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Revolutionizing renewables: Enhancing production efficiency of biogas for a sustainable future

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Abstract

Biogas production through anaerobic digestion offers a promising pathway for sustainable energy generation from organic waste streams. However, current biogas yields and process efficiencies often fall short of economic viability. This review explores how nanotechnology and advanced pretreatment methods can address these limitations and propel biogas towards a central role in our sustainable energy future. We examine recent developments in nanostructured catalysts and nanomaterials that enhance methane production and upgrade biogas quality. Additionally, we assess novel physical, chemical, and biological pretreatment techniques that leverage nanotechnology to improve substrate digestibility and accelerate biogas formation. The synergistic integration of these nano-enabled approaches with traditional anaerobic digestion processes demonstrates significant potential to boost biogas yields, expand feedstock options, and improve overall system performance. By highlighting both the opportunities and challenges, this review provides a roadmap for future research to fully harness the power of nanotechnology in advancing biogas as a cornerstone of sustainable waste management and renewable energy production.

Keywords: Biogas, nanomaterials, pretreatment, renewable energy

Introduction

Biogas, a renewable energy source derived from the anaerobic digestion of organic matter, has emerged as a promising solution in the pursuit of sustainable development and the attainment of the Sustainable Development Goals set forth by the United Nations. The production of biogas can be adapted to various scales, from small-scale systems in rural areas to large-scale facilities in urban centres, making it a versatile technology applicable across diverse settings. In rural regions, biogas can be generated from agricultural waste or animal manure, providing a reliable source of energy for heating, cooking, and electricity generation (Neves *et al.*, 2009) [46]. Likewise, in urban areas, the organic fraction of municipal solid waste can be utilized to produce biogas, addressing the pressing issue of waste management while simultaneously generating renewable energy (Neves *et al.*, 2009) [46]. Anaerobic digestion is a crucial waste management and energy production process that involves the decomposition of organic matter in the absence of oxygen. This process is particularly relevant in the context of the growing global waste crisis, as it provides a sustainable and eco-friendly solution for waste treatment and energy generation. The anaerobic digestion process involves a series of complex microbial reactions that convert organic matter, such as agricultural waste, animal manure, and food waste, into biogas, a renewable fuel composed primarily of methane and carbon dioxide. The purpose of this process is to produce a renewable energy source and an odour-free, nutrient-rich fertilizer (Massi, 2012) [42]. Anaerobic digestion process is influenced by various factors, which can significantly impact the efficiency of biogas production. These factors include pH, temperature, oxidation-reduction potential, and the presence of specific microorganisms, particularly methanogens, which have high environmental requirements (Zuo *et al.*, 2022) [69].

The benefits of biogas extend beyond its energy potential. Anaerobic digestion, the process underlying biogas production, can effectively degrade pollutants, transforming organic waste into valuable byproducts. One such byproduct is nutrient-rich digestate, which can be used as a soil fertilizer, providing nutrients, and improving soil fertility (Uddin *et al.*, 2021) [61].

This not only mitigates environmental degradation by diverting waste from landfills, but also contributes to the circular economy by repurposing waste streams and closing nutrient loops. Furthermore, the use of digestate as a fertilizer can reduce the need for synthetic fertilizers, further enhancing the sustainability of the biogas system.

Moreover, the upgrading of raw biogas into biomethane, a methane-rich fuel with properties akin to natural gas, has expanded the applications of this renewable energy source (Angelidaki *et al*., 2017) [57]. Biomethane can be seamlessly integrated into existing natural gas infrastructure, making it a viable substitute for fossil fuels in various sectors, including transportation and industrial processes (Black *et al*., 2021) [11]. This upgrading process enhances the energy density and purity of biogas, enabling its direct use in applications traditionally dominated by natural gas, such as vehicle fuels and industrial feedstocks. The compatibility of biomethane with existing gas networks and end-use technologies facilitates its widespread adoption and helps to displace the reliance on finite fossil fuel resources, contributing to the overall sustainability of the energy system.

The versatility and multifaceted benefits of biogas technology make it a valuable contributor to the achievement of the Sustainable Development Goals. By providing access to clean, affordable energy, biogas can improve the quality of life for marginalized communities and support economic development. The reduction of waste and the repurposing of organic matter into bioenergy and fertilizers aligns with the goals of responsible consumption and production, as well as climate action. Furthermore, the promotion of biogas systems can foster local job creation, empower rural communities, and enhance food security through the production of nutrient-rich digestate (Gupta *et al*., 2012) [22]. One of the key strengths of biogas is its ability to address the pressing issue of waste management while simultaneously generating renewable energy. Anaerobic (Kapoor *et al*., 2020) [31] digestion, the process underlying biogas production, can effectively degrade pollutants, transforming organic waste into valuable byproducts. This not only mitigates environmental degradation by diverting waste from landfills, but also contributes to the circular economy by repurposing waste streams and closing nutrient loops. Furthermore, the use of digestate as a fertilizer can reduce the need for synthetic fertilizers, further enhancing the sustainability of the biogas system (Kapoor *et al*., 2020) [31]

Sustainable Development Goals (SDGs) and Biogas

The widespread adoption of biogas technology aligns with several of the Sustainable Development Goals set forth by the United Nations. Biogas can play a pivotal role in advancing Goal 7: Affordable and Clean Energy, by providing access to reliable and sustainable energy solutions that can improve the lives of millions (Black *et al*., 2021) [11]. Furthermore, it contributes to Goal 11: Sustainable Cities and Communities, by addressing the challenge of waste management and promoting circular economic principles that can help create more livable and environmentally-friendly urban centers (Neves *et al*., 2009) [46]. Biogas also supports Goal 12: Responsible Consumption and Production, by fostering the efficient use of resources and minimizing waste, which are critical components of sustainable development.

