

Communication

Assessing Biogas Production Potential from Organic Waste and Livestock Byproducts in a Serbian Municipality: Implications for Sustainable Food Systems

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Abstract: In the process of biogas production, various types of substrates with suitable energy potential are utilized to generate biogas in plants designed for cogeneration (CHP) of electricity and heat. This paper presents a literature review focused on different substrates involved in biogas production, emphasizing their optimization potential. Data for this research were gathered through a comprehensive review of scientific and scholarly literature from global databases. The study examines the biogas production capabilities of various feedstocks employed in cogeneration plants, highlighting the energy potential of substrates, including livestock byproducts such as liquid and solid manure, energy crops, organic waste from the food and slaughterhouse industries, as well as municipal wastewater and solid organic waste. Furthermore, we conducted a practical case study in the municipality of Čačak, which provides valuable insights into effective practices and strategies that can be broadly applied to enhance biogas production in similar contexts. The findings reveal significant variations in biogas production potential among different substrates, emphasizing the importance of strategic selection and management practices. This study contributes to the field by providing a clearer understanding of the substrate optimization process and practical insights that can inform the development of more effective biogas production strategies in local municipalities.



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1. Introduction

The increasing global demand for energy, coupled with the urgent need to address climate change and enhance energy security, accelerated the transition toward renewable energy sources [1]. Among these sources, bioenergy—primarily derived from biomass—plays a crucial role. It is utilized for generating heat and electricity, serving as transportation fuel, and producing industrial products [2]. As economic development and global population growth continue, waste generation has risen significantly, highlighting the need for rational utilization strategies. Sustainable waste management is vital for achieving the goals of the circular economy [3]. Processes that convert suitable waste materials into

energy provide a viable means for energy recovery, complementing existing waste management systems. Energy derived from waste can be harnessed for various applications, including electricity generation, process steam for industrial consumers, hot water, and district heating or cooling. In the European Union (EU), energy recovery from waste is a fundamental component of waste management systems that is supported by advanced technologies that minimize health and environmental risks. The growing bioenergy industry is integral to the European Green Deal (EGD) framework, which aims to establish a sustainable and climate-neutral economy in Europe [4]. As a renewable energy source, bioenergy is transforming the continent's energy landscape and significantly reducing its carbon footprint, promoting climate protection while enhancing economic growth.

Europe's strong commitment to renewable energy and sustainable waste management makes it a global leader in biogas production [5], with output reaching around 20 billion cubic meters in 2020. The Treaty on the Functioning of the EU provides a legal framework for environmental protection, including waste management and energy recovery, ensuring compliance among member states. Additionally, European countries are actively investing in research and innovation to improve the efficiency and sustainability of biogas production [6,7]. In the broader context of renewable energy, worldwide employment in the sector reached 12 million jobs in 2020 and continued to grow in 2021. Close to two-thirds of these jobs are located in Asia, with China alone accounting for 42% of the global total. The European Union and Brazil each contribute 10%, while the United States and India account for 7% each. Looking ahead to 2030, under an ambitious energy transition scenario with front-loaded investments, employment in the energy sector could rise to 139 million jobs. This growth includes more than 74 million positions in areas such as energy efficiency, electric vehicles, power systems/flexibility, and hydrogen [8]. This employment growth is particularly beneficial for rural areas, where promoting bioenergy initiatives fosters economic development [9,10]. By incorporating bioenergy into Europe's energy mix, the EGD enhances energy security and encourages sustainable practices, contributing to a greener and more resilient economy. Furthermore, sustainable biomass fuel production aligns with the United Nations' focus on climate protection and supports Sustainable Development Goal (SDG) 7, which aims to provide affordable and clean energy [11,12]. Building on the importance of sustainable energy solutions, biogas emerges as a particularly effective and versatile alternative for both energy production and waste management. Produced through the anaerobic digestion of organic matter, biogas primarily consists of methane and carbon dioxide. This process not only generates electricity and heat through combined heat and power (CHP) systems, but also effectively tackles challenges related to the disposal of organic waste.

In the Republic of Serbia, waste management is governed by regulations [13–15] that have been aligned with EU standards, focusing on a waste management hierarchy that prioritizes waste prevention. When waste generation cannot be prevented, it is essential to ensure conditions for reuse, recycling, energy recovery, and processing. Only after these steps can the remaining waste be safely landfilled in an environmentally friendly manner. Effective waste management technologies, particularly those for energy recovery, are relatively new in Serbia. These technologies aim to provide solutions that address environmental protection and mitigate emissions into air, water, and soil, while also considering human health impacts. Energy recovery from waste is one of the most strictly regulated industrial sectors in the EU, with stringent monitoring of pollutants and lower threshold values compared to other sectors [16].

Unfortunately, a significant portion of waste in Serbia ends up in unsanitary and illegal landfills, leading to environmental pollution and threats to public health [17]. The lack of proper waste treatment and disposal conditions often results in frequent fires, exacerbating

public health risks and long-term environmental degradation [18]. The increasing demand for energy, coupled with rising costs and decreasing availability, motivates both public and private sectors to consider investments in energy recovery facilities. Public participation is essential to ensure compliance with regulations and to guarantee timely information dissemination from relevant authorities. If these conditions are met, there is potential for Serbia's waste management system to evolve into a sustainable model aligned with practices in developed countries, thus mitigating negative impacts.

This study aims to explore and optimize biogas production from various organic substrates, including livestock byproducts and municipal waste, in the context of sustainable food systems within a local municipality in Serbia. By conducting a comprehensive literature review and data analysis, the research seeks to identify the characteristics and potential of different substrates to enhance biogas yield. The findings will provide practical recommendations for local stakeholders and policymakers to implement strategies that maximize energy recovery from waste, thereby contributing to the circular economy and addressing global challenges related to energy demand, sustainable food systems, and waste management. Through this multifaceted approach, the study aims to ensure that diverse feedstocks are leveraged in biogas production, yielding benefits that extend beyond energy recovery to encompass environmental, economic, technological, and social improvements. Ultimately, this study intends to serve as a framework for similar initiatives in other regions, promoting the effective utilization of diverse feedstocks in biogas production.

