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Review

Biogas Production in Agriculture: Technological, Environmental, and Socio-Economic Aspects

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Abstract

This review provides a comprehensive analysis of the technological, environmental, economic, regulatory, and social dimensions shaping the development and operation of agricultural biogas plants. The paper adopts a primarily European perspective, reflecting the comparatively high share of agricultural inputs in anaerobic digestion (AD) across EU Member States, while drawing selective comparisons with global contexts to indicate where socio-geographical conditions may lead to different outcomes. It outlines core principles of the AD process and recent innovations—such as enzyme supplementation, microbial carriers, and multistage digestion systems—that enhance process efficiency and cost-effectiveness. The study emphasises substrate optimisation involving both crop- and livestock-derived materials, together with the critical management of water resources and digestate within a circular-economy framework to promote sustainability and minimise environmental risks. Economic viability, regulatory frameworks, and social dynamics are examined as key factors underpinning successful biogas implementation. The paper synthesises evidence on cost–benefit performance, investment drivers, regulatory challenges, and support mechanisms, alongside the importance of community engagement and participatory governance to mitigate land-use conflicts and ensure equitable rural development. Finally, it addresses persistent technical, institutional, environmental, and social barriers that constrain biogas deployment, underscoring the need for integrated solutions that combine technological advances with policy support and stakeholder cooperation. This analysis offers practical insights for advancing sustainable biogas use in agriculture, balancing energy production with environmental stewardship, food security, and rural equity. The review is based on literature identified in Scopus and Web of Science for 2007 to 2025 using predefined keyword sets and supplemented by EU policy and guidance documents and backward- and forward-citation searches.

Keywords: agricultural biogas production; anaerobic digestion; substrate management; water and soil protection; rural equity; economic viability; legal barriers

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1. Introduction

Due to the increasing demand for food and growing pressure on natural resources, modern agriculture must ensure not only high production efficiency but also the minimisation of environmental impacts. A fundamental requirement in this regard is the use of potentially renewable resources—such as soil, water, and biodiversity—at rates that do not exceed their natural regeneration capacity. Simultaneously, it is essential to reduce the reliance on non-renewable resources and to limit pollutant emissions to levels within the environment's assimilative capacity [1,2]. A key aspect of this transformation involves enhancing resource-use efficiency, particularly in relation to water, energy, fertilisers, and plant protection products [3–5]. Moreover, agriculture can actively contribute to climate change mitigation through increased soil carbon sequestration and reduced greenhouse gas (GHG) emissions, without compromising productivity or the long-term security of food systems [6,7].

In this context, biogas production supports sustainable agricultural practices by enabling the effective utilisation of organic waste materials [8,9], while also contributing to GHG emission reduction [10,11]. In addition, renewable energy generated can significantly reduce agriculture's dependence on fossil energy sources. Furthermore, agricultural and industrial wastes, due to their high carbohydrate content, represent an efficient and locally available feedstock for bioenergy production [12]. According to estimates from the International Renewable Energy Agency (IRENA), the global bioenergy potential of agricultural waste amounts to approximately 13.32×10^{12} MJ annually (equivalent to 3700 TW·h) [13,14].

Biogas is produced under strictly anaerobic conditions through the AD process, during which organic matter is microbially degraded. The process consists of four distinct biological stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These stages collectively result in the formation of biogas, which is mainly composed of methane (CH_4) and carbon dioxide (CO_2). The efficiency of the process is determined by several critical technological parameters, including fermentation temperature (mesophilic or thermophilic), pH, retention time, organic dry matter concentration, and organic loading rate [15,16]. In agricultural biogas plants, various fermentation configurations are employed, such as continuous and batch systems, single- and multi-stage reactors, and technologies incorporating process-enhancing additives, including enzymes and selected microbial consortia [17–19].

Moreover, the AD process constitutes a technologically advanced solution that integrates sustainable energy generation with the controlled management of biodegradable agri-industrial residues. The implementation of AD on an industrial scale prevents uncontrolled methane emissions from untreated biomass that would otherwise occur through spontaneous decomposition [20,21]. This is especially significant given the high global warming potential of methane relative to carbon dioxide [21,22].

Additionally, the use of digestate—a by-product of the AD process—as an organic fertiliser facilitates the closure of nutrient cycles within agricultural systems. This reduces the demand for synthetic fertilisers, improves soil structure and fertility, and enhances overall crop productivity. The potential of liquid anaerobic digestate (LAD) as a renewable source for nutrient recovery—particularly in terms of nitrogen and phosphorus cycling—has been examined by Shafaghat et al. (2024) [23]. In parallel, Sobhi et al. (2024) synthesised regulations governing the application of digestate as a fertiliser [24]. Similarly to other studies [24–26], they reported potential risks comprising nutrient accumulation and contamination with heavy metals, pathogens, antibiotics, and microplastics.

In parallel with the technological and agronomic advantage, the environmental performance of biogas plants must also account for their impact on water resources and soil quality [27]. Anaerobic digestion involves intensive water use, while digestate management determines the extent to which nutrient leaching or groundwater pollution may occur [28–30]. Therefore, circular approaches to water use and soil protection are increasingly promoted within sustainable biogas systems and are examined in detail in this article.

Furthermore, the implementation of agricultural biogas plants is closely linked with economic viability and public acceptance. High capital expenditures and uncertain returns on investment remain significant challenges for farmers and investors [31]. At the same time, the success of such initiatives often depends on local stakeholder involvement and positive community perception. In economic terms, the construction of agricultural biogas plants facilitates the generation of income through the sale of electricity, surplus heat, and digestate. In numerous countries, including EU Member States, support programmes and financial incentive schemes are being implemented to promote renewable energy production. These measures include, among others, feed-in tariffs, investment subsidies, and preferential loan schemes [2,32,33]. Such installations may also serve as a foundation for alternative profitable production processes or be integrated into larger systems, such as a combined facility with a distillery [34–36].

Beyond economic factors directly associated with biogas production, social considerations also play an important role. The establishment and proper operation of biogas plants can yield tangible benefits for the surrounding communities. Agricultural biogas facilities stimulate local economic development, enhance regional economic activity, and create favourable conditions for entrepreneurship. Their construction contributes to the creation of new employment opportunities, thereby increasing regional income levels. Furthermore, they make a notable contribution to the local gross domestic product [9].

Despite its numerous advantages, the biogas sector continues to encounter a range of global challenges. The most commonly reported barriers include high investment costs, fragmented regulations and lengthy approval procedures, limited access to appropriate technologies, a shortage of qualified professionals, and persistent—though diminishing—social opposition [18,32,33]. Nevertheless, the development prospects for agricultural biogas plants remain promising, particularly amid increasing global pressure to reduce emissions and ongoing geopolitical instability.

Although many reviews have addressed various aspects of biogas production [8,9,16,25,33], most have focused separately on technological or environmental issues, often overlooking socio-economic and systemic interactions. The added value of this paper lies in integrating these three dimensions—technological, environmental, and social—within the agricultural context, thereby providing a holistic perspective on anaerobic digestion as a key component of the circular bioeconomy. This review, therefore, fills a gap by linking process-level optimisation with broader sustainability and policy frameworks, highlighting multi-level coordination needs that remain insufficiently synthesised in the existing literature. Accordingly, this article aims to provide an integrated review of (i) the technological foundations and key operational parameters of agricultural AD, (ii) feedstock availability and characteristics relevant to farm-scale systems, (iii) soil–water interactions, digestate management and environmental outcomes, and (iv) the socio-economic drivers, barriers and governance arrangements that condition multi-level coordination. Given these objectives, the scope of this review is primarily European, reflecting the comparatively high share of agricultural inputs in AD and the maturity of EU policy frameworks. Selective contrasts with global contexts are included to indicate where substrate mixes, policy settings and deployment models diverge. A brief outline of the review methodology—covering databases, timeframe, keyword strategy, screening steps and eligibility criteria—is provided in Section 2 ("Review methodology").

2. Review Methodology

This section sets out the methodological framework adopted for the review. It defines the scope and type of analysis, identifies the sources and search strategy, and explains the screening, extraction, and synthesis procedures applied to ensure transparency and consistency.

2.1. Review Scope and Type

This article presents a qualitative, integrative review focused on agricultural anaerobic digestion in the European context, with targeted global contrasts where context-specific conditions materially differ. The synthesis covers technology and operations, soil–water and digestate management, economics and regulation, and social acceptance at farm and territorial scales.

2.2. Sources and Search Strategy

Literature was identified in Scopus and the Web of Science Core Collection for 2007–2025 using predefined keyword combinations. The strings combined terms for the following: (i) system and process (e.g., agricultural biogas, anaerobic digestion, single-/two-stage, mesophilic/thermophilic, OLR, HRT, mixing, enzymes, microbial carriers); (ii) substrates and outputs (feedstock, manure, slurry, crop residues, co-digestion, biomethane, upgrading, digestate); (iii) environment and resources (soil, groundwater, water recirculation, water footprint, LCA, land-use change, GHG); and (iv) economy, policy, and society (LCOE, investment, support schemes, policy, permitting, social acceptance, community). Supplementary searches used EU policy and guidance documents and backward- and forward-citation searches.

2.3. Screening and Eligibility Criteria

Screening proceeded in two steps: title–abstract review followed by full-text assessment. Inclusion criteria: peer-reviewed studies and authoritative reports directly relevant to agricultural AD; clear methods; results applicable at farm or territorial scales; evidence on at least one of the following: technology/operations; soil–water/digestate; economics/regulation; social acceptance. Exclusion criteria: lack of methodological transparency; purely laboratory-scale trials without implications for farm or territorial systems; non-agricultural focus; duplicates. After de-duplication and eligibility checks, 136 sources were retained for synthesis.

2.4. Data Extraction and Synthesis

From each eligible item, information on context (region, scale), system boundaries, methods, and principal outcomes was extracted and synthesised thematically across four axes: (i) technology and operation; (ii) soil–water interactions and digestate management; (iii) economics, regulation, and support schemes; and (iv) social acceptance and governance. Where relevant, contrasts between European and global contexts were noted to delineate limits of transferability.

2.5. Scope of Validity and Limitations

The evidence base is strongest for Europe, where agricultural inputs into AD and policy frameworks are comparatively mature; conclusions are therefore most directly generalisable to European conditions. Targeted global contrasts indicate where substrate mixes, regulatory settings, market signals, or deployment models may lead to different outcomes. As a qualitative synthesis, no meta-analysis was undertaken; heterogeneity in system boundaries and metrics is acknowledged.

3. Potential of Biogas Production in Agriculture

Biogas production constitutes a significant component of sustainable agricultural development, enabling the conversion of biodegradable organic matter into a source of renewable energy. Its effective implementation depends not only on the availability and type of substrates, but also on a thorough understanding of the biological processes and technological frameworks underlying the anaerobic digestion process.

3.1. Fundamental Principles and Technologies of Anaerobic Digestion

An agricultural biogas plant comprises integrated technologies enabling anaerobic digestion of organic substrates—typically on-farm residues and locally available agri-industrial by-products—and the use of outputs after fermentation. The core units are substrate storage, the digester (bioreactor), a gas holder, a combined heat and power (CHP) unit, and digestate storage. Figure 1 presents a general layout of an agricultural biogas plant and the interior of an industrial digester: Figure 1a shows the overall arrangement of the main units, whereas Figure 1b illustrates a cylindrical reactor equipped with a central vertical shaft and horizontal arms (frame/paddle type), a configuration used to promote bulk mixing and limit dead zones within the slurry.