Additionally, the production and utilization of biogas support Goal 12: Responsible Consumption and Production in multiple ways. First, biogas production fosters the efficient use of resources by converting organic waste into a valuable energy source, thereby minimizing waste that would otherwise end up in landfills or the environment (Uddin *et al*., 2021) [61]. Second, the byproduct of the anaerobic digestion process, nutrient-rich digestate, can be used as a sustainable fertilizer, further contributing to responsible production and consumption cycles. By repurposing waste streams and integrating biogas into a circular economy, this technology aligns with the principles of Goal 12 and promotes more sustainable patterns of resource use.

The potential of biogas to address sustainable development and contribute to the achievement of the UN's Sustainable Development Goals is immense. Through the continued advancement of biogas technology and its widespread implementation, we can unlock a future of renewable energy, sustainable waste management, and a healthier environment for all. The adoption of biogas systems holds the promise of unlocking a more sustainable and equitable future, where communities have access to clean energy, waste is repurposed into valuable resources, and the health of our environment is prioritized. By investing in and scaling up biogas solutions, we can take tangible steps towards realizing the ambitious vision of the Sustainable Development Goals and creating a more resilient, circular, and sustainable global economy. The development and deployment of biogas technology hold immense potential in driving sustainable development and realizing the Sustainable Development Goals set forth by the United Nations. Biogas offers a multifaceted solution that combines renewable energy generation, waste management, and nutrient recycling, making it a pivotal component in the transition towards a more sustainable and resilient future.

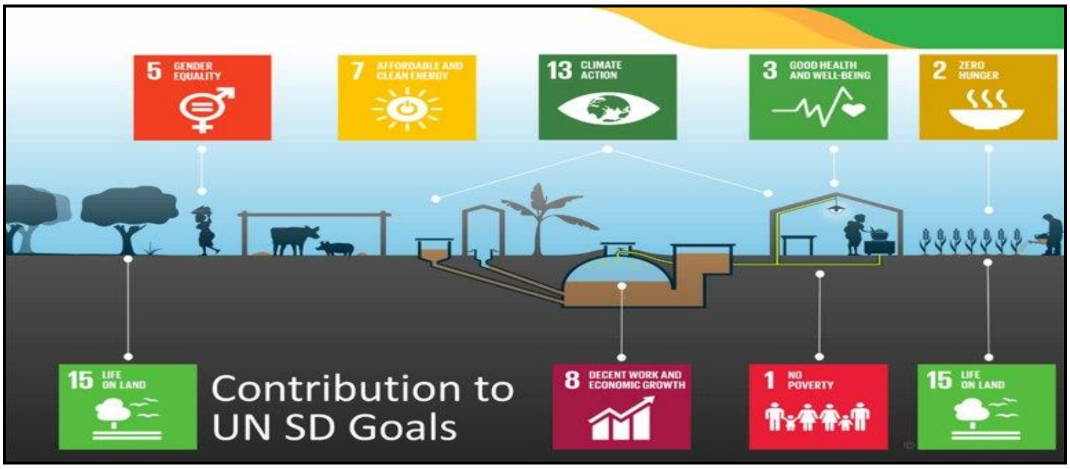

Fig 1: The direct contribution of a biodigester to the United Nations Sustainable Development Goals

Composition of biogas

The energy-rich biogas is primarily composed of methane and carbon dioxide, with trace amounts of other compounds such as hydrogen sulfide (H_2S) and moisture. The composition of biogas and the factors influencing its production are crucial considerations in the effective utilization and management of this valuable resource. Biogas typically consists of 50-70% methane, 30-50% carbon dioxide, and small quantities of other gases. The specific composition of biogas can vary depending on the feedstock, the anaerobic digestion process, and environmental factors (Neves *et al*., 2009) [46] (Black *et al*., 2021) [11].

Factors that can affect biogas production include the type and composition of the feedstock, the temperature and pH of the anaerobic digestion process, the presence of inhibitors or inhibitory substances, and the retention time of the material in the digester (Voicu *et al*., 2015) [63]. The C/N ratio of the feedstock is particularly important, as an imbalance can lead to decreased biogas yields (Voicu *et al*., 2015) [63]. Maintaining optimal environmental conditions, such as temperature and pH, is crucial for the growth and activity of the methanogenic bacteria responsible for biogas production (Voicu *et al*., 2015) [63]. Monitoring and controlling these parameters is essential for maximizing biogas yield and ensuring the efficiency of the anaerobic digestion process. Organic materials with a high carbon-to-nitrogen (C/N) ratio, such as agricultural residues, tend to produce biogas with a higher methane content, while materials with a lower C/N ratio, like livestock manure, may result in biogas with a lower methane concentration (Voicu *et al*., 2015) [63].

In addition to the feedstock composition and environmental factors, the design and operation of the anaerobic digestion system can also impact biogas production. Proper substrate pretreatment, mixing, and the retention time of the material in the digester can all contribute to increased biogas yields (Voicu *et al*., 2015) [63]. The efficient production and utilization of biogas offer numerous benefits, including the generation of renewable energy, the reduction of greenhouse gas emissions, and the effective management of organic waste (Black *et al*., 2021) [11]. Understanding the composition of biogas and the factors influencing its production is crucial for the optimization and widespread adoption of this sustainable energy source.