2. Evaluating Substrate Potential for Biogas Production

The term "substrate" refers to the raw materials used in biogas production. When multiple substrates are combined, the less-utilized material is referred to as a co-substrate. Assessing the availability, cost, and biochemical properties of potential substrates is crucial, as these factors significantly influence the design, operational efficiency, and economic feasibility of biogas plants [19,20].

The first step in assessing the potential for biogas production is the qualitative and quantitative determination of available feedstock for anaerobic digestion. Based on data regarding feedstock for anaerobic digestion, further calculations are performed to estimate the potential biogas yield using literature data or experimental findings on biogas production from the considered raw materials.

All types of biomass available within the local government area of the city of Čačak can be utilized for anaerobic digestion in biogas production. According to the 2022 Agricultural Census [21], the available feedstock includes the following:

- Manure from livestock farms,
- Agricultural production residues,
- Biodegradable organic waste from the food industry and similar sectors,
- The biodegradable fraction of municipal waste and waste from the hospitality sector (food waste),
- Wastewater from the food industry and sewage sludge from wastewater treatment plants,
- Energy crops (corn silage, sorghum, and various grass species).

For the analysis of the utilization potential of available feedstock for biogas production within the local government area of the city of Čačak, data will be used on agricultural crops, waste streams from livestock and poultry production, municipal waste, and designated energy crop production (corn silage).

The energy potential structure of the analyzed available feedstock is as follows:

- Biomass from crop production: 41.99%,
- Waste from livestock production: 16.87%,

- Municipal waste: 8.16%,
- Corn silage: 32.98%.

The biogas yield from a specific substrate is considered potential; however, the actual amount produced in a biogas plant depends on operational conditions and process stability [22]. Therefore, analyzing the characteristics of substrates is essential for determining their potential for biogas production and informing the design of the biogas plant.

In our upcoming discussion, this study aims to provide practical recommendations for enhancing the efficiency and sustainability of biogas production through the strategic use of substrates. By conducting a comprehensive literature review and experimental methodology, we will examine how different substrate characteristics can affect biogas yields and guide best practices that can be applied in various countries around the world.

2.1. Manure from Livestock Farms

Manure from livestock farms represents a suitable feedstock for biogas production, as it not only contains organic matter, but also harbors anaerobic bacteria that can facilitate the initiation of the anaerobic digestion process. There is a strong and stable manure. The liquid consists of animal waste and can be transported by pumps and pipelines to the biogas facility. According to agricultural practices in Serbia, farmers typically collect animal manure in lagoons or storage tanks. Due to the nature of husbandry practices, manure from sheep and goats is challenging to collect and utilize for biogas production.

For the territory of the city of Čačak, based on data from the 2022 Agricultural Census [21], an analysis of livestock herd sizes indicates that approximately 3500 agricultural holdings raise cattle. The majority of cattle are found in the herd size categories of 1–2 animals (approximately 3000) and 3–9 animals (approximately 5500). Pigs are raised on 5800 agricultural holdings, with the highest numbers in the categories of 10–19 animals (approximately 11,500) and 20–49 animals (approximately 10,000). Sheep are raised on 3400 agricultural holdings, predominantly in the categories of 3–9 animals (approximately 11,500) and 10–19 animals (approximately 10,500).

Poultry farming is recorded on 6453 agricultural holdings, with the highest poultry numbers found in the category of approximately 5000 birds per holding. Additionally, around 100,000 birds are raised on five agricultural holdings, while a significant number of holdings falls within the category of 1–49 birds per farm.

Table 1 provides a comparative assessment of different manure types based on their dry matter (DM) and organic dry matter (oDM) content, highlighting their biogas and methane production potential. These data are crucial for evaluating manure suitability as a substrate for anaerobic digestion, optimizing biogas plant efficiency, and enhancing energy recovery from livestock waste. Additionally, the data indicate the following:

- Liquid manures from beef and pork contain lower dry matter content (8–11% and 7%, respectively) but have a high percentage of organic matter (75–86%).
- Solid manures: solid cattle and pig manures have higher dry matter percentages (25% and 20–25%, respectively) than liquid forms, indicating a greater potential for solid substrates in biogas production due to their higher organic content.

The yield of biogas is determined by the amount of fresh, dry, or organic dry matter present in a substrate [23,24]. This directly impacts biogas potential. Substrates with a dry matter content of less than 20% are used for “wet digestion”, and this includes manure [25].

Based on Table 1, it is evident that manure has relatively low potential methane production per unit of organic dry matter [25,26]. This yield depends on the composition; for instance, liquid manure from cattle predominantly contains carbohydrates, whereas liquid manure from pigs is rich in proteins, which results in a higher methane content [27].

Table 1. Biogas and methane (CH₄) production potential from different manure types based on organic and dry matter composition (adapted [22]).

Substrate	Dry Matter, (%)	Organic Dry Matter, (%)	Biogas Yield		Share of CH ₄	
			Stm ³ /t Fresh Matter	Stm ³ /t oDM	(%)	Nm ³ /t oDM (Mean Values)
Pork liquid manure	7	75–86	20–35	300–700	60–70	250
Beef liquid manure	8–11	75–82	20–30	200–500	60	210
Solid poultry manure	32	63–80	70–90	270–450	60	280
Solid cattle manure	25	68–76	40–50	210–300	60	250

Legend: Stm³/t—standard cubic meters per ton, Nm³/t oDM—normal cubic meters per ton of organic dry matter.

