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## The Use of Biogas Technologies for Organic Waste Disposal and Energy Recovery

### Abstract

Organic waste streams from agriculture, municipalities and agro-industrial processes are increasingly recognized as valuable resources for renewable energy production. Anaerobic digestion (AD) enables the controlled conversion of biodegradable substrates into biogas, with reported methane yields ranging from approximately 150 to 550 mL/gVS depending on substrate composition, pretreatment and co-digestion strategies. High-solids AD systems operating at total solids above 15–20% achieve volumetric productivities comparable to conventional slurry digesters, while reducing reactor volume requirements. Modern waste-to-energy configurations are capable of converting hundreds of thousands of tonnes of biomass annually into tens of thousands of megawatt-hours of renewable electricity, demonstrating the scalability of AD in integrated waste-management frameworks. In addition to energy recovery, AD reduces uncontrolled methane emissions, stabilizes organic matter and produces nutrient-rich digestate that can replace mineral fertilizers. Overall, the evidence indicates that biogas technologies form an essential component of sustainable waste management, simultaneously addressing organic waste disposal and renewable energy generation in line with circular-economy objectives.

**Keywords:** *anaerobic digestion, organic waste, energy recovery, circular economy, waste-to-energy*

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## Üzvi tullantıların atılması və enerji bərpası üçün bioqaz texnologiyalarının istifadəsi

### Xülasə

Kənd təsərrüfatı, bələdiyyə və aqrar-sənaye proseslərindən yaranan üzvi tullantı axınları getdikcə bərpa olunan enerji istehsalı üçün dəyərli resurslar kimi tanınır. Anaerob parçalanma (AD) bioparçalana bilən substratların biqaza nəzarətli çevrilməsini təmin edir; bu zaman substratın tərkibindən, ilkin emal üsulundan və birgə parçalanma strategiyalarından asılı olaraq metan çıxımı təxminən 150-dən 550 mL/gVS-ə qədər dəyişir. Ümumi quru maddə miqdarı 15–20%-dən yüksək olan yüksəkkonsentrasional AD sistemləri reaktor həcmi tələblərini azaltmaqla, əhəmiyyətli şlam tipli digestorlarla müqayisə oluna bilən həcm məhsuldarlığına nail olur. Müasir tullantıdan enerjiyə çevirmə konfigurasiyaları hər il yüz minlərlə ton biokütləni on minlərlə meqavat-saat bərpa olunan elektrik enerjisinə çevirə bilər ki, bu da AD texnologiyasının inteqrə olunmuş tullantı idarəetmə çərçivələrində miqyaslı bilənliyini nümayiş etdirir. Enerji bərpası ilə yanaşı, AD nəzarətsiz metan emissiyalarını azaldır, üzvi maddəni stabilləşdirir və mineral gübrələri əvəz edən qida maddələri ilə zəngin digestat yaradır.

Ümumilikdə, mövcud sübutlar göstərir ki, bəzə texnologiyaları dayanıqlı tullantı idarəetməsinin vacib tərkib hissəsidir və dairəvi iqtisadiyyat məqsədlərinə uyğun olaraq eyni zamanda həm üzvi tullantıların utilizasiyası, həm də bərpa olunan enerji istehsalı məsələlərini həll edir.

*Açar sözlər: anaerob parçalanma, üzvi tullantılar, enerji bərpası, dairəvi iqtisadiyyat, tullantıdan enerjiyə çevrilmə*

## Introduction

The global energy system still relies predominantly on fossil fuels, which are responsible for the majority of anthropogenic greenhouse-gas (GHG) emissions. At the same time, increasing quantities of organic waste from agriculture, food processing, municipalities and industry exert significant environmental pressure through uncontrolled emissions, odour generation, nutrient leaching and inefficient land use.