Overall, the composition and production of biogas are influenced by a complex interplay of factors, from the feedstock characteristics to the operational conditions of the anaerobic digestion system. Understanding and optimizing these factors can lead to the effective utilization of biogas as a sustainable and eco-friendly energy source, contributing to the broader shift towards renewable energy solutions.

Biogas Applications

Biogas is globally recognized as a traditional off-grid energy source with potential for electricity generation. Its applications are diverse and expanding**.**

Electricity Generation

Power generation from biomass is a growing market worldwide due to technological advancements, reduced reliance on fossil fuels, and lower greenhouse gas emissions. Biogas can generate electricity in power plants using internal combustion engines (ICEs) or gas turbines (GTs). Micro gas turbines are attractive for their lower NOx emissions and load flexibility. Multiple microturbines ranging from 70 kW to over 250 kW can meet low to medium power demands. On-site electricity generation prevents transport losses and increases reliability. In developed countries like Germany, biogas-generated electricity is even used for e-vehicles in car-sharing associations (Scarlat *et al*. 2018) [54].

Heat Generation

Biogas can be directly combusted in modified natural gas boilers for heat production. In agricultural settings, this heat can be used for heating digesters, farm buildings, greenhouses, aquafarming, cooling/refrigeration, and drying various products. This process adds significant value to farm economies (Herbes *et al*. 2018) [25]. Excess heat, typically 30-50% of generated heat, can be sold for district heating/cooling. Absorption chillers can convert heat into cooling power with efficiencies up to 70% (Rümmeli *et al*. 2010) [50].

Combined Heat and Power (CHP) Generation

CHP systems generate both electricity and heat, significantly improving energy conversion efficiency. While simple electricity generation systems have efficiencies of 20-45% (Muche *et al*. 2016) [44], CHP systems can achieve overall efficiencies up to 90%, producing 35% electricity and 65% heat. The high-temperature exhaust gas from electricity generation serves as a valuable heat source. This enhances system efficiency and improves plant payback periods (Damyanova and Beschkov 2020) [14].

CHP systems commonly use Gas-Otto engines, Pilot-injection gas motors, or Sterling motors. In the EU, four-stroke engines and ignition oil diesel engines each contribute about 50% to CHP applications. Gas turbines, microturbines, and fuel cells are also used in CHP systems.

The main advantage of CHP is its high efficiency and improved economic viability. Excess electricity can be supplied to the national grid, while extra heat can be sold for local use. Some systems incorporate absorption chillers for tri-generation (electricity, heat, and cooling), converting heat to cooling with efficiencies up to 70% (Rümmeli *et al*. 2010) [50].

A CHP cycle can achieve efficiencies up to 90%, producing 35% electricity and 65% heat. In some proposed biogas-based power plant models, the focus is solely on electricity generation, ignoring heat utilization. However, this approach lacks economic justification, as it is crucial to utilize all thermal potential for maximum efficiency and economic benefit (Saadabadi *et al*. 2019) [51].

Sources of Organic Waste for Biogas Production

Biogas production is a crucial aspect of renewable energy generation, and the availability of suitable organic waste sources is a critical factor in its success. (Voicu *et al*., 2015) [63]. Organic waste can be derived from various sources, including agricultural activities, municipal solid waste, and industrial processes. In rural areas, anaerobic digestion of agricultural waste or manure can be used to generate biogas, which can then be utilized to produce electric, thermal, or mechanical energy. (Neves *et al*., 2009) [46] Similarly, the organic fraction of municipal solid waste in urban areas can be used to generate biogas in landfills, providing an alternative energy source. (Neves *et al*., 2009) [46]

The decomposition of organic matter by anaerobic microorganisms can result in the production of two valuable products: digested sludge, which can be used as a soil fertilizer, and biogas, which can be harnessed as a renewable energy source. (Neves *et al*., 2009) [46] Biogas is a mixture of gases, primarily methane, that is produced through the anaerobic digestion of a range of organic materials, including agro-residues, food waste, human waste, and dedicated energy crops. The scale of biogas production can be adapted to the available feedstock, the level of investment, and the supporting policy mechanisms. Raw biogas can be used directly for heating, cooking, and lighting, or it can be upgraded to biomethane, a term used to define methane produced from biogas, rather than methane from fossil natural gas. (Black *et al*., 2021) [11]

The correct management of organic waste is essential, as improper treatment and storage can compromise the quality of the biogas feedstock and the digested sludge. Additionally, the presence of improper materials, such as heavy metals, in the organic waste can increase the complexity of the plant design, requiring special pre-treatment units to prepare a homogenous feeding slurry. (Ellacuriaga *et al*., 2021)

The integration of biogas production into the circular economy concept is a promising approach, as it allows for the recovery of energy from organic waste and the recycling of nutrients when the digestates are applied to agricultural lands. (Ellacuriaga *et al*., 2021) Anaerobic digestion technology is already playing an important role in the agro-industrial sector in Switzerland, displacing emission-intensive waste management strategies like landfilling or incineration. (Bowman *et al*., 2022) [12]

Biogas obtained from the decomposition of organics has a high energy content and is usually used as fuel for producing heat and electricity. The presence of improper materials in organic wastes and in some cases, high concentrations of heavy metals, translates into a plant design of high complexity needing special pre-treatment units for preparing a homogenous feeding slurry. We should also add the intrinsic difficulty of separating inert materials and avoiding the presence of toxic elements in digestates that prevents any agronomic use . Anaerobic digestion is a process that usually involves the recovery of energy from organics and allows the recycling of nutrients when digestates are applied on agricultural lands (Neves *et al*., 2009) [46].

