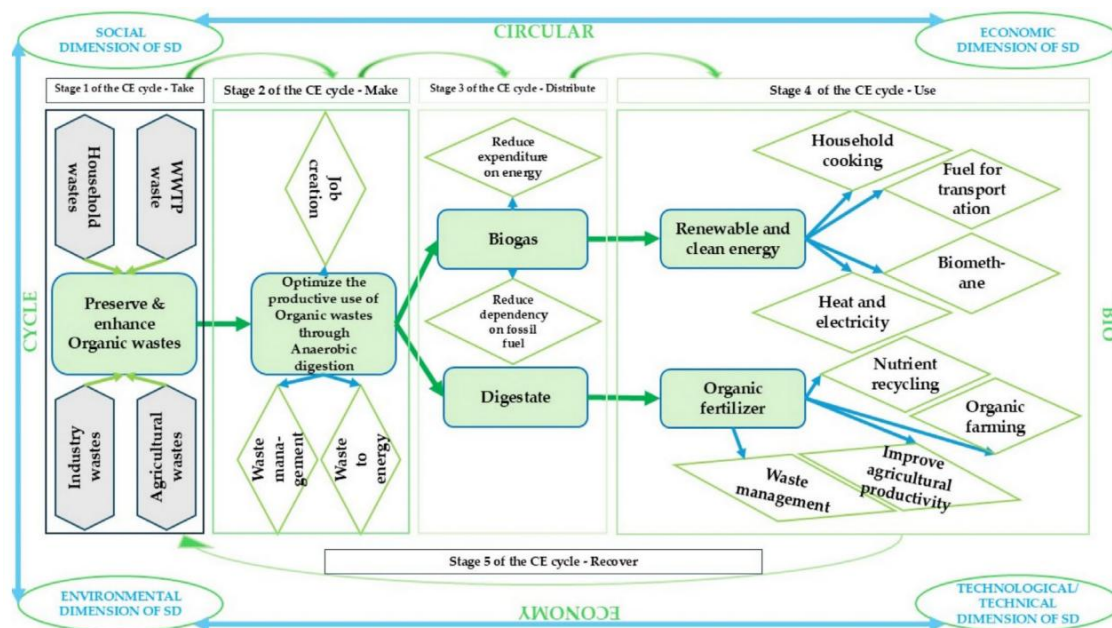


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energy resilience, critical for mitigating the deficiencies observed in rural distribution grids, while simultaneously fostering a circular economy through the valorization of agricultural residues into high-value energetic assets.

Figure 3 – Theoretical/empirical framework of the study that links biogas technology, CE, and Sustainable development.



Source: Lapiso, T. T. and H. Roubik (2025) [10].

4 CONCLUSIONS

Biogas systems are evolving into multi-product platforms central to circular economy strategies. The reviewed literature demonstrates that agricultural, industrial, and municipal residues can be converted into renewable energy and valuable co-products through optimized anaerobic digestion and biorefinery integration.

Key enablers include substrate diversification, advanced pretreatment, and full valorization of digestate and CO₂. Policy incentives and life-cycle assessments are essential to ensure that these systems achieve genuine sustainability.

Future research should emphasize digital monitoring, nutrient recovery technologies, and hybrid processes linking AD to bio-electrochemical systems and green hydrogen routes. Biogas, when coupled with circular economy principles, becomes not only a clean energy source but also a foundation for sustainable industrial symbiosis.

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