Anaerobic digestion (AD) is a key technology that links waste management with renewable energy production. Through microbial processes, organic matter is converted into methane-rich biogas and a nutrient-rich digestate that can replace mineral fertilizers. Compared with other bioenergy pathways, AD is characterized by high energy efficiency, the capacity to process wet and heterogeneous substrates and the co-generation of a valuable fertilizer product (Achinas et al., 2017). Biogas has become an important component of the European energy mix. Primary energy production from biogas in the EU increased from approximately 7,934 ktoe in 2009 to more than 14,000 ktoe in 2016, with Germany, the United Kingdom and Italy being among the leading contributors. Recent IEA Bioenergy assessments emphasize that AD of organic wastes plays a central role in the transition toward a climate-neutral circular bioeconomy by simultaneously supporting waste reduction, renewable energy generation and nutrient recycling (IEA Bioenergy Task 37, 2022). Azerbaijan also possesses substantial organic waste resources originating from livestock farming, crop production, food processing and municipal solid-waste streams. Most of these residues are currently managed through open storage, uncontrolled decomposition or direct landfilling, leading to methane emissions, odour formation and nutrient losses. At the same time, the country aims to expand its renewable-energy portfolio under the “Azerbaijan 2030: National Priorities for Socio-Economic Development”, with particular emphasis on green growth and circular-economy principles. Anaerobic digestion therefore represents a promising solution for simultaneously improving waste management and developing decentralized renewable energy systems in rural regions. The integration of AD technologies could reduce environmental impacts, enhance nutrient recycling and contribute meaningfully to national decarbonization objectives.

## Research

**Methodology.** This study is based on a structured review and synthesis of scientific and technical literature on anaerobic digestion (AD) of organic wastes. The methodological approach integrates peer-reviewed research articles, international reports, technical guidelines and datasets describing operational performance of anaerobic digestion systems treating animal manure, food waste, agricultural residues and agro-industrial by-products. Sources include peer-reviewed scientific articles, international reports from IEA Bioenergy and the European Biogas Association, as well as Russian-language studies on AD process optimization and waste-management practices (IEA Bioenergy Task 37, 2022).

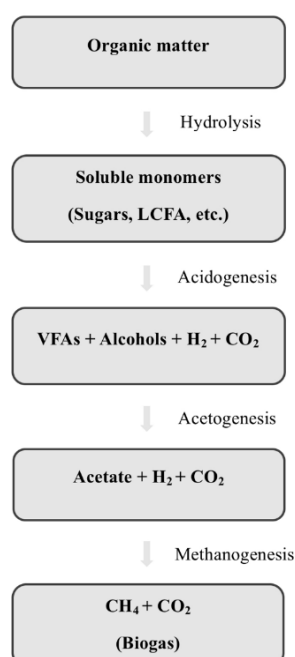
In addition to the qualitative review, quantitative ranges of key process and performance indicators were extracted from published datasets and industrial practice reports. These include typical substrate compositions, methane yields, loading rates, retention times, and energy-production metrics commonly cited for large-scale AD installations. The aim of this analysis is not to assess a specific facility, but to identify typical operational parameters and performance indicators of modern agro-industrial AD systems.

All data incorporated into this article are presented in aggregated or generalized form to reflect sector-wide trends rather than individual installations. This ensures that technological insights and performance characteristics reflect broadly applicable patterns in AD system design and operation.

## 1. *Biogas Technologies for Organic Waste Treatment.*

1.1. *Fundamentals of anaerobic digestion.* Anaerobic digestion is a multi-step biochemical process where hydrolytic, acidogenic, acetogenic and methanogenic microorganisms convert complex organic matter into biogas, mainly composed of methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) (Neri et al., 2023). During hydrolysis, polymers such as carbohydrates, proteins and lipids are broken down into soluble monomers. Acidogenic bacteria then form volatile fatty acids (VFAs), alcohols,  $\text{CO}_2$  and hydrogen. In acetogenesis, VFAs are converted into acetate,  $\text{CO}_2$  and  $\text{H}_2$ , which serve as substrates for methanogenic archaea that finally produce methane via acetoclastic and hydrogenotrophic pathways.

The microbial community is sensitive to pH, temperature, ammonia, sulphides and organic loading rate. Therefore, process stability requires careful control of substrate properties and operating conditions. Mathematical models of AD describe biomass growth, substrate degradation and gas formation using Monod-type kinetics and inhibition terms, and are used to design and optimize full-scale digesters (Ruzhinskaya & Fomenkova, 2014).