The prospects of bioenergy production from organic waste using anaerobic digestion technology are promising, as it can provide essential resources to large populations without causing global warming and can help combat the environmental problems we are confronted with today.

Table 1: Sources of Organic Waste for Biogas Production

Source of Organic Waste	Description	Examples	Biogas Potential	Reference
Agricultural residues	Organic matter left after harvesting crops or from animal husbandry	Corn stover, wheat straw, rice husks, animal manure	High; varies by type	FAO. (2019) [20].
Food waste	Discarded food materials from households, restaurants, and retail	Fruit and vegetable scraps, meat trimmings, dairy products	High; easily digestible	EPA. (2021) [60].
Municipal solid waste	Organic fraction of household and commercial waste	Paper, cardboard, yard trimmings, food scraps	Moderate; requires sorting	World Bank. (2018) [32]
Wastewater sludge	Residual, semi-solid material produced during sewage treatment	Primary and secondary sludge	Moderate; already partially degraded	Water Environment Federation. (2017) [64].
Industrial food processing waste	By-products from food and beverage manufacturing	Brewery spent grain, fruit pulp, vegetable peelings	High; often easily digestible	FAO. (2013) [21].
Lignocellulosic biomass	Plant dry matter high in cellulose, hemicellulose, and lignin	Forestry residues, switchgrass, miscanthus	Low-Moderate; requires pretreatment	U.S. Department of Energy. (2016) [59].
Algae	Aquatic biomass including micro- and macroalgae	Spirulina, kelp, seaweed	High; but cultivation can be energy-intensive	U.S. DOE. (2010) [58].

Lignocellulosic Biomass

The use of plant residues as a feedstock for biogas production has gained increasing attention due to their abundance and the potential to reduce waste. Lignocellulosic biomass, which consists of cellulose, hemicellulose, and lignin, is a promising feedstock for biogas production due to its abundance, renewable nature, and potential to generate clean energy (Li *et al*., 2018) [38]. Biogas, a mixture of methane and carbon dioxide, can be obtained through the anaerobic digestion of lignocellulosic materials, making it a sustainable alternative to fossil fuels (Hossain *et al*., 2016) [27]. The conversion of lignocellulosic biomass into biogas, however, faces several challenges. Lignocellulosic materials are inherently recalcitrant to degradation due to the complex and compact structure of the lignocellulosic matrix, which is resistant to microbial and enzymatic attack (Himmel *et al*., 2007) [26]. The high lignin content in lignocellulosic biomass acts as a physical barrier, preventing access to the cellulose and hemicellulose components, which are the primary substrates for biogas production (Isroi *et al*., 2011) [28].

To overcome these challenges, various pretreatment methods, such as chemical, physical, and biological approaches, have been explored to enhance the digestibility of lignocellulosic biomass (Hossain *et al*., 2016) [27]. Among these, biological pretreatment using white-rot fungi has gained attention due to its simplicity, low capital investment, and ability to effectively degrade lignin (Isroi *et al*., 2011) [28]. White-rot fungi produce ligninolytic enzymes that can efficiently mineralize lignin into carbon dioxide and water, thereby exposing the cellulose and hemicellulose for more efficient bioconversion (Isroi *et al*., 2011) [28]. The pretreatment of lignocellulosic biomass, such as cassava residues, with biological methods has been shown to significantly improve methane production during the subsequent anaerobic digestion process (Zhang *et al*., 2011) [68]. The enhanced biogas yield can be attributed to the increased accessibility of the cellulose and hemicellulose fractions, which are then more readily converted into methane by methanogenic microorganisms (Zhang *et al*., 2011) [68].

Acidic pretreatment, such as the use of dilute acid solutions, can effectively break down the complex lignocellulosic structures and increase the accessibility of cellulose and hemicellulose for enzymatic an microbial digestion. (Kim *et al*., 2016) [35] (Guragain & Vadlani, 2021) [23] This, in turn, can enhance the overall biogas generation efficiency by improving the hydrolysis and fermentation stages of the process. Studies have shown that acidic pretreatment can significantly increase the methane yield from lignocellulosic feedstocks, including agricultural residues and energy crops. (Zhang *et al*., 2011) [68] Additionally, the pretreatment can help reduce the production of inhibitory compounds, such as furfural and hydroxymethylfurfural, which can negatively impact the performance of the anaerobic digestion process. While the benefits of acidic pretreatment are well-documented, it is important to optimize the process parameters, such as the type and concentration of the acid, temperature, and residence time, to achieve the best possible outcomes in terms of biogas yield and process efficiency. (Bhatia *et al*., 2020) [9]

Additionally, the use of engineered enzymes and genetically modified plants has been extensively explored to improve the accessibility and conversion efficiency of lignocellulosic biomass for biofuel production (Himmel *et al*., 2007) [26]. By better understanding and addressing the inherent recalcitrance of lignocellulosic materials, researchers have been able to develop more efficient, cost-effective, and scalable strategies for the effective utilization of this abundant and renewable resource for biogas production (Zhang *et al*., 2011) [68]. These innovative approaches, which combine advancements in genetic engineering, enzyme engineering, and process optimization, hold great promise for unlocking the full potential of lignocellulosic biomass as a sustainable feedstock for bioenergy generation. Beyond lignocellulosic biomass, other organic waste streams, such as agricultural residues, municipal solid waste, and food processing byproducts, have also been investigated as potential feedstocks for biogas production. The anaerobic digestion of these diverse organic wastes not only generates renewable energy in the form of biogas but also helps mitigate environmental pollution and promotes a circular economy by converting waste into valuable resources. The development of integrated biorefinery concepts that can efficiently process a wide range of organic feedstocks, including lignocellulosic biomass, is an active area of research aimed at maximizing the utilization of renewable carbon sources for sustainable bioenergy and bioproduct generation.