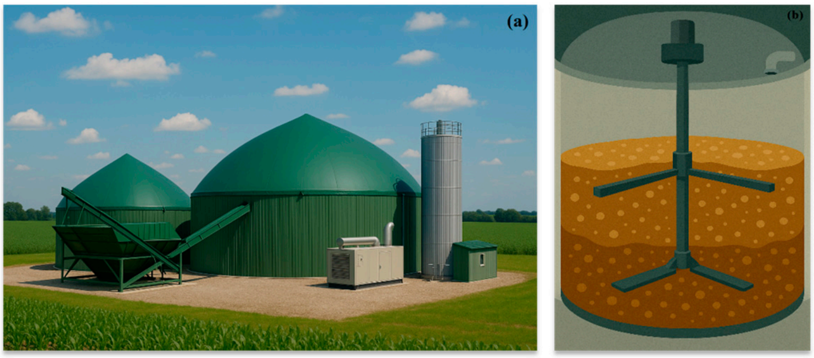

Figure 1. (**a**) General view of an agricultural biogas plant; (**b**) interior of an industrial fermentation chamber (original/own material).

The selection of site and scale should consider the following: (i) optimal use of existing buildings and infrastructure; (ii) proximity to livestock farms supplying suitable substrates and the feasibility of their collection; (iii) opportunities for selling electricity and heat; and (iv) options for digestate management and utilisation [32,37–39].

The AD process consists of microbially mediated stages—hydrolysis, acidogenesis, acetogenesis and methanogenesis—yielding a gas mixture (biogas) rich in CH_4 and CO_2, as shown in Figure 2. Hydrolysis controls the conversion of complex polymers, while syntrophic acidogenesis/acetogenesis sets volatile-fatty-acid balances and hydrogen partial pressures that condition methanogenic activity. Stable methanogenesis, in turn, depends on buffering capacity, trace nutrients and control of inhibitory species.

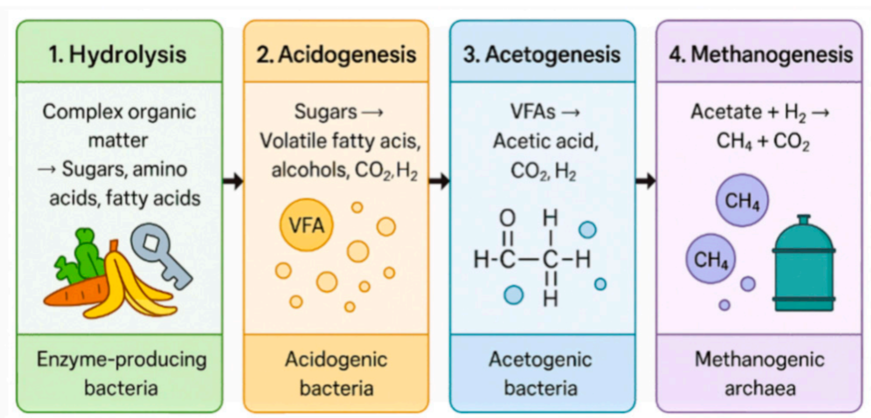

Figure 2. Multi-stage anaerobic digestion process (original/own material).

The principal operating parameters governing these interactions—temperature, hydraulic retention time, mixing, inhibitory compounds, pH and C:N [32]—are outlined in Figure 3.

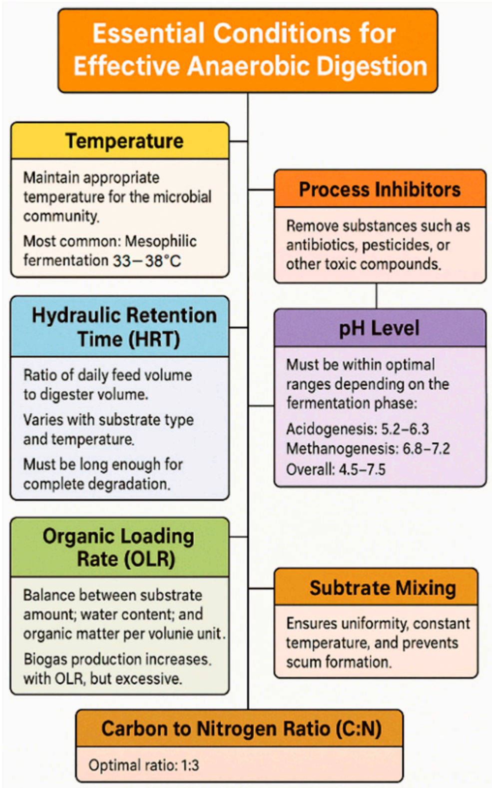

Figure 3. Key parameters of anaerobic digestion with essential specifications (original/own material).

Agricultural biogas is the gas produced from materials of agricultural origin—such as by-products, liquid or solid animal manure, residues from processing of agricultural products, and certain non-arable biomass—while excluding feedstocks from landfills and wastewater treatment plants, including agri-food facilities where industrial effluents are not separated from other sewage and sludge [40]. The methane content depends on substrate type and composition; for agricultural biogas produced from typical farm and agri-food substrates in Central European conditions, the calorific value usually lies in the range 18–26 MJ·m^{-3} and is commonly reported as 6 kWh·m^{-3}. As an indicative calculation, assuming standard conditions (T = 0 °C, p = 101.3 kPa) and a representative agricultural-biogas composition of 55–60% CH_4, the mean energy value is about 21.6 MJ·m^{-3}. Using the conversion factors presented by Gołaszewski [41], this corresponds to an energy content of 6·× 10^{-4} m^3 of diesel fuel or about 1.3 kg of wood.

Biogas is a medium-energy fuel suitable for heat and electricity generation; its most common application is combustion in a CHP unit, delivering higher overall efficiency than separate production [15,42]. Following upgrading, biomethane may be used as a transport fuel or injected into the natural-gas grid, subject to quality requirements and network operator approval [43–45]. For efficient utilisation and equipment protection, a compact cleaning train is typically applied: desulphurisation to remove H_2S (unit sized to expected H_2S; fixed-bed or in situ) [46], dehydration to condense water vapour (often near 100% relative humidity) [47], and CO_2 reduction/upgrading via absorption, chemisorption, adsorption, membrane separation or liquefaction [43]. These steps increase calorific value and safeguard CHP and downstream assets [43,45–47].

At the farm scale, outcomes are governed by a small set of controllable operating choices that recur across configurations and feedstock mixes and correspond to the parameters shown in Figure 3. The key points are as follows:

- Mesophilic operation (35–38 °C) generally offers robustness to feed variability and lower operating costs, whereas thermophilic operation (52–55 °C) increases reaction rates and can raise methane productivity but typically requires tighter process control and shows greater sensitivity to inhibition [5,32].
- A higher organic loading rate (OLR) increases space–time productivity but elevates the risk of VFA accumulation and instability; a longer hydraulic retention time (HRT) improves degradation and stability at the expense of larger volume and capital cost [16]. Overall, temperature regime and OLR/HRT settings critically determine methane yield, stability, and the capital–operating cost balance at the plant level [15,32].
- Nitrogen-rich feeds (e.g., manures, proteinaceous wastes) can raise TAN/NH_3 and inhibit methanogenesis; effective measures include C:N balancing via co-digestion, controlled dosing, pH/temperature management (lower temperature reduces free NH_3), buffering and, where appropriate, staged digestion [4,32].
- The aim of mixing is uniform contact without excessive power demand; intermittent, controlled mixing is often sufficient for manure/co-digestion slurries, whereas continuous, high-intensity mixing may increase energy use and disturb floc structure [15,32].

These operating decisions have first-order effects on methane yield, process stability and energy use, and thus on the overall economic viability of farm-scale plants.

3.2. Anaerobic Digestion Technologies

The selection of fermentation technology governs the efficiency, stability and economic viability of a biogas plant—a reactor configuration tailored to substrate characteristics and operating conditions maximises methane yield while minimising the risk of process upsets.

Below, the key anaerobic digestion technologies employed in agriculture are described.

- Single-stage and multi-stage fermentation

In industry, single-stage and multi-stage anaerobic digestion processes are distinguished to allow plant designs to prioritise either operational simplicity or precise process control. In single-stage digestion (see Figure 4a), the entire breakdown of organic material—from hydrolysis through methanogenesis—occurs in one reactor. This arrangement is easier to construct and operate, reducing capital expenditure, but it offers limited control over individual phases and often yields lower methane production. By contrast, multi-stage systems (see Figure 4b) perform specific phases—such as hydrolysis and acidogenesis—in separate reactors, enabling tighter regulation of process conditions and typically increasing biogas output, albeit with higher capital and operating costs [48].

Ruiz-Aguilar et al. (2022) compared single-stage (SAD) and two-stage (TAD) digestion of raw tomato plant residues under optimised mesophilic conditions [49]. The SAD system achieved a cumulative methane yield of 0.3654 m^3 $CH_4 \cdot kg^{-1}$ VS, compared to 0.2523 m^3 $CH_4 \cdot kg^{-1}$ VS in TAD, with no statistically significant difference in total methane production. Given its simpler reactor design, shorter incubation time, and equivalent (or superior) energy recovery, the authors concluded that SAD is the more technically and economically viable option for renewable energy recovery from tomato waste. Conversely, Van et al. (2020) reported that TAD outperformed SAD in terms of efficiency, stability, and process rate [50]. In their study, TAD converted 41.7% of initial carbon into biogas (versus 17.8–22.3% in SAD) with a methane content of 71.7–81.0% (44.1–48.7% in SAD), exhibited faster methanogenic kinetics and demonstrated greater resilience to fluctuations in organic loading. They also noted that a substantial fraction of hydrolysed carbon remained unconverted to biogas, indicating potential for further process optimisation.

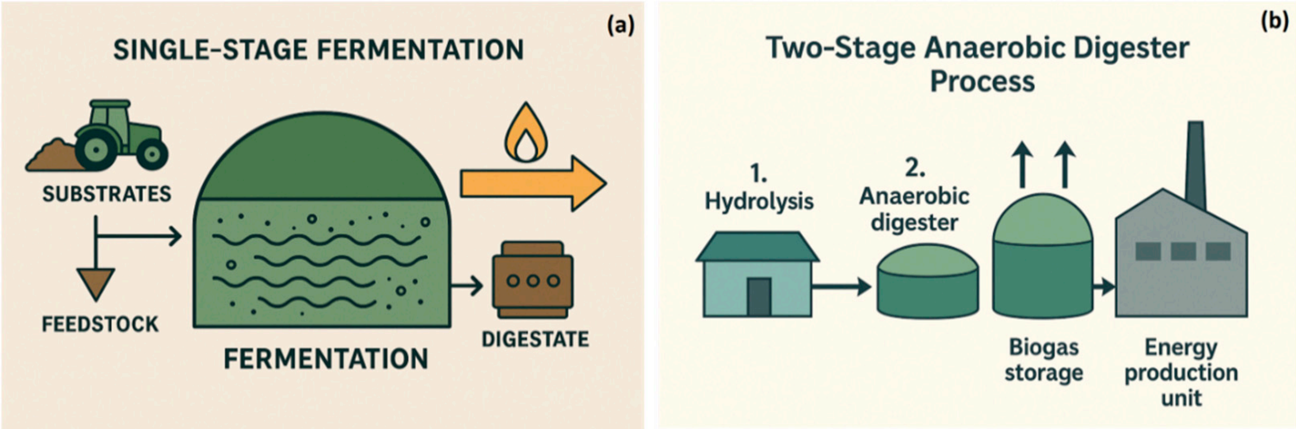

Figure 4. Anaerobic digestion configurations: (**a**) single-stage process with all decomposition phases in one reactor; (**b**) two-stage process separating the hydrolytic phase from the other phases into separate reactors (original/own material).