Regarding the biogas yields (in Stm³/t) and the methane (CH₄) content for different manure types, key findings include the following:

- Solid poultry manure produces the highest biogas volume, ranging from 70 to 90 Stm³/t of fresh matter, while consistently maintaining a methane content of approximately 60%.
- Solid pig manure also demonstrates notable performance, yielding between 55 and 65 Stm³/t, highlighting its suitability as an effective substrate for biogas production.

The biogas yield in bovine liquid manure ranges from 20 to 30 m³, which is slightly lower than that of pig liquid manure, which ranges from 20 to 35 per ton of fresh matter (Table 2) [28,29].

Table 1 presents the potential methane yields from organic dry matter across different types of manure. The results show the following:

- Poultry manure exhibits the highest average methane yield at 280 Nm³/t of organic dry matter. This is closely followed by both pork liquid manure and solid beef manure, each yielding 250 Nm³/t, demonstrating their considerable effectiveness in methane generation.

The water content of manure is high, ranging from 68% to 93%, which reduces its energy potential. However, this moisture is beneficial when combined with other substrates that have higher dry matter contents, such as corn silage. When comparing manure to corn silage, manure can yield up to ten times less biogas per unit weight. This means that for the same size biogas plant, ten times more manure is required than corn silage [22]. Therefore, for a plant with a nominal electrical capacity of 150 kW, at least 1000 conditional heads of cattle would be necessary, as one conditional head of cattle, weighing 500 kg, generates only 0.11 to 0.15 kWe [22]. Economic analysis indicates that constructing and operating larger plants, with a nominal electrical capacity of 500 to 1000 kW, is more cost-effective [22]. Consequently, modern plants utilize a mix of manure and other substrates, such as energy crops.

2.2. Energy Plants

Energy crops serve not only as co-substrates, but also as the primary raw material in biogas plants. These energy plants are specifically cultivated biomass, which is usually ensiled for storage [30]. The most commonly utilized options include corn silage, silage from whole grain plants such as rye, and various cereal types or their mixtures, alongside cereal grains, grass silage, beet silage (either fodder or sugar), and sugar beet leaves [31]. Beyond using the entire plant as corn silage, popular forms include silage made from corn cobs and husks, a mixture of grain and cobs, as well as grain corn focusing solely on cobs.

The data presented in Table 2 provide valuable information regarding Biogas yield and methane production potential from the organic dry matter of different energy crops and protein sources. This table highlights the composition of energy proteins, which can influence their suitability as substrates for biogas production.

Table 2. Methane (CH₄) yield potential from organic dry matter of various energy crops and protein sources (adapted by [22,32]).

Substrate	Dry Matter (%)	Organic Dry Matter (%)	Biogas Yield		Potential Yields of CH ₄	
			Stm ³ /t Fresh Matter	Stm ³ /t oDM	CH ₄ (%)	Nm ³ /t oDM (Mean Values)
Corn silage	20–35	85–95	170–200	450–700	50–55	340
Grass silage	25–50	70–95	170–200	550–620	54–55	380
Sugar beet	23	90–95	170–180	800–860	53	350

Legend: Stm³/t—standard cubic meters per ton, Nm³/t oDM—normal cubic meters per ton of organic dry matter.

The percentage of dry matter is highest in grass silage at 50%, while it is lowest in sugar beet leaf at 16%. The percentage of organic dry matter is highest for rye and whole plant silage at 98%, with the lowest for grass silage at 70%. We hypothesize that substrates with higher organic dry matter content and an optimal balance of carbohydrates and proteins will yield significantly greater volumes of biogas and methane compared to those with lower organic dry matter content. Energy crops and silages with a dry matter content of about 35% or more are commonly used in a type of anaerobic digestion known as “dry digestion”. A dry matter content of less than 28% in maize can lead to the occurrence of leachate, resulting in significant energy losses [33]. For silage of whole cereal plants, harvesting should occur when dry matter yields are highest (in a monoculture system), which is at the end of milky ripeness or the beginning of waxy ripeness [33]. In grass silage, it is crucial that the dry matter content does not exceed 35%, as this increases the proportion of lignin and fiber, leading to a decrease in methane yield compared to organic dry matter [33].

Table 2 outlines the potential yields of methane-containing biogas from different types of energy crops. This table shows the possible biogas yields rich in methane from various energy crops, offering insights into their efficiency as substrates for biogas production. Key points include the following:

- Sugar beet shows high biogas yields (170–180 Stm³/t) and high methane content (around 53%).
- Corn silage also demonstrates significant potential with yields of 170–200 Stm³/t, indicating its effectiveness as a substrate.

Table 2 also illustrates the potential methane yield from organic dry matter in various energy plants, highlighting their efficiency in converting organic matter into methane and emphasizing the differing contributions of these plants to biogas production.

- Cereal grains offer the highest yield potential at 380 Nm³/t, while corn silage also ranks favorably at 340 Nm³/t, underscoring their efficiency in methane generation.

Cereal grains are used as a supplement to existing substrates, where the type of grain is not important, and they are particularly well-suited for precise management of biogas production [34,35]. Due to its favorable energy yields per hectare and fermentation properties, maize is particularly well-suited for biogas production [34]. From one ton of corn silage, 350 to 400 kWh is obtained [22]. For a plant with a nominal power of 500 kWe, 170 to 250 acres would be required for maize silage production. In countries with favorable

feed-in tariffs, the share of biogas produced from silage ranges from 30% to 100% [22]. Collectively, Table 2 emphasizes the significance of both energy protein and energy crop selection in optimizing methane production for biogas applications.