Industrial Effluent

The utilization of industrial effluent for biogas production has gained significant attention in recent years as a viable solution to address the growing energy demands and environmental concerns. Biogas, a biofuel consisting primarily of methane, can serve as a renewable energy source, offering an alternative to natural gas or liquefied petroleum gas.

Anaerobic digestion, a process in which microorganisms break down organic matter in the absence of oxygen, has proven to be an effective method for generating biogas from industrial effluents. Industrialized and urbanized areas are often plagued by the generation of organic waste, which can be a considerable source of pollution. However, by harnessing the power of anaerobic microorganisms, these organic pollutants can be degraded, resulting in two valuable products: digested sludge and biogas. Digested sludge can be used as a soil fertilizer, while biogas can be utilized to generate electric, thermal, or mechanical energy, making it an attractive alternative energy source. Moreover, biogas from sewage sludge can be used for heat and power generation or further processed into biomethane, liquid fuels and chemicals. Further processing involves an upgrading mechanism aiming to enhance the value of the product. For instance, in the conversion of biogas to biomethane, the calorific value and density of the biomethane are enhanced to be equal to that of natural gas (Enebe *et al*., 2023) [17]

The digested sludge can be used as a soil fertilizer, while the biogas can be exploited as a renewable energy source. Anaerobic treatment of industrial effluents has emerged as a technically simple and relatively inexpensive technology, consuming less energy, space, and producing less excess sludge compared to conventional aerobic treatment methods. Furthermore, the net energy production from biogas makes the anaerobic treatment technology an attractive option over other treatment methods.

Increasing industrialization worldwide has led to the generation of large quantities of industrial effluents with high organic content. Anaerobic digestion has proven to be the most suitable option for the treatment of these high-strength organic effluents, as it can effectively recover energy in the form of biogas while reducing the environmental impact (Neves *et al*., 2009) [46].

The application of anaerobic technology has improved significantly in recent decades, with the development of differently configured high-rate treatment processes, particularly for the treatment of industrial wastewaters. This advancement in technology has made the utilization of industrial effluent for biogas production a more viable and attractive option, contributing to the integration of circular economy principles and the sustainable management of organic waste streams. (Sawatdeenarunat *et al*., 2019) [53]

Livestock Waste

Amidst the global pursuit for renewable energy solutions, the untapped potential of livestock waste stands as a promising avenue for biogas production. Anaerobic digestion has emerged as an efficient technology that not only generates biofuel but also offers sustainable waste management. (Martin & Souza, 2007) [41]. Worldwide, the accumulation of waste has prompted environmental hazards, and anaerobic digestion provides a green and efficient alternative for the removal of toxic waste while simultaneously producing energy. This process involves the breakdown of organic matter by microorganisms in the absence of oxygen, resulting in the generation of biogas, a methane-rich fuel that can be utilized for various applications. (Achinas *et al*., 2017) [2]. Recent studies have highlighted the multifaceted benefits of this technology, emphasizing its potential to combat the impact of greenhouse gases and meet the growing global energy demand. (Achinas *et al*., 2017) [2]. Livestock waste represents a significant feedstock for anaerobic digestion. This organic matter can be transformed into biomethane, which is chemically similar to natural gas, making it a viable alternative to fossil fuels (Muscolo *et al*., 2017) [45]

Furthermore, the co-digestion of recalcitrant agricultural wastes, such as olive waste and citrus pulp, in combination with livestock waste, straw, and cheese whey, has been explored for enhanced biogas production. (Muscolo *et al*., 2017) [45] This approach not only improves the efficiency of the anaerobic digestion process but also addresses the management of digestion residues, a key factor in the sustainability of these systems.

The sustainable deployment of anaerobic digestion technology for biogas generation from livestock waste holds immense promise in addressing the environmental and energy challenges faced by society. Harnessing this renewable energy source can not only mitigate the environmental impact of waste accumulation, but also contribute to meeting the growing global demand for sustainable energy solutions. By converting livestock waste into a valuable biofuel, this technology offers a multifaceted approach to tackling pressing issues related to waste management and renewable energy production.

Algal Biomass

Renewable energy sources have gained increasing attention in recent years as the world grapples with the pressing issues of climate change and dwindling fossil fuel reserves. Among the various renewable energy options, biogas production from algal biomass has emerged as a promising solution. Algae are photosynthetic organisms that can efficiently convert carbon dioxide into organic matter, making them an attractive feedstock for biogas production (Bhushan *et al*., 2020) [10] (Bharathiraja *et al*., 2015) [8]. Several studies have highlighted the advantages of using algal biomass for biogas production. Microalgae and cyanobacteria, in particular, offer several advantages over plant-based biofuels, such as high growth rates, the ability to be cultivated on non-arable land, and the potential to be grown in wastewater (Zuorro *et al*., 2020) [70]. Additionally, the production of algal biomass can be directed toward the synthesis of various compounds of commercial interest, including biofuels (Zuorro *et al*., 2020) [70].