Studies conducted by two research teams—Ruiz-Aguilar et al. (2022) [49] and Van et al. (2020) [50]—reveal somewhat divergent conclusions: Ruiz-Aguilar et al. (2022) [49] reported comparable methane yields in single-stage and two-stage anaerobic digestion (SAD and TAD), favouring SAD for its simpler reactor design and shorter retention time, whereas Van et al. (2020) [50] demonstrated a clear advantage of TAD in terms of carbon conversion, methane content and process stability under variable organic loading. Overall, it should be emphasised that multi-stage anaerobic digestion with a dedicated hydrolysis phase is particularly advantageous for substrates rich in complex organic compounds or subjected to fluctuating loadings, as it allows for precise control over individual process stages, higher methane yields, and improved process stability. A dedicated hydrolysis phase also proves especially effective for lignocellulosic substrates such as grass silage, cereal straw, or high-fibre energy crops.

- Mesophilic and thermophilic fermentation

Temperature is a critical parameter governing microbial activity in anaerobic digestion. Mesophilic fermentation represents the most stable and widely adopted regime in agricultural biogas plants, as outlined in Section 3.1. Thermophilic fermentation accelerates organic matter breakdown and increases biogas yields; however, it necessitates more precise temperature control and is more susceptible to process variations, which is likewise discussed in Section 3.1.

As demonstrated in the study by Labatut et al. (2014) [51], the temperature of anaerobic digestion significantly influences process performance and stability, affecting, among other factors, the hydrolysis rate and the physical state of long-chain fatty acids. Based on the conducted analyses, the authors observed that thermophilic digestion is more prone to instability when processing substrates with a high lipid content and low fibre content. However, with an appropriate fibre-to-lipid ratio, it may achieve slightly higher methane yields and improved organic matter stabilisation. In contrast, mesophilic digestion exhibits greater resilience to variations in substrate composition and operational conditions, making it a more stable and cost-effective option in typical manure-based installations.

However, the implementation of anaerobic digestion of lipid-rich substrates under thermophilic conditions can be fully justified. The study conducted by Hamzah et al. (2019) [52] demonstrated that the digestion of acidified palm oil mill effluent at 55 °C stabilises more rapidly (44 days) compared to mesophilic conditions (52 days), while simultaneously achieving higher biogas production. The findings of this research team also emphasise that proper monitoring of acclimation conditions is crucial for maintaining process stability and minimising the risk of destabilisation.

- Continuous and batch fermentation systems
  The selection of an appropriate anaerobic digestion configuration is critical to process stability and overall plant performance. In practice, two principal systems are utilised as follows:
  - ➢ Continuous anaerobic digestion (see Figure 5a), in which the organic feedstock is introduced to the reactor in a continuous or semi-continuous mode, whilst digestate is withdrawn concurrently. This arrangement affords an uninterrupted operation, yielding a uniform and steady biogas output and maintaining stable microbiological conditions, but it necessitates highly accurate feed-and-effluent control systems [53].
  - ➢ Batch anaerobic digestion (see Figure 5b), carried out in discrete cycles during which the reactor is loaded with substrate and then emptied at the end of the fermentation period. Although structurally simpler, this approach can result in pronounced fluctuations in biogas production and demands more meticulous operational management [54].

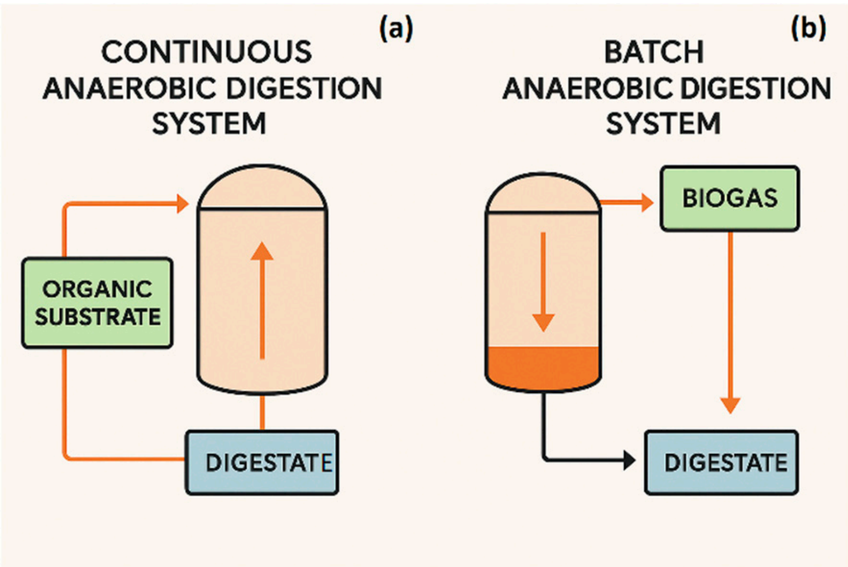

Figure 5. Comparative diagram of two anaerobic digestion systems: (**a**) continuous and (**b**) batch (original/own material).

To facilitate comparison of the technological options discussed above, a concise overview of the most common agricultural AD configurations is provided in Table 1. The table contrasts single- and two-stage systems, mesophilic and thermophilic operation, and batch versus (semi-)continuous modes, and it reports indicative methane-yield ranges together with the corresponding levels of process control and operational stability; it also indicates, in qualitative terms, the typical scale and investment (capital expenditure, CAPEX) implications, rather than specifying project-specific cost values.

The choice of technology is governed by farm scale, feedstock characteristics and available financial resources. For small-to-medium-sized agricultural holdings, a single-stage mesophilic digestion often represents the optimal compromise, combining minimal operational complexity with satisfactory performance. In such installations, the process is conducted within sealed containers and the biogas produced is typically utilised on-site—for example, for space heating. In turn, larger-scale investments may warrant the consideration of multi-stage systems, operating under mesophilic or thermophilic regimes, in order to exploit the full energetic and volumetric potential of the biogas [53]. A case in point is the continuous digestion of cattle manure and maize silage in a sizable agricultural biogas facility, where substrates are dosed daily and the biogas is valorised for both electrical and thermal energy generation.

Table 1. Comparative characteristics of agricultural anaerobic digestion (AD) configurations (author's own elaboration based [15,32,48,49,51]).

Process Dimension	Configuration Type	Indicative Methane Yield Range	Control/Monitoring Complexity	Process Stability	Typical Scale/CAPEX Implication
Reactor staging	Single-stage	lower–medium	low–medium	high (for uniform feeds)	small/farm-scale
	Two-stage/ multi-stage	medium–high	high	high (for variable/ lignocellulosic feeds)	medium–large
Temperature regime	Mesophilic (35–38 °C)	medium	low	high	small–medium
	Thermophilic (52–55 °C)	medium–high	high	medium (sensitive to shocks)	medium–large
Operating mode	Batch	wide range, but fluctuating output	low–medium	medium	small/low CAPEX
	Continuous/ semi-continuous	medium–high, stable output	high	high (with stable feeding)	medium–large

The study by Facchin et al. (2013) [55], which evaluated mesophilic anaerobic digestion of food waste under both batch and continuous (Continuous Stirred-Tank Reactor, CSTR) configurations, demonstrated significant disparities in trace metal supplementation efficacy. While batch reactors exhibited a marked increase in methane yield following metal addition, CSTRs showed only marginal improvements—insufficient to warrant industrial-scale dosing. These results carry important technological and economic implications for the large-scale implementation of trace metal supplementation. The next study by Zhu et al. (2023) [56] found that semi-continuous systems outperform batch reactors in terms of process stability, methane yield and microbial community resilience, particularly during the co-digestion of challenging substrates such as pig manure and corn stover. More recently, Azkarahman et al. (2025) reported that the direct transfer of kinetic parameters from batch trials to a CSTR led to operational failure, underscoring the distinct optimal operating conditions required by each system [57]. They also observed that methane production rates in the CSTR declined several-fold before stabilising, a behaviour linked to shifts in microbial community composition and the methanogenesis pathway.

- Advanced technologies with the use of enzymes, microorganisms, and microbiological carriers

To enhance the efficiency of the AD process, additives such as enzymes, specialised microbial strains, and microbiological carriers are applied to accelerate the degradation of complex organic compounds. This strategy can shorten the retention time and increase the biogas yield. However, it entails additional costs associated with the purchase and dosing of these agents; hence, the use of affordable and readily available solutions is recommended where possible.

Biological pretreatment of lignocellulosic biomass with microbial consortia and enzymes enhances degradability, accelerating fermentation and biogas production. Fugol et al. (2023) demonstrated that biochemical supplementation of maize and grass silages can elevate biogas production by up to 62%, depending on the additive and feedstock [58]. Xing et al. (2024) subsequently showed that, in a continuous anaerobic dynamic membrane bioreactor (AnDMBR), a composite enzyme cocktail (laccase, endo-β-1,4-glucanase and xylanase) increases methane yield by over 12% and significantly improves removal of cellulose, hemicellulose and lignin [59]. Ferdes et al. (2020) confirm that biological and enzymatic enhancements are an effective, eco-friendly and cost-efficient strategy for optimising anaerobic digestion [60]. In the field of microbial carriers, Pilarska et al. (2022) found that incorporating tailored carrier materials (e.g., silica/lignin, diatomaceous earth/peat composites) into the AD of food waste can improve biodegradation rates, microbial activity and both the quantity and calorific value of the resulting biogas [61].

In summary, the choice of an appropriate AD technology in agriculture depends on various factors, including the type of available substrates, production scale, financial resources, and expected performance. Each of the technologies described has its own advantages and limitations that must be considered during the design and operation of an agricultural biogas plant.

3.3. Substrates for Agricultural Biogas Production

Biogas production in agriculture relies on the use of various organic substrates, the availability and characteristics of which determine the efficiency of the methane fermentation process. The selection of appropriate feedstock is crucial for optimising the performance of the biogas plant and ensuring its economic viability.

Almost any substance containing organic compounds can be used as a substrate in the anaerobic digestion (AD) process. However, according to the definition provided by the law [40], agricultural biogas is derived from specific types of substrates. The vast majority of waste generated in agriculture and food processing is organic waste, making it suitable for use in biogas plants. These materials typically contain more than 50% organic components on a dry mass basis [17].