The methane yield potential presented in Table 2 highlights the variability in biogas production efficiency among different energy crops and protein sources, which can be further influenced by climate-induced changes in substrate composition. As climate change alters moisture content, nutrient balance, and biochemical properties of organic materials, the actual methane output from these feedstocks may deviate from standard values, underscoring the importance of continuous monitoring and adaptive feedstock selection in anaerobic digestion systems. Recent agrometeorological reports from Serbia [36] highlight substantial climatic shifts, including rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. The 2023/2024 agricultural season recorded temperatures exceeding the multi-year average by 3.4 °C to 4.2 °C, with prolonged heat waves, drought periods, and uneven rainfall distribution. These conditions significantly impacted soil moisture, plant growth, and overall crop productivity, leading to lower yields and changes in the composition of harvested biomass. In light of these climatic trends, our study recognizes that climate change may affect substrate characteristics in anaerobic digestion through the following:

Moisture content variability: reduced and irregular rainfall, coupled with higher evapotranspiration rates, directly influences the moisture content of organic substrates [37]. **Nutritional composition:** Climate-induced changes in plant physiology and biochemical composition can impact the carbon-to-nitrogen (C/N) ratio and digestibility of biomass [38]. Elevated CO₂ levels and temperature fluctuations can modify the lignocellulosic structure of crops, alter nitrogen content, and affect methane production potential. For instance, the observed shorter growing seasons and heat stress in Serbian agriculture may lead to lower starch and sugar accumulation in certain crops, reducing their fermentability in biogas systems [36].

Feedstock availability and adaptation strategies: As climate change affects crop performance and residue generation, the availability and consistency of biogas feedstocks may fluctuate [39]. To adapt, anaerobic digestion facilities could explore alternative or more resilient substrate sources, such as heat-tolerant crop varieties or diversified organic waste streams. Additionally, co-digestion techniques could be employed to counteract variations in substrate composition and enhance methane yield despite changing environmental conditions.

2.3. Organic Waste of the Food Industry

Organic waste from the food industry is generated in various processes, such as the production of sugar, alcohol, oil, beer, and the processing of fruits and vegetables [40]. These substances are produced during the processing of plants, essentially the constituent parts of plants [41]. Pomace, a byproduct, forms during the processing of grapes and fruits into wine and fruit juices [42], it is also produced when alcohol is made from cereals, beets, potatoes, or fruit [43]. In the production of beer, it appears as a secondary product known as beer trop. Sugar production generates sugar beet noodles as a byproduct. Molasses and beet noodles, due to their residual sugar content, serve as suitable substrates for biogas production [32]. While the potential uses of these byproducts are uncertain, their high biogas yield makes them appropriate as substrates or co-substrates for biogas production. This holds true for byproducts from alcohol production, which yield biogas comparable to manure [22].

According to data from the 2022 Agricultural Census [21], the most widely cultivated fruit species in the Čačak region is plum, with approximately 690,000 trees across the city's

territory. Other fruit species under cultivation include apple (approximately 656,000 trees), pear (approximately 205,000 trees), and apricot (approximately 187,000 trees). The number of cherry, peach, and sour cherry trees ranges between 25,000 and 50,000, while walnut, quince, and hazelnut are less represented.

Vegetable production within the local administrative area of Čačak, both in open fields and protected environments, is organized either as garden-scale production or for commercial market purposes. The cultivation of major arable crops occupies a total area of 10,932.26 hectares, representing 37.21% of the total agricultural land available to farmers. The predominant crop is maize, covering 5099.97 hectares (46.64%), followed by wheat with 2604.57 hectares (23.82%), potato with 1465.21 hectares (13.40%), barley with 1184.34 hectares (10.84%), and oat with 578.34 hectares (5.29%).

According to the 2022 Census [21], out of 1795 agricultural holdings engaged in primary agricultural production, a total of 921 hectares are dedicated to vegetable crops, including tomatoes, cabbage and kale, peppers, onions (both red and white), cauliflower, carrots, peas, and other fresh vegetables, as well as melons and strawberries.

The production of major arable crops (maize, wheat, potato, barley, and oat) covers approximately 11,000 hectares within the city of Čačak, accounting for 37.21% of the total agricultural land available to producers. In terms of orchard production, significant agricultural residues could be utilized for biogas production. Based on data from the 2022 Agricultural Census, orchards cover approximately 4200 hectares, while vineyards occupy around 30 hectares. The largest orchard area is under plum cultivation (approximately 2000 hectares), whereas the smallest area is allocated to other berry fruits (approximately 5 hectares). These agricultural residues represent a viable raw material source for biogas production.

Table 3 provides comprehensive data on organic waste from the food industry and its potential for biogas production, detailing various aspects critical to understanding its viability as a substrate. Table 3 shows the percentages of dry matter and organic dry matter for different types of organic waste produced by the food industry. This information reveals the composition of each waste type, highlighting the relative amounts of dry matter and organic content, which are essential factors influencing the efficiency of biogas production. Notable observations include:

- Molasses has a high dry matter content of 80–90% and a significant organic matter percentage of 85–90%, emphasizing its potential as a valuable substrate for biogas production.

Table 3. Potential yields of methane-containing (CH_4) biogas for different types of organic waste from the food industry (adapted by [22]).

Substrate	Dry Matter (%)	Organic Dry Matter (%)	Biogas Yield		CH_4 (%)
			Stm^3/t Fresh Mater	Stm^3/t oDM	
Potato pomace	6–7	85–95	36–42	400–700	58–65
Fruit pomace	2–3	95	10–20	300–650	58–65
Molasses	80–90	85–90	290–340	360–490	70–75

Legend: Stm^3/t —standard cubic meters per ton.

The potential yield of methane is a key criterion for evaluating the various substrates suitable for use in biogas plants during anaerobic digestion [23,27,44]. Table 3 presents biogas yields and methane content for various types of organic waste from the food industry. In this table, the expected biogas production potential for each waste category is quantified,

with an emphasis on identifying the types most effective for methane generation and renewable energy contribution.