The process of producing biogas from algal biomass typically involves several stages, including strain selection, cultivation, harvesting, and conversion (Bhushan *et al*., 2020) [10]. The quality and quantity of the biomass, as well as the available media source, cultivation system, and environmental conditions, all play a crucial role in the selection of the appropriate algal strain (Bhushan *et al*., 2020) [10]. Once the biomass is harvested, it can be subjected to various pretreatment and conversion processes to produce biogas, such as anaerobic digestion or fermentation (Dutta *et al*., 2023) [15]. One of the key benefits of using algal biomass for biogas production is the potential for integrated biorefinery systems. The remaining biomass after the extraction of valuable compounds can be utilized for the production of secondary products, such as biogas, butanol, or ethanol, through further fermentation processes (Dutta *et al*., 2023) [15]. This approach allows for the efficient utilization of the entire algal biomass, maximizing the recovery of value-added products and reducing waste.

Despite the promising potential of algal biomass for biogas production, there are still several technical and economic hurdles that need to be addressed to make the process commercially viable (Bhushan *et al*., 2020) [10]. Ongoing research and development efforts are focused on improving cultivation techniques, harvesting methods, and conversion processes to enhance the overall efficiency and cost-effectiveness of algal biogas production (Khoo *et al*., 2019) [34].

The use of algal biomass as a feedstock for biogas production holds significant promise as a renewable energy solution. The integration of algal biorefinery systems, where multiple products are extracted from the biomass, can contribute to the economic feasibility of this approach (Khoo *et al*., 2019) [34]. Continued advancements in algal biotechnology and process optimization will be crucial in unlocking the full potential of algal biomass for sustainable biogas production.

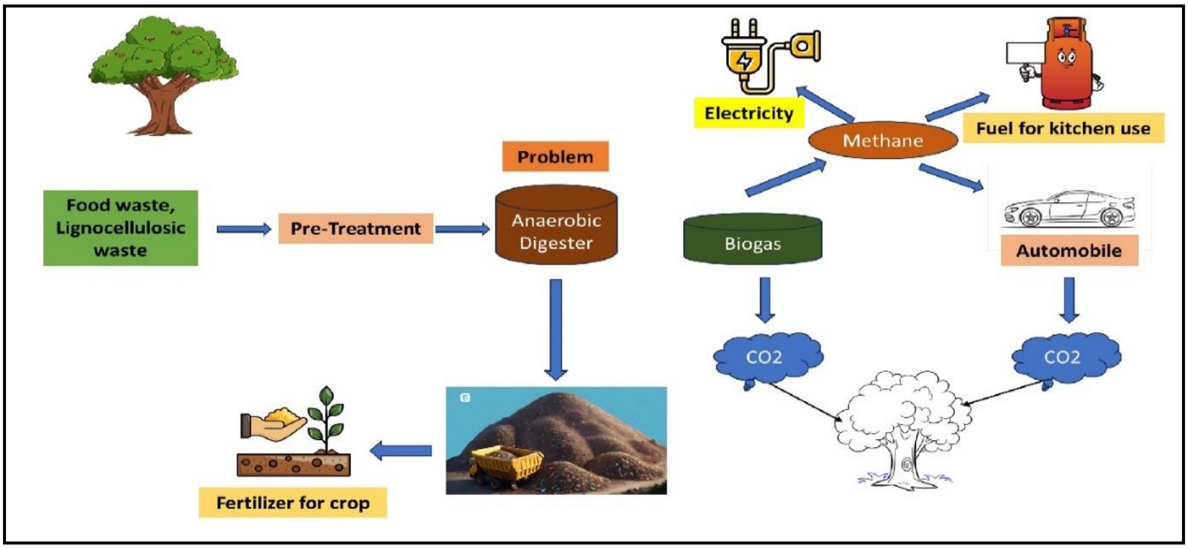

Fig 2: Bioconversion of agro-industrial waste into biogas through the anaerobic digestion process

Advancement of Nanoparticles in Pretreatment and Hydrolysis Processes for Biogas Generation

In recent years, the scientific community has increasingly focused its attention on the potential of nanomaterials to enhance the efficiency and sustainability of various industrial processes, including the production of biogas, a renewable energy source derived from the anaerobic digestion of organic matter. The incorporation of nanomaterials into the biogas production process has been shown to have a significant impact on various aspects of the process, from increasing the overall biogas yield to improving the quality of the resulting fuel. The utilization of nanoparticles has garnered significant attention in the field of biogas production due to their potential to enhance the efficiency of anaerobic digestion processes. Nanoparticles, with their unique physicochemical properties, can interact with the substrate and microorganisms involved in the anaerobic digestion process, thereby influencing the rate and yield of bio methane production (Barrena *et al*., 2022) [6]. One of the key advantages of using nanoparticles in biogas generation is their ability to improve the pretreatment and hydrolysis stages, which are critical steps in the overall process (Baniamerian *et al*., 2019) [5].