1.2. *Reactor configurations and operating modes.* Biogas plants treating organic wastes typically employ continuously stirred tank reactors (CSTRs) for livestock manure, food waste and industrial effluents, operated at mesophilic (35-38 °C) or thermophilic (50-55 °C) temperatures; plug-flow digesters and high-solids reactors for stackable substrates such as crop residues and municipal solid waste, sometimes combined with leachate recirculation and an up-flow anaerobic filter (UAF); two-stage systems where hydrolysis/acidogenesis and methanogenesis are spatially separated to improve stability for easily acidifying substrates like food waste.

High-solids digestion is particularly relevant for solid organic waste disposal because it enables treatment at total solids contents above 15-20 %, increasing volumetric gas productivity and reducing reactor volume, although often at the cost of slightly lower gas yield per kg of volatile solids.

## 2. *Organic Waste Substrates and Their Biogas Potential.*

2.1. *Animal manure.* Animal manure is a major substrate for farm-scale and centralized biogas plants due to its high moisture content, buffering capacity and continuous availability (Nasir et al., 2012). In the EU-27, livestock production generates more than 1,500 million tonnes of manure annually, representing a large biogas resource and a significant pollution risk if mismanaged (Holm - Nielsen et al., 2009).

**Table 1.**

Summarizes key physicochemical characteristics and methane yields for selected manures based on a recent review (Biogas Energy, 2019; Hawrot-Paw & Tapczewski, 2025).

Animal manure	pH	TS (%)	VS (%)	C/N	CH <sub>4</sub> yield (mL/gVS)
Cattle	7,1 – 8,6	14,5 – 22,7	11,9 – 72,0	14,6 – 18,9	157 - 395
Pig	6,4 – 7,5	8,2 – 36,7	6,2 – 82,8	5,7 – 13,5	204 - 438
Chicken	6,9 – 7,4	20,0 – 92,6	18,3 – 84,1	7,5 – 9,8	160 – 396
Sheep	7,2 – 8,1	22,3 – 40,0	18,7 – 72,7	11,3 – 14,7	207 – 357
Goat	~7,9	33,7 – 55,5	27,7 – 89,4	~18,0	402 – 500
Donkey	6,8	19,8	14,4	-	~380

These data show that goat and pig manure typically provide the highest methane yields (above 400 mL/gVS), while cattle manure often gives lower yields due to its higher lignin content (Bachmaier et al., 2020). Co-digestion of manure with energy- and nutrient-rich co-substrates such as poultry litter, sugar beet pulp or food waste can substantially increase gas yield and improve nutrient balance.

2.2. *Agricultural residues and lignocellulosic biomass.* Crop residues, energy crops and other lignocellulosic materials are abundant but more difficult to digest, as cellulose and hemicellulose are protected by a lignin matrix. Pretreatments such as mechanical size reduction, thermal or alkaline treatment, and biological processes increase surface area and improve biodegradability, though they add cost and energy demand (Bachmaier et al., 2020).

Studies on high-solids digestion of agro-residues mixed with cattle dung at total solids of 16-19% have reported volumetric biogas productivities of about 200-250 L·m<sup>-3</sup>·d<sup>-1</sup>, similar to conventional low-solids digesters, but with reduced reactor volume requirements. This makes high-solids AD an attractive option for treating straw, leaves and other fibrous residues that are not suitable for slurry-type digesters.

2.3. *Food waste and municipal biowaste.* Food waste and the organic fraction of municipal solid waste (OFMSW) present both a challenge and an opportunity: they are highly biodegradable and energy-rich, but their uncontrolled decomposition in landfills leads to methane emissions and leachate generation.

Biomethane yields from food waste can reach 380-550 mL/gVS, particularly for lipid-rich wastes, but process stability is sensitive to rapid acidification and ammonia inhibition (Zhang et al., 2014). Co-digestion with manure or sewage sludge is often used to provide buffering capacity and trace nutrients. For example, co-digestion of food waste with cattle manure at an optimal ratio of 2:1 has been reported to produce around 388 mL CH<sub>4</sub>/gVS in batch tests and ~317 mL CH<sub>4</sub>/gVS in semi-continuous operation, while maintaining stable pH and avoiding VFA accumulation (Neri et al., 2023).