The substrates used in agricultural biogas plants can be classified based on their origin into plant-based and animal-based categories.

The following chart (Figure 6) illustrates the quantity of raw materials (in tonnes) used in agricultural biogas plants. As observed in the data, slurry and residues from vegetables and fruits appear to dominate among the substrates, certainly due to economic reasons.

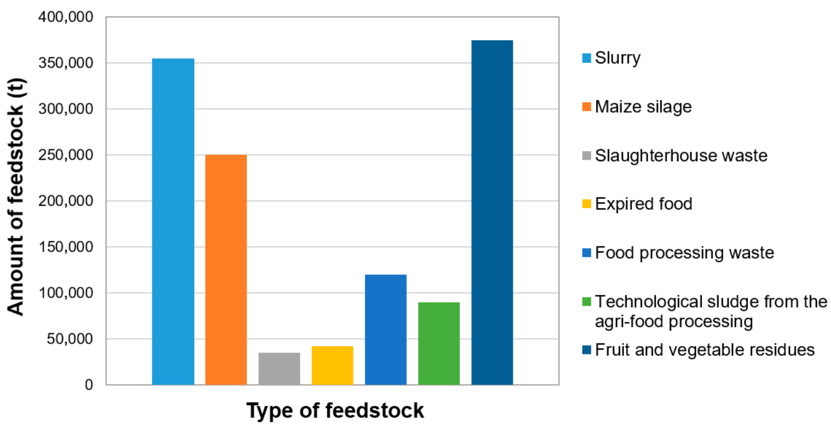

Figure 6. Amount of raw materials in tonnes used for agricultural biogas production in 2018 (original/own material based on [62]).

To contextualise the Polish data in a broader perspective, it is instructive to compare the national feedstock mix with prevailing European trends. While Figure 6 captures the mass of substrates supplied to agricultural biogas plants in Poland, the structure of inputs across the European Union is more heterogeneous and increasingly oriented towards waste and residue streams. Accordingly, Table 2 summarises the ten most prevalent sub-streams used in EU biogas/biomethane production, based on IEA Europe 2022 feedstock categories [63], with sub-stream allocation provided by the authors for clarity and comparability. In line with the scope of the cited source, the table reports relative prevalence (rather than national tonnages), and includes brief technical notes to highlight operational considerations (e.g., ammonia management for slurry-rich feeds, contamination control in municipal biowaste). This juxtaposition enables a like-for-like reading of the Polish profile against EU-level practice, without conflating country-specific mass balances with Europe-wide categorical shares.

Table 2. Feedstock types used for agricultural biogas/biomethane in the European Union—the most prevalent sub-streams based on IEA Europe 2022 feedstock categories (author's own elaboration based [63]).

Feedstock (EU)	IEA Category	Relative Prevalence (EU)	Brief Technical Note
Cattle slurry	Manure	High	Stable base substrate; buffers pH; commonly co-digested with silages/residues.
Pig slurry	Manure	High	Elevated NH_4^+ requires controlled loading and C/N balancing.
Municipal biowaste (OFMSW)	Municipal biowaste	High	EU-mandated separate collection; contamination control essential.
Wastewater sludge (WWTP digesters)	Wastewater sludge	High	Mature pathway with large installed base; digestate use regulated.
Fruit and vegetable residues (processing)	Agri-food industrial waste	High	Readily biodegradable; seasonal variability warrants adaptive feeding.
Maize silage (legacy fleets)	Energy crops	Medium → declining	Consistent yields; capped/limited in several Member States.
Grass silage/perennial grasses	Energy crops	Medium	Useful co-substrate for slurry; size reduction improves hydrolysis.
Cereal by-products (e.g., spent grain)	Agri-food industrial waste	Medium	High VS; protein can raise ammonia—dose accordingly.
Whey and dairy by-products	Agri-food industrial waste	Medium	High soluble COD; risk of rapid acidification without alkalinity control
Slaughterhouse waste (cat. 2/3)	Agri-food industrial waste	Medium	Very high methane yield; strict hygiene/pasteurisation requirements.

Beyond origin-based classification, substrates may also be categorised by their functional and technological characteristics.

Classification of substrates based on functional characteristics [64]:

- ○ diluting—substrates with a dry matter content below 8%, e.g., slurry;
- ○ concentrating—substrates with a dry matter content above 8% (e.g., any type of silage);
- ○ efficiency-enhancing—substrates with a high content of macronutrients, which increase biogas and methane yield;

- fermentation stabilising additives—chemical substances typically added in small quantities, which help maintain biochemical parameters at the appropriate levels.

Classification of substrates based on technological characteristics [65]:

- inoculating—groups of methanogenic bacteria that allow for inoculating the fermentation mixture to initiate the technological start-up (e.g., cattle manure or slurry from dairy cows);
- adhesive—substrates with a high cellulose content that aid in the metabolic activity of bacteria, which adhere to particles;
- easily fermentable—substrates whose use stabilises and facilitates the control of the fermentation process;
- difficult to ferment—substrates from group II and III of slaughterhouse waste, certain agricultural and food processing waste, where it is important not to exceed the maximum substrate dose.

The selection of substrates is one of the most critical tasks for investors, as it directly determines whether the investment will deliver the expected outcomes. Since the procurement and storage of substrates can account for up to 50% of a biogas plant's operating costs, the types of feedstocks should be defined at an early stage of project planning. When making this selection, attention should also be given to the distance between the substrate source and the biogas facility to avoid excessive transport costs [66]. Additionally, substrate availability must be assessed, including whether the materials are accessible throughout the year or only seasonally, and in what quantities. To maintain a stable fermentation process, it is advisable to combine several types of substrates, a practice referred to as co-fermentation.

The Ministry of Agriculture and Rural Development emphasises the need to consider a long-term perspective when utilising agricultural biomass for energy purposes. Global food production continues to rise, while it is essential to maintain agricultural production capacity. Currently, biogas production relies on surplus food production or crops from dedicated cultivation [9].

Plant-based substrates commonly used in biogas production include maize, sugar and fodder beets, potatoes, rye, triticale, wheat, grasses, and sorghum. Additionally, dedicated energy crops such as miscanthus, reed canary grass, and millet are frequently employed. In general, almost any type of plant biomass—excluding woody species—can be utilised in the anaerobic digestion process [67]. The growing interest in energy crops has led to an increased use of silage, which constitutes a major portion of plant-based feedstocks. Among them, maize silage stands out due to its high dry matter yield per hectare and superior biogas productivity compared to other crops. Its additional benefits include adaptability to a range of environmental conditions, low cultivation costs, tolerance to monoculture practices, and a broad spectrum of available cultivars.

Cereal crops, including both winter and spring varieties, are also well-suited as substrates for agricultural biogas plants. They can be utilised in the form of grains, straw, or entire plants, with hybrid rye being particularly valued for its low soil fertility requirements and high drought resistance. Whole-plant silage, known as GPS, is considered the most effective form. Another group of widely available substrates consists of grasses. However, the biogas yield from grasses is highly dependent on the harvest timing, management intensity, and prevailing soil and climatic conditions [64]. Grasses from intensively utilised meadows tend to produce substantially higher methane yields than those from extensively managed systems.

The biochemical methane potential (BMP) is a key parameter used to evaluate the capacity of different substrates to produce methane. It is defined as the volume of methane generated per unit mass of a given substrate under standardised anaerobic conditions [68,69]. Due to differences in chemical composition, equal quantities of various substrates yield different methane volumes. Hence, BMP serves as a fundamental indicator of substrate quality and energy potential in biogas production.

The BMP of a substrate is typically determined through batch anaerobic digestion tests carried out in laboratory settings. These tests involve mixing a measured amount of the substrate with an inoculum containing active methanogenic microorganisms in sealed reactors. The reactors are kept at a constant temperature, and biogas production is continuously monitored throughout the process. The methane content of the produced gas is analysed, most commonly by gas chromatography or infrared sensors. The tests are conducted until biogas production plateaus, which typically occurs after 20 to 40 days. The results are expressed in normal litres of methane per kilogram of volatile solids (NL $CH_4 \cdot kg^{-1}$ VS, where 1 NL = 0.001 m^3) under standard conditions (0 °C and 1.01325 bar). The methodology is most often based on the German standard VDI 4630 [70], which outlines detailed procedures for reactor setup, inoculum selection, process monitoring, and data evaluation. This ensures reproducibility and comparability of BMP values across laboratories and research studies [61,71].

To facilitate comparison across substrates, Table 3 collates indicative ranges of total solids (TS), volatile solids as a fraction of TS (VS/TS), and biochemical methane potential (BMP) expressed as m^3 $CH_4 \cdot kg^{-1}$ VS under standard conditions. Values reflect typical laboratory BMP testing of ensiled or fresh material and may vary with cultivar, harvest timing and pre-treatment. For clarity, 1 m^3 $CH_4 \cdot kg^{-1}$ VS ≡ 1000 m^3 $CH_4 \cdot Mg^{-1}$ VS.

Table 3. Key parameters of selected energy crops and agricultural residues, including biochemical methane potential (author's own elaboration based on [72–75]).

Substrate	Total Solids, TS (% of Fresh Mass)	Volatile Solids, vs. (% of TS)	BMP (m^3 $CH_4 \cdot kg^{-1}$ VS)
Maize silage	28–35	90–96	0.30–0.37
Grass silage	25–35	85–92	0.28–0.34
Fresh grass (herbage)	15–25	80–90	0.25–0.33
Hay (dried grass)	84–90	85–90	0.20–0.30
Cereal straw (wheat/rye)	85–92	80–90	0.20–0.27
Sugar beet (root)	18–23	90–95	0.33–0.40
Fodder beet (feed beet)	18–23	90–95	0.33–0.38
Sugar beet tops/leaves	15–25	85–92	0.25–0.33
Oilseed rape silage	25–35	85–92	0.25–0.32
Bean silage (field bean)	25–35	85–92	0.27–0.33

Notes: ranges collected from several studies [72–75] to reflect variability across cultivars, sites and methodologies. BMP reported as m^3 $CH_4 \cdot kg^{-1}$ VS at standard conditions; where studies report NL $CH_4 \cdot kg^{-1}$ VS, values are directly interpretable as m^3 $CH_4 \cdot kg^{-1}$ VS (1 NL = 0.001 m^3).

Animal-based substrates can be categorised into solid and liquid forms. Animal excreta, which are by-products of agricultural activities, may be utilised as feedstock for biogas plants. This approach is both rational and environmentally beneficial, as it enables the management of waste materials while minimising environmental impact [76]. The primary animal-derived substrates include slurry, manure, liquid manure, and farmyard manure.

The volume of biogas that can be produced from such substrates—similarly to other organic materials—depends on their chemical composition. In the case of animal-derived materials, factors such as animal species, diet, and age may significantly influence substrate quality [68]. It is well established that excreta from ruminants typically yield lower biogas outputs due to partial fermentation of feed occurring in the rumen.

Slurry is one of the principal substrates used in agricultural biogas plants. It is a mixture of faeces and urine from livestock, combined with water. The properties of slurry may vary depending on the amount of water used and the animals' diet. Its fundamental parameters are as follows:

- ○ pH range: 6.5–7.9,
- ○ specific density: 900–1400 kg·m^{-3},
- ○ freezing point: approximately −2 °C,
- ○ tendency to stratify during storage,
- ○ presence of microelements essential for biochemical processes,
- ○ average carbon-to-nitrogen (C:N) ratio for cattle slurry: approximately 6.8:1.