Stm³/t of fresh matter:

- This metric indicates the total volume of biogas produced per ton of fresh organic waste. It includes all components in the waste, regardless of their dry matter content. For example, molasses yields between 290 and 340 Stm³/t of fresh matter, which illustrates its potential to produce significant amounts of biogas due to its high organic content.

Stm³/t of organic dry matter:

- This metric focuses on the biogas yield relative to the organic dry matter present in the waste. It provides a more accurate measure of the substrate's effectiveness for biogas production because it accounts only for the decomposable organic components. In the case of molasses, the high organic dry matter percentage contributes to its strong yield, making it an efficient substrate for anaerobic digestion.

Examining both metrics reveals how various types of organic waste differ in their potential for biogas production, which is shaped by their composition and moisture levels. This combined analysis enhances our understanding of which substrates could be more effective for maximizing biogas yields.

Other potential substrates (beet pulp, cereal pomace, potato, fruit, and brewer's pulp) have a significantly lower potential biogas yield per ton of fresh mass; for example, beer pomace can yield up to 130 m³, while beet pulp can yield up to 75 m³. However, the highest potential yield of biogas per ton of organic dry matter comes from beer pomace at 750 m³, followed by cereal and potato pomace at 700 m³ and fruit pomace at 600 m³, with methane content reaching up to 75% (Table 3). Table 4 details the methane yield from organic dry matter for different substrates derived from the food industry. By comparing the efficiency of methane production across these substrates, this table identifies the most promising options for maximizing biogas yield. The highest mean value for potential methane yield per ton of organic dry matter is found in apple pomace at 453 m³, followed closely by grape pomace at 448 m³ and rapeseed cake at 396 m³ (Table 4).

Table 4. Methane yield from organic dry matter for different types of substrates from the food industry (adopted by [32]).

Substrate	(Nm ³ /t oDM)—Mean Values
Apple pomace	453
Grape pomace	448
Rapeseed loaf	396
Grain pomace	385
Potato pomace	362
Potato pulp	336
Beer trope	313
Molasses	308
Fruit pomace	285
Sugar beet noodles	218
Crude glycerin	185

Legend: Nm³/t oDM—normal cubic meters per ton of organic dry matter.

2.4. Organic Waste from the Animal Food Production Industry

Waste raw materials from the meat processing and dairy industries represent valuable feedstocks for biogas production in anaerobic digestion facilities due to their high concentrations of organic matter, particularly proteins and fats. Waste generated from the meat processing industry arises from industrial operations such as slaughterhouses, meat

processing plants, and related facilities [45]. The European Union Regulation classifies waste generated by the slaughterhouse industry into three categories: (high, medium, and low risk) [46]. Based on these categories, the requirements for disposal are also defined [22]. One of the technologies for collecting this waste is biogas technology. Slaughter waste from categories medium and low risk is primarily used as a substrate for producing rich meat [22]. The legal framework for biogas production from animal waste, including deceased animals, in Serbia was adopted in 2011 and since underwent some updates, fully aligning it with EU regulations [47]. The implementation of biogas technology in facilities generating this type of waste provides an effective solution for waste disposal while also offering an opportunity for these facilities to receive compensation for the waste delivered to biogas plants for treatment.

Biogas plants that utilize organic waste from the slaughterhouse industry typically include a system for shredding and homogenizing slaughterhouse waste [22]. Depending on the condition and classification of the substrate, processing in special tanks is required for a specific period of time at a certain temperature and pressure before anaerobic digestion in a fermenter. The typical biogas yield from waste streams in the meat processing industry ranges between 225 and 978 m³ of methane per ton of organic dry matter derived from meat processing waste [48,49]. Additionally, wastewater and waste from dairy processing, such as whey and off-specification products, are biodegradable and represent an optimal feedstock for biological treatment aimed at biogas production.

2.5. Municipal and Wastewater of the Food Industry

Municipal wastewater, or household wastewater, originates from residential areas and results primarily from human metabolism and household activities [50]. Wastewater generated in the food industry, on the other hand, stems from the production process [51]. Municipal wastewater and that generated in the food industry are often discharged directly into watercourses and lakes, which negatively impacts the environment. Consequently, wastewater must be treated; thus, the methods and conditions for discharging wastewater into recipients are defined to prevent environmental pollution [52,53]. Before being discharged to the recipient, wastewater undergoes treatment through physical, biological, and chemical processes [54]. Wastewater treatment yields sludge, which can be either treated or untreated residue remaining after the treatment process. One of the challenges is the proper disposal of sewage sludge, ensuring it is managed in a manner that does not threaten the environment or human health. With an anaerobic process, organic stabilization and hygienization of waste sludge can be achieved [22]. After anaerobic digestion, if the analyses indicate it, the waste sludge can be safely disposed of in a landfill or used on agricultural land [22]. The dry matter percentage in the sludge reaches up to 5 percent, whereas municipal and wastewater from the food industry generally contain a low proportion of dry matter, sometimes less than 1%, meaning they have a water content, which impacts the size of the biogas plant [22]. Biogas plants that use wastewater as a substrate for biogas production are primarily part of the wastewater treatment system; by generating electricity from biogas, they partially meet their energy needs [22].

2.6. Municipal Solid Organic Waste

In addition to solid biofuels, municipal and industrial waste also play a crucial role in the worldwide bioenergy landscape, contributing about 21.4 gigawatts to the total. Municipal solid organic waste consists of biodegradable materials suitable for anaerobic digestion, including waste from gardens, parks, food, and household kitchen scraps, as well as waste from restaurants and catering services involved in maintaining green areas [55]. This type of waste is characterized by a heterogeneous composition and inconsistency, which necessi-

tates primary waste separation. As urban areas continue to face increasing waste volumes, utilizing waste for energy production has become increasingly significant [56]. The global waste-to-energy market was valued at USD 34.50 billion in 2023 and is expected to expand from USD 35.84 billion in 2024 to USD 50.92 billion by 2032, reflecting a compound annual growth rate (CAGR) of 4.5% during the forecast period [57]. In 2023, the Asia-Pacific region led the waste-to-energy market, holding a market share of 47.24%.