Microalgal biomass, which can be grown on wastewater and flue gases, is another promising substrate. Mono-digestion of microalgae typically yields 287-611 L·kg<sup>-1</sup>VS of biogas, whereas co-digestion with bakery waste increased yields to almost 500 L·kg<sup>-1</sup>VS in one study; methane concentration reached about 60-65% (Hawrot-Paw & Tapczewski, 2025). This illustrates how biogas technologies can valorize both primary biomass and food-industry residues.

2.4. *Industrial and agro-industrial residues.* Many agro-industrial processes generate concentrated biodegradable effluents, including those from sugar factories, distilleries, dairies and slaughterhouses. These wastes typically exhibit high moisture content, elevated chemical oxygen demand and rapid biodegradability, making them suitable substrates for methane fermentation.

Russian-language studies report that two-stage AD configurations incorporating hydrolysis and multi-section methanogenic reactors can reduce hydraulic retention time and enhance methane yield when treating liquid effluents from agro-industrial complexes (Okovitya et al., 2021).

Integrated processing strategies frequently combine anaerobic digestion of stillage, beet pulp and manure with downstream treatments such as composting or pelletizing of solid fractions. Such configurations support nutrient recycling and enable the production of marketable organic fertilizers, contributing to the expansion of circular-economy models in agriculture (Saifutdinova et al., 2025).

Large agro-industrial digestion systems treating residues from sugar-beet processing and distillery operations commonly operate with electrical capacities in the 3-5 MW range, utilizing 160,000-180,000 tonnes of feedstock per year. Reported energy outputs for such facilities reach 30,000-40,000 MWh annually, consistent with performance levels expected for high-rate AD systems processing carbohydrate-rich substrates. These generalized values highlight the capacity of AD to convert low-value by-products into renewable energy and stabilized digestate suitable for agricultural use.

### 3. Energy Recovery and Environmental Benefits.

3.1. *Application of Anaerobic Digestion Technologies in Agro-Industrial Systems.* Energy generation from agro-industrial AD systems depends on substrate composition, reactor configuration and operating conditions. Facilities processing mixtures of liquid stillage and sugar-processing residues typically achieve methane yields in the upper range reported for carbohydrate-rich feedstocks. When operated continuously for more than 8,000 hours per year, such systems can supply substantial quantities of renewable electricity or upgraded biomethane.

Typical performance indicators for large agro-industrial AD plants include electrical efficiencies of 35-40% for combined heat and power units, parasitic consumption of approximately 5-8% of generated electricity, and specific energy yields near 0.1 MWh per tonnes of processed biomass. These values align with international benchmarks for industrial digestion systems and demonstrate the strong energy-recovery potential of AD when integrated into existing processing chains.

Environmental benefits include mitigation of uncontrolled methane emissions, significant reduction of odour and nutrient losses, and production of a stabilized digestate rich in nitrogen, phosphorus and potassium. When applied to agricultural soils, digestate contributes to nutrient cycling and reduces the demand for mineral fertilizers, thereby enhancing the sustainability of regional agro-ecosystems.

**Table 2.**

Typical operational parameters for industrial anaerobic digestion systems (Holm-Nielsen et al., 2009; Scarlat et al., 2018).

Parameter	Typical Range
Organic loading rate (OLR)	1,5 – 4,0 kg VS/m <sup>3</sup> ·day
Hydraulic retention time (HRT)	15 – 40 days
Mesophilic temperature	35 – 38 °C
Thermophilic temperature	50 – 55 °C
Specific methane yield	0,20 – 0,35 m <sup>3</sup> CH <sub>4</sub> /kg VS
Electrical efficiency (CHP)	35 – 40%
Heat recovery efficiency	40 – 50%
Parasitic electricity consumption	5 – 10% of output
Operating hours	7500 – 8400 h/year

3.2. *Environmental and circular-economy aspects.* Several studies have quantified how AD of organic wastes reduces GHG emissions compared with uncontrolled storage or landfilling. The replacement of fossil-based electricity and heat, combined with the avoidance of methane emissions from manure and waste heaps, can reduce overall emissions by 30-70 kg CO<sub>2</sub>-equivalent per kg of nitrogen surplus when manure is digested and nutrients are better recycled.