Unlike solid manure, slurry can be easily transported to the biogas plant via pipelines. Its consistency also makes it highly compatible with other co-substrates [77,78].

Different types of animal manure offer varied fermentation potential (see Table 4). Swine slurry, for example, is generally richer in easily degradable organic matter compared to cattle slurry and thus often yields more biogas. Poultry manure, although rich in nutrients and dry matter, requires careful dosing due to its high nitrogen content, which may lead to ammonia inhibition. Additionally, by-products such as rumen contents, blood, and dairy waste (e.g., whey or discarded milk) may be used as co-substrates to enhance process performance, provided that hygienisation or regulatory compliance is ensured.

Table 4. Key parameters of animal-based waste, including biochemical methane potential (author's own elaboration based on [68,76,79,80]).

Substrate	Total Solids, TS (% of Fresh Mass)	Volatile Solids, vs. (% of TS)	BMP (m^3 CH_4·kg^{-1} VS)
Dairy cow slurry	6–12	75–85	0.20–0.30
Calf slurry	4–10	75–85	0.22–0.30
Pig slurry	2–8	70–80	0.25–0.35
Cattle manure (solid, farmyard)	18–30	70–80	0.20–0.28
Pig manure (solid)	20–30	75–85	0.20–0.30
Poultry manure (litter)	50–75	70–80	0.15–0.30
Sheep manure	25–35	70–80	0.18–0.28
Goat manure	20–35	75–85	0.18–0.26
Dairy effluent (slurry/residues)	2–6	70–85	0.16–0.28
Whey (cheese whey)	4–7	90–98	0.35–0.55

Notes: ranges collected from several studies [68,76,79,80] to reflect variability across breeds, diets, housing and sampling points. BMP reported as m^3 CH_4·kg^{-1} VS at standard conditions; where studies report NL CH_4·kg^{-1} VS, values are directly interpretable as m^3 CH_4·kg^{-1} VS (1 NL = 0.001 m^3).

Co-digestion of animal-derived substrates with plant-based materials improves the overall stability of the anaerobic digestion process by balancing nutrient content, particularly the C:N ratio, and supporting microbial activity. It also reduces the risks associated with mono-fermentation of nitrogen-rich materials. Animal-based substrates play a vital role in agricultural biogas production due to their availability, consistency, and inoculation potential. Their utilisation supports both renewable energy generation and environmentally responsible waste management.

4. Water and Soil Pathways in Biogas Production: Circularity, Benefits and Risks

Biogas production involves intensive water use and impacts on the soil environment, particularly through the application of digestate. This chapter analyses water management in biogas facilities, with a focus on circular strategies, resource recovery potential, and environmental risks associated with pollutant emissions to water and soil.

4.1. Water Management in Agricultural Biogas System

In biogas plants, water plays a vital role as a process medium—it is used for substrate preparation and dosing, cleaning of installations, cooling of cogeneration units, and feeding steam boilers. In conventional energy systems, water consumption can reach several dozen litres per kilowatt-hour (kW·h; 3.6 MJ) of electricity produced. Under conditions of declining water availability and increasing frequency of extreme weather events (droughts, heatwaves), this creates significant operational and environmental risks. Increasing demands for environmental protection and resource efficiency (energy, nutrients, and water) are driving the development of systems that treat process water as a valuable resource and seek to close the water loop within the technological process.

In response to these challenges, more biogas plants are being designed with closed-loop systems aimed at maximum recirculation and regeneration of process water. These systems can be divided into three main circuits:

- digestate circuit—after separation of the solid fraction (using flocculation or gravitational methods), the digestate undergoes microfiltration and ultrafiltration, followed by nanofiltration; the resulting water, with reduced total dissolved solids (TDS), meets the quality requirements for cooling systems and steam boilers;
- process water circuit—condensate generated during reactor cooling and biogas condensation is collected in dedicated tanks, treated through coagulation and flotation, and then reintroduced into the technological system as a heat carrier or cooling medium; this approach, similar to sustainable ecological sanitation systems, enables water recovery and closes the resource loop;
- external wastewater circuit—municipal and industrial wastewater, after preliminary solids removal and reduction in chemical oxygen demand (COD), can be co-digested with conventional biogas substrates [81,82].

This allows for increased biogas production efficiency and reduced demand for fresh water.

Implementing these circuits can, as an engineering design target, enable about 60–70% internal water recirculation and thereby a 30–40% reduction in freshwater intake, provided that digestate separation is coupled with micro-/ultrafiltration and nanofiltration and that condensate streams are recovered. These are optimisation values reported for closed-loop, high-integration layouts and should not be read as sector-wide averages. For comparison, the optimisation study by Wei et al. (2025) on a multi-stream biogas facility reported a 34% reduction in freshwater withdrawal under economically optimal conditions [81]. This demonstrates the difference between technical potential and modelled, site-specific performance. In EU practice, achievable recirculation levels are further conditioned by integrated environmental permitting and water-quality requirements, which in many Member States prioritise discharge compliance over maximum internal reuse and can therefore cap practical recirculation below the technical optimum [27,30].

In the context of water-saving strategies and reduced consumption of primary resources, the concept of Eco-Industrial Parks (EIPs) is also worth mentioning. These are clusters of industrial facilities that cooperate in exchanging materials, energy, water and by-products [83]. In such systems, biogas plants can serve as central units for water and nutrient recovery. Digestate is separated and treated, enabling the recovery of water and fertiliser components such as nitrogen and phosphorus, while the solid fraction can be used as fertiliser or fuel. These solutions lower treatment costs, reduce emissions and improve resource efficiency. In the European context, water-loop choices and digestate handling are increasingly shaped by integrated environmental requirements and permitting practice, which may constrain reuse below technical maxima [27,30,83].

4.2. Impact of Agricultural Biogas Plant on Water Quality

The positive environmental impact of biogas technology is not automatically guaranteed—management of production and digestate handling is crucial, especially regarding water quality [84].

The literature shows varied views on how anaerobic digestion (AD) affects water quality, particularly groundwater and surface water. Ferdes et al. (2019) state that a well-designed biogas plant poses no risk to these waters, as no process wastewater is produced [84]. Digestate is processed, and recovered water is reused in the system. Excess water treated by two-stage reverse osmosis reaches a quality suitable for industrial and agricultural use. Small amounts of wastewater may be sent to local treatment plants, and roof rainwater is directed to separate drainage systems, reducing contamination risks.

Biogas plants can also help reduce eutrophication in surface waters by neutralising organic compounds that would otherwise enter the environment. Using stabilised digestate as fertiliser lowers the risk of nutrient runoff, including nitrogen and phosphorus [9]. Ferdes also notes that unprocessed crop residues left over winter decompose and release nitrogen, contributing to eutrophication. Additionally, pig slurry fertiliser may contain heavy metals like copper and zinc, threatening water quality if untreated.

Conversely, agrohydrological simulations [85] suggest that the impact of biogas production on water quality may be ambivalent. If digestate is applied at rates similar to untreated slurry without any modification of agricultural practices, nitrogen leaching into groundwater may remain unchanged. This indicates that anaerobic digestion alone does not ensure improved water quality; appropriate agronomic measures—such as optimising fertiliser application rates, timing, and methods—are essential.

A management approach based on sustainable agricultural principles, including crop rotation and site-specific fertilisation planning, has been shown to reduce nitrogen losses to surface and groundwater. However, such strategies may also result in lower yields, thus highlighting the need to balance economic performance with the protection of natural resources.

Logan and Visvanathan (2019) emphasise the importance of digestate quality and its appropriate management [86]. They point out that direct application of digestate to agricultural land can contribute to pollution if sanitary and environmental requirements are not met. Therefore, current management strategies—often focused primarily on maximising energy recovery—should also incorporate environmental protection objectives, particularly with regard to water resources.

Therefore, the influence of biogas production on water quality depends on substrates, fermentation technology, digestate management, and farm practices. When performed sustainably, with advanced purification and appropriate fertilisation, biogas production can improve groundwater and surface water quality [24]. Poor management may worsen eutrophication and nitrate contamination. A systemic, interdisciplinary approach to biogas plant planning and operation is essential, combining energy, environmental, and agronomic factors.

The schematic below (see Figure 7) presents the impact of biogas production on water management and soil quality, highlighting the importance of digestate management to limit nutrient leaching—particularly nitrogen and potassium—into groundwater. It also demonstrates the beneficial use of digestate as a fertiliser, supplying essential nutrients (N, P, K) to crops. This topic will be briefly discussed in the following subsection.

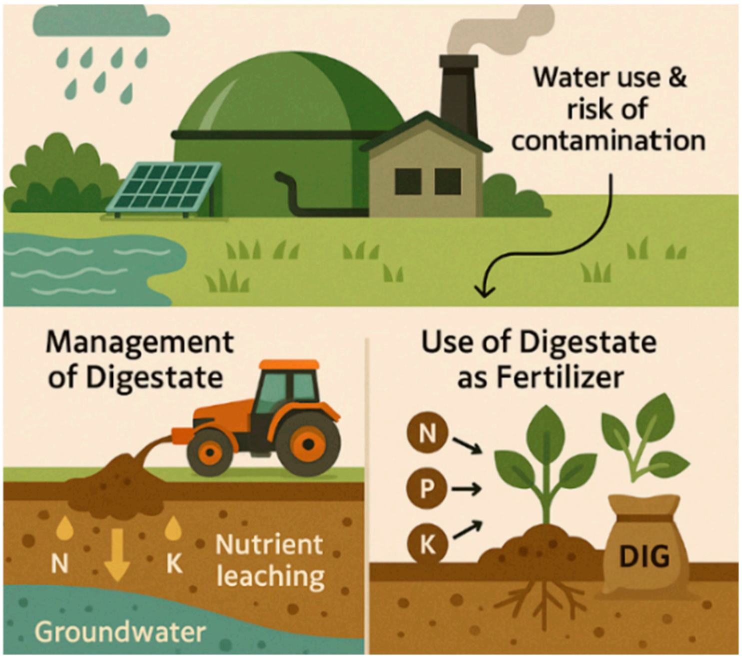

Figure 7. Impact of biogas production on water management and soil quality (original/own material).

4.3. Soil Quality Implications of Digestate Use

Digestate, a by-product of anaerobic digestion, retains 85–95% of the original substrate mass and contains 2–3% total nitrogen, along with phosphorus, potassium, micronutrients, and trace amounts of heavy metals. The organic fraction present in digestate improves soil structure by increasing porosity and water-holding capacity, which may support moisture retention during drought conditions. In addition, organic compounds promote the development of soil microflora, enhancing mineralisation processes and nutrient availability to plants [87,88]. Recommended application rates and timing should follow national guidance and routine digestate analysis (N, P, K, salinity, heavy metals) to minimise leaching and salinisation; requirements are particularly explicit across the EU and may differ elsewhere [24,27,30]. In the EU, the agri-environmental regime commonly applies the limit of 170 kg $N \cdot ha^{-1} \cdot yr^{-1}$ to digestate from livestock-based systems, with higher allowances (up to about 250 kg $N \cdot ha^{-1} \cdot yr^{-1}$) reported for the UK and selected derogations [24]. Outside the EU, application limits are often set case by case rather than as a uniform ceiling, which increases the importance of periodic digestate characterisation and soil/water monitoring [24,27].