Over the past few decades, energy generation from solid biomass in Europe has significantly risen, reaching a peak of over 100 million metric tons of oil equivalent in 2021 [58]. The biomass resources utilized for energy include various materials. Often, wood from trees and forest debris is used in the form of logs, chips, or pellets; energy crops are cultivated specifically for their high yield and energy content; and biogas can also be produced from livestock manure. Additionally, the bioenergy sector exploits waste products to generate energy, such as landfill gas, solid municipal waste, and sewage sludge. Within the European Union (EU), biomass plays a crucial role in the renewable energy landscape. In 2022, it contributed 169.4 terawatt hours of electricity, making it the third-largest source of renewable energy in the region after wind and hydroelectric power.

Biogas plants utilizing this waste must be equipped to separate large impurities and metals, along with devices for shredding the substrate. In terms of dry matter content, it significantly exceeds that of manure and is comparable to energy crops. Consequently, the estimated yield of biogas from this substrate is approximately 100 m³ per ton. In contrast, the potential methane yield from one ton of organic dry matter from green waste is 369 m³ [32].

Data from sources [32] indicate that green waste has a potential methane yield of 369 Nm³/t of organic solid matter (oSM), a significant figure in the context of municipal solid organic waste (MSOW) for several reasons: 1. High methane potential: The value of 369 Nm³/t suggests that green waste is an effective substrate for biogas production. This makes it a valuable component of municipal organic waste management strategies, as it can contribute significantly to methane generation through anaerobic digestion. 2. Waste management: Utilizing green waste for biogas production helps reduce the volume of organic waste that would otherwise end up in landfills. This aligns with sustainable waste management practices and can mitigate greenhouse gas emissions associated with waste decomposition in landfills. 3. Resource recovery: The high methane yield from green waste indicates an opportunity for municipalities to recover energy from organic waste. This can support local energy needs and contribute to renewable energy targets. 4. Integration with other substrates: In the context of municipal solid organic waste, green waste can be co-digested with other organic materials (such as food waste) to optimize biogas production, leveraging the complementary characteristics of different substrates. The construction of a biogas plant that uses this type of substrate would not only solve the issue of the disposing of municipal biodegradable waste, but also generate revenue from producing electricity and heat.

3. Optimizing Biogas Production: Case from Practice

Biogas plants are defined as small-scale facilities that generate biogas from suitable substrates, feedstocks, or biomasses with sufficient energy potential [59,60]. Biomass refers to the biodegradable fraction of products, waste, or residues of biological origin, providing a diverse range of organic materials capable of undergoing anaerobic decomposition [61]. During the anaerobic digestion process, biogas—primarily composed of methane and carbon dioxide—is produced. To maximize energy recovery, the biogas generated in small biogas plants is best utilized in CHP systems, which enhance efficiency by simultaneously generating electricity and heat [62].

A practical example of optimizing biogas production can be observed in the implementation of a biomass utilization project in Čačak, Serbia. This initiative, titled “Use of Biomass for Cogeneration in a Wastewater Treatment Facility”, was developed as part of a broader effort to enhance renewable energy applications in wastewater management. The primary objective of the project was to evaluate the potential for biomass-based cogeneration within the wastewater treatment facility in Čačak, enabling a more sustainable and energy-efficient process. The project aimed to achieve the following:

- Assess the availability and quality of biomass resources in the region.
- Develop a feasibility study on integrating biomass into the existing wastewater treatment infrastructure.
- Provide technical recommendations for optimizing biogas production and energy recovery.
- Support policy and decision-making for future large-scale implementation of biomass utilization.

Figure 1 illustrates the location of the wastewater treatment facility in Čačak, where a biogas plant is planned for construction. Figure 2 presents the conceptual design of a lab-scale two-phase anaerobic digestion reactor for the biogas plant, as designed in the study by Čurčić et al. [63].

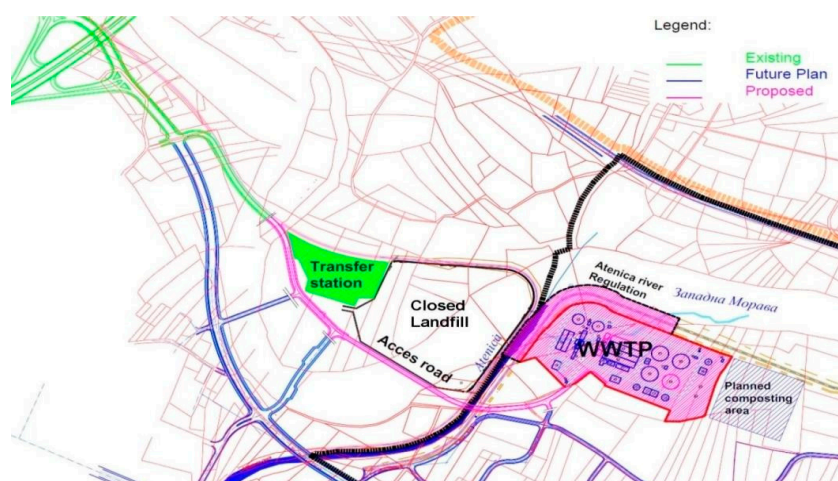


Figure 1. Location of the Prelići wastewater treatment plant (WWTP) and related infrastructure. The map (scale 1:30,000) highlights key facilities: the transfer station for collected waste (green), the wastewater treatment plant (purple), and the composting plant (gray). The planned biogas plant site is positioned below the wastewater treatment and composting plants. Source: Eptisa, 2019. Project on Wastewater Collection and Treatment in Čačak [63].