The digestate – the residual slurry after digestion – retains most of the nitrogen, phosphorus and potassium, making it a high-value fertilizer that can substitute synthetic fertilizers whose production is energy-intensive and relies on natural gas and mineral phosphates (Agapkin & Makhotina, 2021). The use of digestate therefore closes nutrient loops between livestock, biogas plants and crop production, which is a central element of circular agriculture.

At the same time, biogas plants provide a controlled environment for the hygienisation of organic wastes; pathogen reduction, odour mitigation and lower risk of groundwater contamination are consistently reported benefits when manure and organic wastes are digested rather than stored or landfilled.

## Conclusion

The reviewed literature demonstrates considerable variability in methane yields across different substrate categories. Animal manure shows methane production in the range of approximately 157 – 500 mL/gVS, with pig and goat manure generally achieving the highest values due to their favourable biochemical composition (Bachmaier et al., 2020). Food waste and lipid-rich organic residues exhibit even higher biomethane potentials, reaching up to about 550 mL/gVS, although such substrates often require co-digestion or two-stage processing to maintain pH stability and prevent ammonia-induced inhibition (Neri et al., 2023).

High-solids anaerobic digestion systems were found to be effective for treating stackable agricultural residues and the organic fraction of municipal solid waste, operating successfully at total solids contents above 15-20%. These systems achieve volumetric productivities comparable to conventional slurry-based digesters, while offering reduced reactor volume requirements. In addition, co-digestion approaches – including combinations such as poultry litter with swine wastewater or microalgae with bakery waste – consistently enhance gas yield and improve nutrient balance and buffering capacity relative to mono-digestion.

Industrial-scale agro-industrial digestion systems reported in the literature demonstrate that large facilities treating carbohydrate-rich by-products from sugar or distillery processing can achieve substantial energy-recovery performance. Typical installations in this category operate within the multi-megawatt range and process several hundred thousand tonnes of wet biomass annually, with annual electricity outputs reaching tens of thousands of megawatt-hours. These values correspond to specific energy yields commonly found in international benchmarks (around 0.1 MWh per tonnes of processed biomass), underscoring the significant contribution that integrated waste-to-energy systems can make to renewable-energy generation. At a broader scale, widespread deployment of such technologies can meaningfully reduce greenhouse-gas emissions, divert biodegradable waste from landfills, and strengthen circular-economy practices in rural and agro-industrial regions (Scarlat et al., 2018).

*Discussion.* The findings show that biogas technologies offer an effective pathway for the sustainable treatment of organic wastes. In the case of animal manure, anaerobic digestion reduces odour, pathogens and uncontrolled emissions, while converting an environmental liability into a valuable energy resource. However, relatively low methane yields and high processing volumes often require co-digestion or policy incentives to ensure economic feasibility.

For agricultural residues and lignocellulosic biomass, the main barrier is low biodegradability. While pretreatments can enhance methane production, they must be justified by energy and cost considerations (Nasir et al., 2012). Combining moderate pretreatment with co-digestion of easily degradable substrates appears more efficient than intensive processing of lignocellulosic materials alone. Food waste and OFMSW are high-energy substrates suited for urban waste-to-energy systems,

but their treatment requires careful process control due to rapid acidification tendencies and contamination by non-biodegradable materials. Two-stage digestion and co-digestion with manure or sludge help stabilize these streams (Zhang et al., 2014).

Reported operational ranges show that full-scale agro-industrial AD plants can achieve high energy recovery. However, high capital costs and dependence on stable feedstock supply and policy incentives remain important limitations.

Digestate utilization is a key factor influencing environmental performance. When applied appropriately, digestate replaces synthetic fertilizers and closes nutrient loops; where land availability is limited, further processing is required to prevent nutrient accumulation.

In the context of Azerbaijan, where livestock farming, food processing and municipal waste streams generate substantial quantities of biodegradable residues, the deployment of anaerobic digestion could provide significant environmental and energy benefits. The technology aligns with national priorities on green growth and waste minimization, offering a pathway to reduce methane emissions from manure storage, divert organic waste from landfills and support decentralized renewable-energy generation in rural regions. These considerations highlight that the broader trends identified in this review are directly applicable to Azerbaijan's evolving waste and energy management strategies.

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