Consequently, properly processed digestate can partially replace mineral fertilisers by supplying plants with macro- and micronutrients while enriching the soil with organic matter (see Figure 7). Field trials have shown yield increases of 5–15% following the application of 20,000 $L \cdot ha^{-1}$ (20 $m^3 \cdot ha^{-1}$) compared to mineral fertilisation alone [87]. The main benefits include reduced fertilisation costs, lower CO_2 emissions related to synthetic fertiliser production, improved soil biological activity, and enhanced water retention capacity, all contributing to greater crop resilience during drought.

Effective digestate utilisation requires meeting certain conditions. Separating liquid and solid fractions improves nutrient bioavailability. Digestate is most suitable for crops with high organic matter demands, provided that soil nutrient levels and groundwater quality are regularly monitored [24]. Its application should be carefully aligned with crop nutrient needs and seasonal timing to minimise losses. Excessive application can cause soil degradation and environmental harm. Applying more than 30,000 $L \cdot ha^{-1}$ (30 $m^3 \cdot ha^{-1}$) may lead to soil salinisation and heavy metal accumulation, which negatively affect germination and crop quality [89]. Excess nitrogen and phosphorus increase the risk of leaching and eutrophication. Therefore, digestate composition should be routinely analysed, and national application guidelines strictly followed.

Proper management of the fermentation process, water circulation, and digestate application is crucial to maximise environmental benefits while reducing risks to soil and water quality. This requires precise dosage control, suitable infrastructure, and ongoing environmental monitoring.

At the same time, it is important to consider that, despite these benefits, wider environmental impacts related to biomass sourcing cannot be overlooked. The growing demand for energy crops used in biogas production may encourage the expansion of monoculture systems, especially maize cultivation, which carries risks of biodiversity loss and soil degradation [90,91]. Intensive cropping without adequate rotation often leads to increased soil erosion, depletion of soil organic matter, and elevated nutrient runoff, thereby worsening eutrophication pressures [92]. Furthermore, large-scale cultivation of biogas feedstocks typically requires substantial fertiliser and pesticide use, which can adversely affect groundwater quality and potentially reduce some of the environmental gains achieved through digestate recycling.

Therefore, sustainable biogas production must involve not only careful digestate management but also responsible feedstock sourcing. Agroecological practices, such as multispecies cover cropping and integrating catch crops and agricultural residues, offer effective ways to reduce these risks while ensuring sufficient feedstock supply [93].

5. Economic and Social Aspects of Agricultural Biogas Production

This chapter provides an analysis of the key factors influencing the profitability and social aspects of investments related to biogas production. The connection between economic and social aspects in this context forms the foundation for the sustainable development of rural areas and shapes the distinctive nature of such ventures.

5.1. Economic Balance, Key Investment Determinants, and Support Systems

Evaluating the profitability of agricultural biogas plants requires considering both the financial aspects and the overall return on investment. Cost–benefit analysis remains a key tool in this process, allowing a structured comparison between incurred costs and the revenues generated by energy production and plant operation. This type of analysis helps determine whether a project is financially viable and attractive from an investor’s perspective.

The most important factors in such an evaluation are typically the following [94,95]:

- Capital expenditures—These involve the initial outlays needed to build and start up the plant: purchasing and installing equipment, developing infrastructure, acquiring land, and securing permits. If an existing facility is being modernised, additional adaptation costs must be taken into account. In Poland, the cost of building an agricultural biogas plant with an electrical output of approximately 500 kW usually ranges from PLN 12 to 18 million. Micro-installations tend to be much less expensive. The return on investment can be expected within 6 to 10 years, especially when low-cost substrates are available, energy is used efficiently on site, and public funding (e.g., KPO or NFOŚiGW) is obtained.
- Operating costs—These cover everyday expenses, such as staff salaries, procurement and transport of substrates, routine maintenance, digestate handling, and compliance with legal and technical standards. A share of the produced energy is typically used to power the plant’s internal systems (e.g., pumps, mixers, fermentation heating), helping to lower electricity bills.

- ○ Feedstock availability and costs—These have a direct impact on the plant's economic performance. The most efficient setup involves placing the plant near substrate sources and energy consumers—farms or food processors, for example. Using organic waste from agriculture or municipalities can further reduce input costs.
- ○ Energy production and utilisation—The plant's profitability also depends on how efficiently it runs and how much of the generated energy can be used. Self-sufficiency is the goal, and smart use of heat—for instance, in drying systems or farm operations—can significantly improve financial outcomes.
- ○ Environmental and social benefits—Although not always easy to quantify, these include lowering greenhouse gas emissions, cutting down organic waste, improving waste management systems, and contributing to local job creation and rural development. These factors also weigh into the broader assessment of the plant's value.

To gauge economic performance, financial metrics such as net present value (NPV), internal rate of return (IRR), payback period, and profitability index (PI) are applied. Using different scenarios—optimistic, baseline and conservative—makes it possible to evaluate how the investment would cope with changing feedstock prices or market conditions [96].

To illustrate the current scale and regional diversity of biogas deployment, Table 5 presents the primary energy production from biogas in EU countries in 2022, expressed in kilotonnes of oil equivalent (ktoe). It differentiates between sources such as landfill gas, sewage sludge gas, biogases from anaerobic digestion, and thermal biogas. As shown in the table, Germany leads with approximately 8109 ktoe, followed by Italy (2033 ktoe) and France (1627 ktoe), reflecting strong national frameworks and infrastructure. These three countries together contributed as much as 75% of the total EU-27 primary biogas production in 2022. In contrast, Poland's production reached 319 ktoe, with a relatively small share from agricultural biogas. Denmark (689 ktoe) and the Netherlands (415 ktoe) demonstrate more diversified source profiles. The dataset illustrates significant disparities in production levels across the EU, underlining the need for targeted support in less developed biogas markets.

Table 5. Primary biogas production by selected EU Member States in 2022, in ktoe (authors' own elaboration based on [97]).

Country	Landfill Biogas	Sewage Sludge Biogas	Other Biogases from AD	Thermal Biogas	Total
Germany	112.3	472.9	7523.6	0.0	8108.8
Italy	261.1	48.7	1715.9	7.2	2033.0
France	377.5	27.2	1222.2	0.0	1626.9
Denmark	3.5	26.0	659.5	0.0	689.0
Czech Republic	19.8	41.9	535.4	0.0	597.1
The Netherlands	9.7	65.0	340.5	0.0	415.2
Spain	154.8	98.2	79.1	0.0	332.1
Poland	47.5	119.0	152.5	0.0	319.0
Bulgaria	0.0	5.2	46.9	0.0	52.1
Romania	0.0	0.0	23.2	0.0	23.2
Cyprus	0.0	0.3	5.2	0.0	5.5
Malta	0.0	0.0	1.7	0.0	1.7

It is also worth noting that, outside the EU—summarised in Table—biogas portfolios in other regions (e.g., North America and East Asia) are more heavily weighted towards wastewater sludge and landfill gas or policy-driven rural digesters, implying different cost structures, revenue streams and support-scheme sensitivities [98–100].

Among renewable energy sources, biogas stands out as one of the most capital-intensive technologies, primarily due to its high infrastructure costs and substantial ongoing operational expenditures. According to recent data from the International Renewable Energy Agency [98], the Levelised Cost of Electricity (LCOE) for biogas remains higher than for solar PV or onshore wind, ranging between 100 and 150 USD/MWh (approx. 10–15 euro cents per kWh), depending on scale, feedstock type, and technology. This underlines the importance of effective support schemes, which play a decisive role in shaping the development of the biogas sector [99].

Globally, the development of agricultural biogas is strongly influenced by national support systems, which determine the economic viability and attractiveness of such investments [33]. These mechanisms typically include feed-in tariffs, investment grants, tax exemptions, and market-based instruments such as renewable energy auctions or certificates [101]. Their design reflects broader energy, agricultural, and climate strategies, as well as institutional and market maturity.

In Asia, countries such as India have introduced comprehensive support programmes. The SATAT initiative guarantees offtake for compressed biogas and offers fiscal incentives, while GOBAR-DHAN supports small-scale rural installations [102]. In the United States, biogas producers benefit from federal schemes such as the Renewable Fuel Standard and state-level instruments like California's Low Carbon Fuel Standard, complemented by USDA investment grants [100]. Brazil's RenovaBio programme enables biomethane producers to trade decarbonisation credits, thereby enhancing project bankability [103].

In Europe, early support models were based on feed-in tariffs (e.g., in Germany and Italy), gradually replaced by auction systems and feed-in premiums. Countries such as Denmark and France offer stable, multi-year remuneration schemes, while Sweden promotes biomethane through tax relief and integration into the transport sector. At the EU level, the REPowerEU strategy targets 35 bcm of biomethane production by 2030, supported by harmonised guarantees of origin and targeted subsidies [104].

In Poland, the support framework includes feed-in tariffs for micro-installations (<500 kW) and feed-in premiums for larger plants, implemented through the national auction mechanism. Additional financial assistance is available via the National Fund for Environmental Protection and Water Management (NFOŚiGW) and EU structural funds [105]. However, regulatory instability and procedural complexity are repeatedly cited as major barriers to scaling up investments [106,107].

The examples presented show that biogas systems can develop under diverse regulatory arrangements. Their economic feasibility and investor confidence, however, hinge on long-term policy certainty, stable remuneration, and transparent, non-discriminatory access to infrastructure.

5.2. Social Aspects of Biogas Plant Operation

Social factors play a crucial role in the planning and operation of agricultural biogas plants. Cooperation with local communities, public acceptance, and stakeholder engagement can significantly influence the success of such projects [108].

One of the key non-technical barriers to biogas development is insufficient social acceptance. In some cases, local opposition may lead to the cancellation of projects, even when economically viable. Such resistance typically stems from limited knowledge of biogas processes, digestate use, safety, or site selection. Therefore, assessing community attitudes is advisable at the early planning stage [109]. Importantly, social acceptance is not independent of earlier technical choices. As noted in the technological section on plant layout and siting, project scale, location, and transport logistics determined at the design stage (access roads, distance to substrate sources, proximity to housing) strongly condition later community reactions [32,37–39]. Larger or centrally located plants tend to intensify concerns about odours, traffic and landscape impact, whereas smaller, farm-integrated units are more easily legitimised when coupled with local heat use and transparent communication [108,109]. For this reason, social-impact assessment and stakeholder dialogue should be linked directly to technology selection and siting decisions, not treated as a separate, late-stage activity. It should be emphasised that properly designed and well-sited biogas plants offer substantial environmental benefits (greenhouse gas emission reduction, improved organic waste management). However, without transparent communication and stakeholder engagement, public concerns may intensify [108]. Effective strategies include consultation meetings, information campaigns, site visits, and structured dialogue. Investor transparency and inclusion of local views are essential for both implementation and ongoing operation.