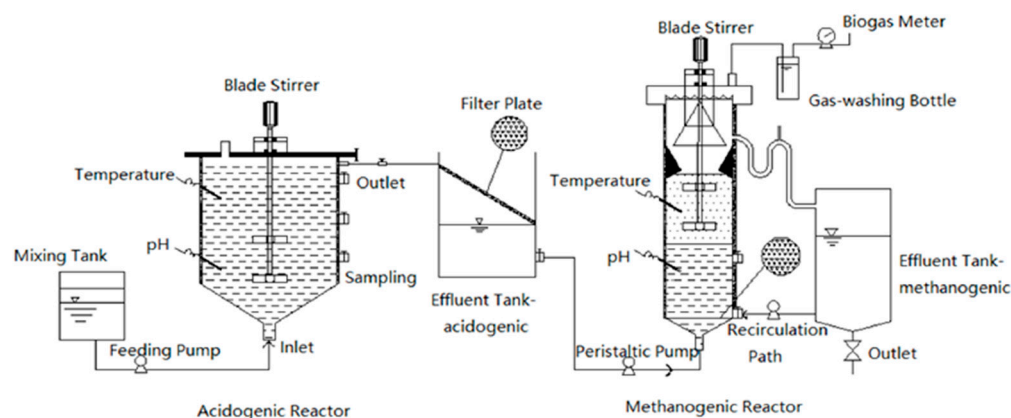


Figure 2. The configuration of the lab-scale two-phase anaerobic digestion reactor [63].

The available substrates for biogas production with energy potential for biogas generation at the wastewater treatment plant (WWTP) in the area of the municipality of Čačak are presented in Table 5. The substrate mixture comprises bovine solid manure and pig liquid manure, each representing 41% of the total substrate intake. The remainder of the substrate consists of clover silage. The daily substrate intake is approximately 15 tons, with an average dry matter content of 20%. Liquid manure is pumped from a 300 m³ pit into the fermenter, while solid substrates are introduced into the fermenter via a 12 m³ device mounted on the concrete flat roof of the fermenter.

Table 5. Available energy potentials for biogas production at the wastewater treatment plant (WWTP) in the area of the municipality of Čačak.

Products/Byproducts	m ³ /Biogas/t Accepted Value	t/Year	Total Biogas m ³ /Year
Liquid cattle manure	300	3650	1.095000
Poultry manure	280	75	21,000
Corn silage	330	1300	420,000
Potato pomace	360	3000	1.080000
Fruit processing residues	100	2000	200,000
Vegetable processing residues	120	300	36,000
Molasses	290	1500	335,000
Grain residues	310	2800	868,000
Used cooking oil	500	80	40,000
Herbaceous green mass	70	3000	210,000
Food waste	395	150	59,250
Bakery product waste	450	40	18,000
Wastewater treatment residues	70	1000	700,000
TOTAL			5.082250

The fermenter has a working volume of 850 m³, while the post-fermenter has a volume of 1400 m³ with an integrated biogas storage capacity of 450 m³. The fermenters are heated to 44 °C and 38 °C, respectively (mesophilic mode). The average total hydraulic retention time is 150 days, which meets the legal requirement that the 1800 m³ residual fermentation tank does not need to be covered. The cogeneration plant, equipped with a gas engine, has an installed electrical power of 75 kW and an electrical efficiency of about 37%. The total electricity output of 1780 kWh per day is supplied to the grid. Operational needs for the biogas plants account for 10% electricity and 19% heat relative to the generated quantities. Approximately 22% of the generated heat energy is used to heat the pig barn, farm buildings, and four residential properties.

The total cost of the investment was EUR 550,000. The average annual income is approximately EUR 168,500, with 87% generated from electricity sales, while the remainder comes from the marketing of fermentation byproducts and the utilization of thermal energy. Annual costs are around EUR 110,500, with 23% allocated for substrate purchases, 40% for depreciation, 31% for operating expenses, and 6% for labor costs.

Additionally, the economic implications of substrate selection are substantial. The costs associated with obtaining high-quality substrates can affect the overall viability of biogas production. Our findings suggest that while the most effective substrates may be more expensive, they could yield significant returns through enhanced methane production. Future research should focus on assessing the long-term economic benefits of employing various substrates, including the operational expenses related to maintaining optimal digestion conditions.

The findings of this study underscore the importance of substrate selection in maximizing biogas production. The study reveals that the organic dry matter content is a critical

factor influencing biogas yield. This is consistent with previous research by Weiland [27], who emphasized that the substrate's composition significantly affects methane potential. In this study, the analysis shows that liquid manure varies in methane yields based on its organic matter composition. For instance, while bovine liquid manure has a higher dry matter content, pig manure contains greater overall organic dry matter, resulting in a higher methane yield. This observation aligns with Kafle and Kim [26], who found that protein-rich substrates generally produce more methane compared to those high in carbohydrates.

Operational conditions also play a vital role in optimizing biogas production. Factors such as retention time and temperature are crucial for the efficiency of anaerobic digestion. The study highlights that methanogenesis is influenced by substrate composition, fermenter filling rate, retention time, and temperature [64,65]. Moreover, anaerobic microorganisms require specific conditions to thrive, including the absence of oxygen, adequate nutrients, consistent mixing, and a pH level between 5.5 and 8.5 [26,66]. The anaerobic digestion process can operate under various temperature regimes, including psychrophilic (below 20 °C), mesophilic (30–42 °C), and thermophilic (43–55 °C) conditions [67].

Recent research explored strategies to enhance biogas yield, particularly through anaerobic co-digestion and process parameter optimization. Cheong et al. [68] developed a simulation model for co-digesting food waste with sewage sludge, identifying optimal conditions for maximizing biogas production. Additionally, studies examined volatile fatty acid (VFA) accumulation, offering insights into thermophilic anaerobic digesters [69]. The co-digestion of distillery wastewater with molasses and glycerol has shown promising benefits, and the feasibility of using brewery spent grain in anaerobic digestion has also been explored [70].