Pretreatment methods, such as mechanical, chemical, or biological approaches, aim to disrupt the recalcitrant structure of lignocellulosic biomass, making it more accessible to the hydrolytic enzymes during the subsequent hydrolysis stage. Nanoparticles can be utilized to enhance the efficiency of these pretreatment and hydrolysis processes, leading to increased biogas yields (Faisal *et al*., 2018) [19]. The addition of zero-valent metallic nanoparticles, such as iron or copper, has been shown to improve the hydrolysis of complex organic matter, resulting in higher biogas production rates . (Barrena *et al*., 2022) [6] Moreover, metal oxide nanoparticles, like titanium dioxide or zinc oxide, can act as catalysts in the pretreatment and hydrolysis stages, promoting the breakdown of recalcitrant biomass. Carbon-based nanomaterials, such as graphene or carbon nanotubes, have also been explored for their potential to enhance the adsorption and desorption of organic substrates, ultimately improving the efficiency of the anaerobic digestion process (Baniamerian *et al*., 2019) [5]. One of the most well-documented effects of nanomaterials on biogas production is their ability to increase the yield of the process. Studies have reported that the addition of nanoparticles, such as iron oxide (Fe3O4) nanoparticles, can lead to an increase in biogas production of up to 200% (Faisal *et al*., 2018) [19]. This enhancement is believed to be due to the unique properties of nanomaterials, which can facilitate the transfer of electrons between microbial communities and the organic matter undergoing digestion, thereby enhancing the efficiency of the overall process (Khan *et al*., 2022) [33]. In addition to increasing biogas yield, the presence of nanomaterials in the anaerobic digestion process has also been shown to improve the quality of the resulting biogas. This can be attributed to the ability of nanoparticles to optimize the various stages of the anaerobic digestion process, such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Barrena *et al*., 2022) [6]. Several recent studies have reported that the addition of certain nanomaterials can lead to a significant increase in the methane content of the biogas, making it a more valuable fuel source (Barrena *et al*., 2022) [6] This effect is particularly important, as the methane content of biogas is a key factor in determining its energy content and potential for use as a renewable energy source.

The incorporation of nanomaterials in the pretreatment and hydrolysis stages of biogas generation has demonstrated promising results in terms of increased biogas yields and improved methane content. However, it is important to note that the effects of nanomaterials on the anaerobic digestion process can vary depending on the specific type, concentration, and interaction with the microbial community. Therefore, further research and optimization are necessary to fully understand and harness the potential of nanomaterials in enhancing the efficiency of biogas production. The use of nanomaterials can provide opportunities to improve the overall process, but their implementation requires careful consideration and evaluation to ensure optimal performance and mitigate any potential adverse effects on the system. Additionally, the release of nanomaterials into the environment, particularly through wastewater treatment plants, has become a growing concern, as they may have adverse effects on the anaerobic digestion process (Chen *et al*., 2014) [13]. The addition of iron oxide (Fe3O4) nanoparticles to the anaerobic digestion process led to a significant increase in methane production, as well as improved the overall kinetics of the process (Zuo *et al*., 2022) [69]. The researchers attributed this enhancement to the ability of the iron-based nanoparticles to influence the electron donation and acceptance capabilities of methanogens, as well as their role as a cofactor in key enzymatic activities (Ugwu & Enweremadu, 2020) [62].

To enhance the efficiency of the anaerobic digestion process, researchers have explored the use of engineering nanomaterials, such as iron oxide (Fe3O4) nanoparticles, which can positively impact methane production and the overall kinetics of the process (Zuo *et al*., 2022) [69]. In contrast, other studies have reported that certain nanomaterials, such as silver nanoparticles, can have a toxic effect on the anaerobic digestion process, inhibiting the growth and activity of the microorganisms involved (Chen *et al*., 2014) [13].

Nanoparticle interaction mechanism

The efficiency of substrate digestion in anaerobic digestion (AD) processes is primarily regulated by complex microbial interactions, with a particular emphasis on electron transfer mechanisms between diverse microbial species (Harirchi *et al*., 2022) [24]. This process requires an intricate system of electron exchange between syntrophic bacteria and methanogenic archaea to facilitate successful methanogenesis. Any disruption in this system can lead to decreased rates of hydrolysis and methanogenesis, subsequently reducing methane and biogas yields.

The introduction of nanoparticles (NPs) to the AD process has been observed to enhance both direct and indirect interspecies electron transfer, thereby accelerating hydrolysis and acidification processes, which ultimately results in increased biogas production. Two primary mechanisms of interspecies electron transfer have been identified: Mediated Interspecies Electron Transfer (MIET) and Direct Interspecies Electron Transfer (DIET).

MIET utilizes electron carriers such as formate or hydrogen. When formate acts as the electron carrier, the process is termed Interspecies Formate Transfer (IFT), whereas when hydrogen serves this role, it is referred to as Interspecies Hydrogen Transfer (IHT). In contrast, DIET facilitates electron transfer without the involvement of intermediate electron carriers. Consequently, DIET is generally considered more efficient than both IFT and IHT due to the absence of these carriers.

The subsequent section provides a comprehensive analysis of these electron transfer mechanisms and their implications for anaerobic digestion processes, elucidating the fundamental principles underlying the enhancement of biogas production through nanoparticle-mediated electron transfer in AD systems.