Biogas plants support rural socio-economic development. Unlike fully automated industrial sites, these facilities require personnel for operations, monitoring, servicing, and administration. For instance, constructing three biogas plants with an installed electrical capacity of 500 kW each in one municipality may generate five full-time jobs. Seasonal labour is also needed, particularly during biomass harvesting and transport. Local firms in transport, construction, and maintenance can cooperate with plant operators, while biogas equipment suppliers may benefit from increased demand. Such investments stimulate local entrepreneurship and reinforce regional supply chains [110]. This energy can heat public buildings, schools, or agricultural facilities, reducing municipal costs and improving energy autonomy. Another advantage is access to digestate, a natural biofertiliser, as discussed earlier in relation to animal-based substrates. Biogas investments contribute to increasing local gross domestic product (GDP), stimulate structural economic shifts, and promote infrastructure development [111,112]. Host regions are often seen as progressive and environmentally responsible, attracting further investment. Plant operators may also support local initiatives in education and infrastructure, reinforcing community ties [32].

It is worth noting, however, that alongside the aforementioned socio-economic benefits, an increasing number of studies highlight potential social conflicts arising from land-use changes linked to the intensification of biogas production for energy purposes. The diversion of arable land from food to energy production may exacerbate food security concerns and increase competition for land, particularly in regions with limited agricultural area [113]. In extreme cases, this may contribute to rising food prices or displace traditional farming systems, disproportionately affecting smallholder farmers. Large-scale monoculture plantations for biogas feedstock can also lead to the consolidation of land ownership and marginalisation of local communities [114]. These dynamics underscore the need to balance energy production objectives with broader rural development goals and ensure that biogas investments do not compromise food systems or social equity. To address these concerns, integrated land-use planning and participatory governance models are increasingly recommended, allowing local stakeholders to participate in decision-making and define acceptable trade-offs between energy, food, and environmental priorities [115].

Figure 8 summarises the socio-economic benefits of agricultural biogas plants: job creation, business participation, and utilisation of heat and digestate. Collectively, these factors enhance regional development through increased GDP, improved infrastructure, investment appeal, and educational engagement—strengthening social acceptance and integration of renewable energy.

Figure 8. Socio-economic and community development impacts of agricultural biogas plants (original/own material).

Environmental education also plays a growing role in fostering acceptance [116,117]. Biogas plants may serve as educational platforms for schools and universities, enabling site visits, training, and research (see Figure 8). Combining energy production with outreach promotes sustainable values and strengthens public trust.

Community involvement is increasingly vital. Shared ownership models—such as cooperatives or community-led biogas plants—allow residents to invest and participate in decision-making. These models distribute benefits locally and empower communities to shape renewable energy development.

In summary, the social dimension of agricultural biogas plants is complex but offers tangible benefits for regional growth. While potential social conflicts related to land-use changes require careful management, educational efforts, transparency, and successful implementations contribute to rising public support and community participation in biogas initiatives.

6. Barriers to the Implementation of Biogas Plants in Agricultural Areas

Despite significant advances in the development of agricultural biogas plants and growing awareness of the environmental, energy security, and economic benefits of biogas, a number of barriers still hinder its expansion in production and utilisation. These barriers comprise a set of technical, legal, economic, social, environmental institutional factors.

6.1. Technical and Technological Barriers

The implementation of agricultural biogas plants is hindered by a complex interplay of technical and technological challenges, many of which translate directly into economic barriers that limit their scalability and viability within the agri-energy sector. A key issue is the lack of standardisation in fermentation modules. Since each installation requires bespoke design and sizing, this increases unit costs, extends project timelines, and complicates Logistics [118].

These structural inefficiencies are further compounded by the complexity of process control. Stable operation requires precise regulation of parameters such as temperature, pH, and gas composition, necessitating advanced automation systems and extensive sensor networks [34]. While integration with SCADA (Supervisory Control and Data Acquisition) systems enables remote monitoring and data collection, the installation costs and need for ongoing specialised maintenance often exceed the capacity of small and medium-sized farms. Moreover, without adequate pre-treatment technologies—such as shredding, homogenisation, and retention time control—the fermentation process remains highly sensitive to the physicochemical properties of feedstock, which can severely impact methane yield and process stability.

Additional technical burdens arise from the need to purify raw biogas before it can be effectively utilised or injected into gas grids [119]. Although effective desulphurisation and dehydration technologies exist, they impose further operating costs and require periodic servicing, representing significant challenges for smaller agricultural plants. Seasonal temperature fluctuations introduce another constraint: lower ambient temperatures reduce microbial efficiency and gas production, while mitigation measures like reactor heating or insulation increase both capital and operational expenditures [118]. This issue is compounded by the limited availability of skilled technical services in rural areas, resulting in prolonged downtimes due to equipment failures or delayed maintenance.

Finally, ensuring reliable access to sufficient feedstock remains a persistent challenge. The dispersed nature of biomass sources, seasonal variability, and inadequate transport infrastructure complicate consistent supply, directly impacting biogas productivity [116]. This logistical complexity often necessitates coordinated collection systems or regional cooperation between farms to stabilise input flows.

Overcoming these multifaceted barriers requires a coordinated strategy that integrates standardisation, investment in rural service infrastructure, workforce training, and improvements in local feedstock logistics to make agricultural biogas a genuinely viable and competitive renewable energy source.

6.2. Economic and Legal Barriers

The implementation of agricultural biogas plant projects faces significant economic challenges and barriers. High initial capital investment, including the construction of reactors, feedstock preparation systems, and biogas purification units, represents a substantial obstacle for many investors, including farmers [96]. Even when organic feedstock is available at no cost, expenses related to its transportation and pre-treatment can markedly reduce the project's economic viability, especially in dispersed rural settings.

A further economic barrier is the lack of preferential financial instruments such as grants, concessional loans, or tax incentives, which is particularly problematic in developing countries attempting to deploy costly, innovative technologies [119]. Investors frequently have to rely on expensive commercial financing, which increases investment risk and lowers profitability [120]. Additionally, the absence of clearly defined fiscal policies and long-term financial support strategies complicates the ability to forecast returns on investment reliably. High levelised cost of energy (LCOE) for biogas and the volatility of electricity market prices further exacerbate these challenges [121]. Consequently, overcoming the economic challenges requires not only optimisation of technological costs but also the creation of a stable, transparent financial support system.

If legal barriers are taken into consideration, the literature indicates that, in the context of agricultural biogas development, they are present in many countries worldwide. Such restrictions often coexist with economic challenges, particularly in African and Asian regions [32,116]. At the international level, legal and regulatory obstacles vary significantly by region, often reflecting differences in energy policy maturity and administrative capacity.

Within the European Union, the most influential legal instruments include the Renewable Energy Directive (EU) 2018/2001, which established binding targets for the integration of renewable energy [121]. Its revision, Directive (EU) 2023/2413, further strengthens the framework for biomethane deployment by introducing accelerated permitting procedures and enhancing the system of Guarantees of Origin [122].

Also in Poland, as an EU member state, directives are transposed into national law amid regulatory fragmentation across the Energy Law [123], Construction Law [124], and Waste Act [125]. Support includes feed-in tariffs for micro-installations and premiums for larger plants, plus co-financing from the National Fund for Environmental Protection and Water Management (NFOŚiGW) and European Union structural and investment funds [95]. Nevertheless, regulatory instability and complex procedures hinder biogas investment growth, highlighting the need for simplification to boost investor confidence.

In contrast, emerging economies face persistent legal fragmentation and weak enforcement. For example, in India, biogas development is hindered by the lack of a comprehensive legal definition of biogas within energy market regulations, despite central programmes such as the Sustainable Alternative Towards Affordable Transportation (SATAT) [126]. Similarly, in Sub-Saharan Africa, legal gaps, inconsistent land tenure systems, and the absence of quality and safety standards obstruct investment confidence [98]. These global discrepancies highlight the importance of establishing coherent, technology-specific regulatory frameworks that can reduce administrative burdens and enhance investor certainty.

6.3. Institutional Barriers

The development of agricultural biogas plants is significantly constrained by institutional barriers, which—although often less visible than financial or legal obstacles—play a decisive role in shaping the pace and scope of implementation. In Poland, the biogas sector, like the entire renewable energy sector, competes with conventional energy, which has been supported for decades by extensive technical, institutional, and financial infrastructure, largely developed with public funding.

One of the most persistent obstacles is the fragmented institutional structure at the central government level. The division of responsibilities, absence of a leading coordinating body, and limited experience of public institutions in managing RES projects hinder the development of coherent, long-term strategies [127]. Research activities related to biogas production and utilisation are dispersed across numerous institutes and universities, with no central institution to consolidate expertise and set priorities. This fragmentation results in a lack of systematic support for domestic producers of biogas technologies.

International literature confirms that similar barriers to biogas deployment are encountered globally. A lack of political will, weak policy coordination, and an unstable legislative environment discourage private sector involvement. Complex administrative procedures and bureaucratic inefficiencies significantly delay project implementation, as seen in countries such as Austria and China [128]. In highly centralised and hierarchical systems—such as in China and some African nations—the absence of decentralisation and limited competencies at the local level also hinder project deployment.

In summary, institutional barriers—from poor coordination and administrative inefficiency to unstable support schemes—represent a major challenge to the development of agricultural biogas. Overcoming these issues requires not only technical expertise and regulatory reform, but also strong political commitment and a long-term approach to energy transition.

6.4. Social Barriers

The implementation of biogas plants in rural areas faces a range of social barriers that significantly affect the pace and extent of development in this sector. Farming communities, which are directly adjacent to these investments, often express concerns regarding the potential impact of biogas installations on the local environment, public health, and everyday life in the countryside. Insufficient knowledge about the benefits and operational principles of biogas systems frequently results in mistrust and social resistance [109].

Moreover, limited organisational capacity among rural residents hinders their active involvement in decision-making processes related to such projects. The absence of effective consultation mechanisms between investors, local authorities, and the community deepens the sense of distance and contributes to misunderstandings.

Cultural factors and agricultural traditions also play a significant role in shaping perceptions of and acceptance of innovative technologies. For many residents, biogas plants may be perceived as externally imposed solutions, highlighting the importance of building trust and fostering open social dialogue. An instructive example comes from countries such as Ghana, Malaysia and China, where low levels of environmental and social awareness pose substantial obstacles to the adoption of biogas technology [127,128]. In certain cultural contexts, the use of biogas derived from animal waste is met with social rejection, due to religious beliefs or traditional norms. While similar concerns were observed in Poland in the early stages of biogas development, systematic educational efforts and informational campaigns have led to growing public awareness. This, in turn, has contributed to increasing acceptance and expansion of biogas technologies.

Overall, social barriers in rural areas are multidimensional and require a comprehensive approach, with education, communication, and mechanisms for community participation forming the foundation for the effective implementation of agricultural biogas plants.

6.5. Environmental Barriers

When examining environmental barriers to the implementation of agricultural biogas plants, the foremost consideration must be local natural conditions, which can markedly constrain both the efficiency and reliability of the installation. Climatic variability—particularly periodic droughts or insufficient rainfall—makes it difficult to secure the water required for anaerobic digestion. As a result, retention reservoirs and liquid recirculation systems may be necessary [129].