Incorporating co-substrates, such as energy crops, can further enhance biogas production. For example, combining corn silage with manure has been found to increase overall biogas yield. This supports earlier research indicating that co-digestion exploits the synergistic effects of various substrates, thereby improving methane production efficiency [71]. The variability in biogas yield emphasizes the need for ongoing assessment of substrate combinations to identify optimal mixes for maximizing methane output.

This case study highlights the practical steps taken to optimize biogas production in a real-world setting. By leveraging biomass resources for cogeneration, the project demonstrated a viable pathway toward energy-efficient wastewater treatment. The findings and methodologies developed in this initiative can serve as a model for similar projects seeking to enhance biogas production through strategic biomass utilization. Overall, the insights from this study contribute to a deeper understanding of biogas production dynamics. By emphasizing the importance of substrate characteristics—such as organic dry matter content and nutrient composition—alongside operational parameters such as temperature and retention time, the study identifies critical opportunities for optimizing biogas technology. Future research should focus on innovative substrates, including agricultural residues and food waste, and their combinations, as well as optimizing operational conditions to fully leverage the potential of biogas technology in waste management and renewable energy production.

The effect of substrate retention time and temperature on the relative yield of biogas is illustrated in Figure 3. The growth and activity of anaerobic microorganisms, or the efficiency of anaerobic digestion, are affected by the absence of oxygen, the availability of nutrients, the mixing intensity, and the presence and quantity of inhibitors [23,27]. Along with anaerobic conditions, essential factors include a constant temperature and a pH value ranging from 5.5 to 8.5 [26,66]. The effect of temperature on the growth of methanogenic bacteria is a critical factor in anaerobic digestion. The minimum residence time varies

depending on the temperature regime, with thermophilic bacteria requiring 15–20 days, mesophilic bacteria 30–40 days, and psychrophilic bacteria 70–80 days. These differences influence the overall efficiency and stability of the biogas production process [67].

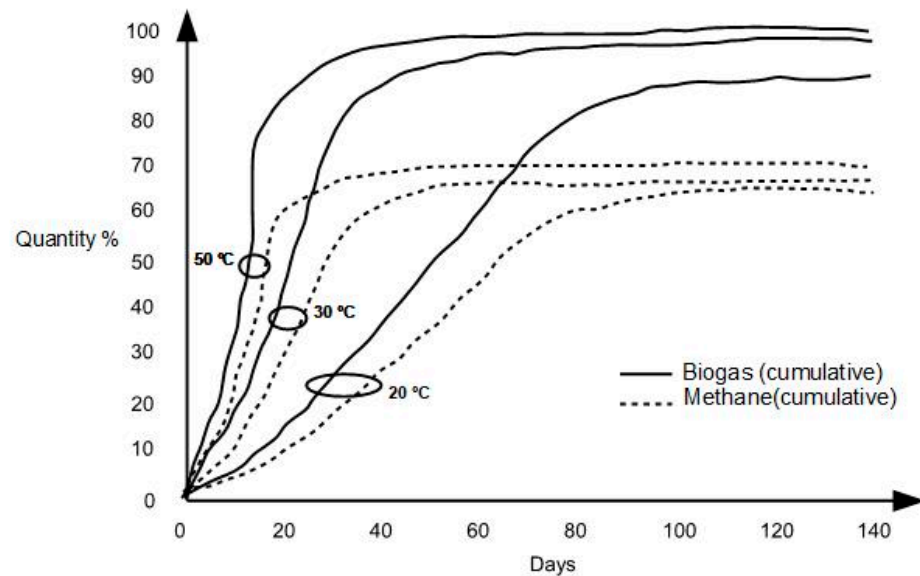


Figure 3. Influence of temperature and retention time of the substrate on the relative yield of biogas and methane [63].

Specifically, the optimal temperature range for mesophilic bacteria (30–42 °C) promotes a more stable digestion process, as reported by Sárvári Horváth et al. [67]. Our analysis suggests that maintaining these conditions is essential for enhancing biogas yield, reinforcing the idea that operational stability is vital for the economic viability of biogas plants.

Study Limitations

While the findings of this study offer valuable insights into the biogas production potential from organic and livestock waste in the selected Serbian municipality, certain limitations should be acknowledged. First, the analysis relies on secondary data and literature-based biogas yield coefficients, which may not fully capture local variability in substrate composition, moisture content, or digestion efficiency. Second, the absence of on-site pilot testing or experimental validation introduces a degree of uncertainty in the projected energy outputs. Third, logistical constraints and a lack of detailed waste characterization data limited the granularity of input estimates, particularly for household and market waste fractions.

Furthermore, this study does not include a detailed techno-economic assessment or lifecycle analysis, both of which are essential for full-scale feasibility studies. Future research should focus on field-based validation, incorporate dynamic modeling to account for seasonal variations, and explore integration with broader sustainable energy systems.

4. Conclusions

This study investigated the potential for biogas yields from suitable available substrates, quantifying yields per unit of fresh and organic dry matter. The findings highlight the potential of co-digestion strategies to improve biogas production. To optimize biogas yields, individual substrates should ideally be utilized at specific time intervals whenever feasible. If this is not possible, co-digestion should be designed to ensure that the most read-

ily available resources dominate during each defined period, enhancing overall efficiency and resource utilization.

In addition to maximizing yields, this research underscores the key role of biogas plants in the sustainable management of various organic waste streams, including slaughterhouse waste, food industry byproducts, and municipal solid waste. Anaerobic digestion in these facilities offers a valuable pathway to reducing reliance on non-renewable energy sources while mitigating various forms of environmental pollution. The total amount of biogas that can be produced at the Čačak wastewater treatment plant is estimated at 5,082,250 m³ per year.

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