The next critical challenge is emissions and system leakages. Noise generated by pumps and agitators may exceed permissible limits, while the release of raw biogas—a mixture of methane, carbon dioxide and hydrogen sulphide—increases greenhouse-gas emissions and provokes odour complaints [116]. Even minor leaks in digester covers or valves can permit methane to escape into the atmosphere, undermining the overall environmental balance of the process.

A further significant barrier is the risk of contaminating groundwater and surface waters. Improper storage or spillage of digestate may lead to the leaching of nutrients (nitrogen, phosphorus) and pathogens into soils and watercourses, posing serious threats to water-resource quality. Addressing this requires the adoption of stringent control procedures, watertight tank constructions and continuous water-quality monitoring [60,85].

It is also imperative to respect the requirements for protecting areas of high conservation value. Erecting biogas plants in proximity to Natura 2000 sites, nature reserves, or ecological corridors entails additional constraints—from prohibitions on habitat disturbance, through the requirement for environmental permits, to the implementation of habitat-compensation measures [130].

Thus, environmental barriers to deploying agricultural biogas plants encompass four principal domains. These are: ensuring adequate water supply and erosion control; eliminating emissions and odours through sealed systems and leak monitoring; safeguarding water resources against contamination; and complying with nature conservation requirements in protected areas [131]. Overcoming these barriers demands the design of comprehensive engineering solutions and close collaboration with environmental-protection authorities.

The presented chapter shows that the development of agricultural biogas plants is held back by a range of closely connected barriers—technical, economic, legal, institutional, social, and environmental. These issues often overlap and make project planning and implementation more difficult, especially in rural areas. Effective support for the sector requires coordinated actions across different levels of policy, technology, financing, and community involvement.

7. Discussion

Agricultural biogas plants have increasingly gained attention as multifunctional installations that address key challenges of the agri-food and energy sectors. Their relevance extends beyond energy production to encompass greenhouse gas mitigation, waste valorisation, and the promotion of circular economy principles in rural areas. However, as this review demonstrates, the mere deployment of such technologies does not automatically guarantee environmental or socio-economic benefits. The effectiveness of biogas systems is highly dependent on context-specific conditions, integration into regional resource flows, and long-term policy coherence. The synthesis presented in this paper is most directly generalisable to the European context, with targeted references indicating the global implications of differing technological, environmental, and socio-economic trade-offs.

These interrelated environmental, economic, and social dimensions are illustrated in Figure 9, which synthesises the key impact areas of agricultural biogas plants. The diagram highlights the multifunctional character of biogas systems as enablers of rural development, environmental protection, and economic resilience, while also pointing to areas of potential trade-offs and policy tension.

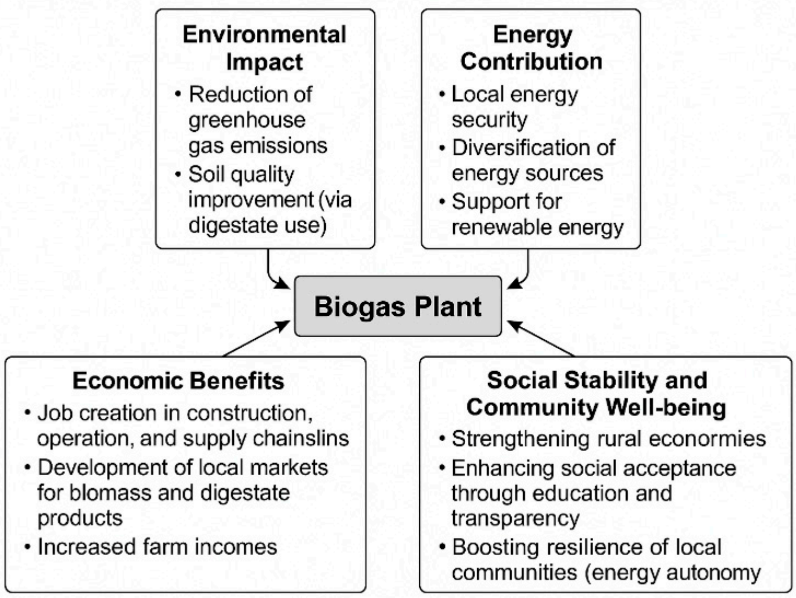

Figure 9. Key impact areas of agricultural biogas plants on rural development, environmental protection and economic stability (original/own material).

One of the most critical aspects is the management of digestate and feedstock sourcing, which directly influences the net environmental impact. While digestate has substantial fertilising value, improper application or oversaturation of agricultural land may contribute to nitrate leaching and eutrophication. These risks are exacerbated when energy crop monocultures dominate substrate supply, leading to soil degradation and loss of biodiversity. Several studies, including those by Svoboda et al. (2013) [132], highlight the negative ecological consequences of large-scale maize cultivation for biogas production. To avoid such trade-offs, recent research promotes agroecological strategies, such as cover cropping, crop diversification, and the use of agri-food residues, as more sustainable alternatives.

Moreover, economic viability remains a central determinant of biogas system expansion [133]. Despite the availability of support mechanisms in some EU countries, high investment costs, market volatility, and regulatory fragmentation continue to hinder wider adoption—especially in Eastern Europe and smallholder contexts [33]. The financial performance of biogas plants is also influenced by substrate logistics, process stability, and the capacity to valorise by-products. Integrated business models—combining biogas production with services such as wastewater treatment, fertiliser sales, or district heating—can enhance profitability and resilience [134].

In the social domain, public acceptance and participatory planning emerge as decisive factors. Studies indicate that resistance is rarely rooted in opposition to renewable energy per se, but rather in concerns about odours, traffic, and perceived exclusion from decision-making processes [109,110]. Transparent stakeholder engagement and inclusive governance models—such as energy cooperatives or community-owned installations—are therefore essential to ensure fair benefit-sharing and local legitimacy.

It is also necessary to consider the role of national and EU-level strategies in shaping the trajectory of the biogas sector. The European Commission's REPowerEU plan (2022) sets ambitious targets for biomethane production (35 bcm by 2030), requiring substantial scaling-up of decentralised, sustainable AD technologies [104]. However, effective implementation will demand harmonised permitting procedures, robust sustainability criteria, and investment in rural infrastructure and skills. The deployment of digital monitoring tools and automation (e.g., SCADA systems) could support process optimisation and regulatory compliance, though cost and complexity remain barriers for smaller plants. At the same time, EU- and national-level ambitions need to remain consistent with the agronomic and social constraints identified above—particularly with regard to digestate management, nutrient load limits and the avoidance of energy-crop monocultures—so that quantitative expansion targets do not trigger qualitative environmental or land-use conflicts.

Against this policy and implementation background, a number of innovation-oriented pathways have gained visibility in 2024–2025. It should also be noted that, alongside the mature agricultural AD pathways re-viewed here, several frontier directions have gained visibility in 2024–2025, notably biological methanation and power-to-methane integration with surplus renewable electricity, advanced or hybrid upgrading trains for high-quality biomethane, and socio-economic assessment frameworks aligned with the SDGs and just-transition agendas [128–130]. These pathways are technologically and systemically adjacent to agricultural biogas, but they primarily respond to gas-system decarbonisation and energy-system integration needs rather than to the day-to-day operational, soil–water and rural-development challenges that form the analytical core of this paper. These developments are closely related to biogas but operate at the interface with gas-system decarbonisation and energy-system integration, and therefore fall outside the operational, soil–water and rural-development focus adopted in this paper. They are, however, relevant for defining realistic future research and investment priorities—especially in Member States that plan to couple agricultural biomethane with grid injection or with hydrogen-based flexibility options. They are mentioned here only to delimit the scope of the contribution and to indicate where future extensions of the review could be directed.

Collectively, the above considerations indicate that further development of agricultural biogas systems will depend less on incremental process-level improvements. It will depend more on the ability to align technological configurations, feedstock-supply strategies, environmental safeguards and social licence within a single, coherent policy framework. The sustainable development of agricultural biogas systems depends on multilevel coordination: from local resource planning and social engagement, through national support schemes, to international sustainability frameworks [135]. Future research should first concentrate on comparative, multi-site case studies of integrated agri-cultural AD systems at farm and territorial scales, conducted under shared protocols (common functional units, harmonised system boundaries, and explicit counterfactuals). In parallel, harmonised life-cycle assessments are needed that explicitly account for direct and indirect land-use change, soil-carbon dynamics, water balances, and digestate-substitution credits, with uncertainty ranges reported [24,81,86]. Quasi-experimental evaluations of coordinated support instruments aligned with nutrient-management and water-quality regulation are also required, including assessment of distributional effects and social acceptance [104,108,109]. To enable robust cross-context comparison and transferability, studies should report a concise, comparable set of indicators: system-level GHG intensity ($gCO_2e\cdot kWh^{-1}$), net nutrient balance ($kg\ N,P\cdot ha^{-1}\cdot yr^{-1}$), water withdrawal per unit energy ($L\cdot kWh^{-1}$), soil-health indicators, levelised cost of energy (LCOE), and measures of community acceptance [98,108].

8. Conclusions

The integration of biogas production into agricultural systems constitutes a multifaceted contribution to sustainable development, encompassing environmental, energy, economic, and social dimensions. As demonstrated in this review, anaerobic digestion technologies enable not only the recovery of renewable energy from agricultural residues. They also support circular resource flows through the utilisation of digestate, water recirculation, and the mitigation of uncontrolled methane emissions. However, the effective implementation of biogas projects requires a systemic approach that accounts for local conditions and the interdependencies between technology, policy, and society.

Technological efficiency, though fundamental, must be embedded within a broader framework that considers resource availability, economic feasibility, regulatory clarity, and public engagement. The performance of AD systems depends on substrate quality and diversity, reactor configuration, temperature regimes, and the use of biological or enzymatic enhancers. Nonetheless, the widespread deployment of such technologies calls for stable and transparent support mechanisms, as well as simplified administrative procedures—particularly for decentralised or small-scale installations.

The environmental benefits of agricultural biogas production are conditional upon appropriate digestate management and responsible substrate sourcing. Without sound agronomic practices—such as nutrient dose control and regular soil monitoring—the risk of leaching and water contamination may outweigh the ecological gains. Likewise, the extensive cultivation of monoculture energy crops can contribute to biodiversity loss and soil degradation. To mitigate such risks, agroecological alternatives and integrated land-use planning should be prioritised.

From a socio-economic perspective, biogas installations offer tangible potential to diversify farm incomes, stimulate rural entrepreneurship, and strengthen regional energy self-sufficiency. However, public acceptance remains a decisive factor in project success. Transparent communication, participatory planning processes, and targeted educational efforts are essential to reconcile technological innovation with local expectations and values.

The future advancement of the sector will depend on coordinated action at multiple levels: further development of AD technologies adapted to regional conditions; targeted financial instruments; harmonised and enabling legal frameworks; and inclusive governance models. Only through such an integrated strategy can biogas become a resilient pillar of agricultural energy transition—contributing meaningfully to climate neutrality, food system resilience, and rural equity. These conclusions are grounded primarily in European evidence. Selected contrasts with major global economies delineate the limits of generalisation and indicate where policy and market contexts may alter outcomes.

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