Mediated interspecies electron transfer

During AD process, a cooperative symbiosis between methanogens and fermentative bacteria is observed which also known as syntrophic methanogenesis. MIET is considered the most predominant method and the major driving force for syntrophic methanogenesis. This method utilizes soluble electron carriers such as formate or hydrogen for the exchange of electrons between the electron-donating microorganisms and electron-accepting microorganisms. Based on the electron carrier involved in methanogenesis, the MIET can be classified as IFT or IHT, involving formate or hydrogen as electron carriers, respectively. The extracellular electron exchange in IFT and IHT is carried out with the involvement of two key enzymes such as formate dehydrogenase and hydrogenase, respectively (Roden *et al*., 2010) [48]. The following major steps are involved during the IHT process. At first, the electrons are generated during the hydrolysis of complex organic matter into its monomers. Subsequently, the released electrons reduce the protons to H_2 by the enzyme hydrogenase. Finally, the hydrogenotrophic methanogens utilize the produced H_2 to produce methane. Whereas, in case of IFT, formate dehydrogenase enzyme coupled with electrons is involved in the reduction of CO2 to formate, which is later involved during the methanogenesis process (Li *et al*., 2019) [37]. The efficiency of this process is slow due to the limitations in diffusion of electron carriers.

Direct interspecies electron transfer

Direct interspecies electron transfer (DIET) is an alternative pathway for the transfer of electrons between the fermentative bacteria and methanogenic archaea during the AD process. During this process, the transfer of electrons occurs without the involvement of different electron carriers. However, the transfer of electrons in this method occurs through biologically conducting structures such as c–type cytochromes (c–Cyts) or pili (Barua *et al*., 2017) [7]. The transferred electrons are used by methanogens for the conversion of carbon dioxide to methane. The DIET holds several advantages over the MIET due to many reasons which include low consumption of energy, no requirement of external mediators for electron transfer, no toxic volatile fatty acids accumulation, and no involvement of complex enzymatic steps for production, consumption, and diffusion of redox mediators (Ajay *et al*., 2020) [3]. In addition, DIET is more thermodynamically favourable, and the rate of electron transfer is much higher compared to IHT (Storck *et al*., 2016) [56]. As per the previous report, approximately 85 kJ/mol can be conserved while transferring 50% of the electron during propionate oxidation through DIET instead of IHT (Wu *et al*., 2020) [65]. The DIET is further classified into three types based on the transfer of electrons, which includes (A) DIET via conductive pili, (B) DIET via membrane-bound electron transport protein, and (C) DIET through abiotic conductive materials.

Size and dosage of NPs

Currently, use of NPs for the improvement of methane and biogas production from organic waste is a promising approach to reduce environmental pollution while simultaneously producing bioenergy. The size/shape and dosage of NPs are the two critical factors that influence various stages of AD process, i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Studies also investigated the influence of size and shape of NPs over their physical properties (Ly *et al*., 2023) [40]. Typically, the size of NPs varies between 1 and 100 nm. The size of NPs can be controlled by varying the method of synthesis, pH, temperature and pressure of reaction, and the concentration of precursor/solvent. It is also essential to determine the optimum size of NPs to augment the AD process. Further, high dosages of NPs negatively affect the biogas production process while causing inhibition to microorganisms, and even cell lysis. Jiao *et al*., (2022) [30] reported the combined NPs (NZVI and biochar) with concentrations below 9 mg/L improved the biogas production from corn straw. With further increase in NPs concentration (12 and 15 mg/L), a decrease in biogas production by 1.8–2.8% was observed which possibly could be due to the inhibition of microorganisms at higher concentrations. In contrast, the study reported by Jadhav *et al* (2022) [29] for AD of palm oil mill effluent showed a decrease in biogas production at lower (10 mg/L) concentrations of Fe–Co–Cu trimetallic NPs. The choice of concentration that impacts AD depends on the types NPs and the organic waste used in the process

Table 2: Doses of different nanomaterials

Nanomaterial	Dosage	Reference
Iron oxide nanoparticles (Fe_3O4)	20-100 mg/L	Zhang *et al*. (2019) [67]
Titanium dioxide nanoparticles (TiO_2)	10-50 mg/L	Abdelsalam *et al*. (2016)
Zinc oxide nanoparticles (ZnO)	30-150 mg/L	Yan *et al*. (2018) [66]
Carbon nanotubes (CNTs)	50-200 mg/L	Kumar *et al*. (2021) [36]
Graphene oxide (GO)	0.05-0.5 g/L	Liu *et al*. (2015) [39]
Nickel oxide nanoparticles (NiO)	5-25 mg/L	Tian *et al*. (2017) [57]

Environmental Implications and Scalability of Nano-Enabled pretreatment

One of the primary benefits of incorporating nanomaterials in biogas production is the potential for significant yield increase. Certain nanomaterials, such as metal and metal oxide nanoparticles, have been shown to stimulate the growth and activity of anaerobic microorganisms responsible for the biogas generation process. This effect can lead to up to a 200% increase in biogas production, making the technology more economically viable and scalable.

However, the implementation of nano-enabled technologies in biogas production is not without its challenges. The long-term environmental implications of nanomaterial accumulation in the digestate, the end product of the anaerobic digestion process, remain a concern. Nanomaterials may persist in the environment and potentially disrupt ecosystems, highlighting the need for comprehensive risk assessment and mitigation strategies (Zuo *et al*., 2022) [69]. Another critical aspect of nano-enabled biogas production is the scalability of the technology. While laboratory-scale studies have demonstrated promising results, the successful large-scale deployment of these nano-enhanced systems remains a significant hurdle. The integration of nanomaterials into existing biogas production facilities requires careful consideration of factors such as cost, ease of implementation, and potential operational challenges. Ultimately, the widespread adoption of nano-enabled biogas production technologies will depend on the ability to address the complex environmental implications and scalability concerns through a comprehensive and multifaceted approach.

To address these concerns, ongoing research is focused on developing sustainable and environmentally friendly nanomaterials, as well as exploring alternative nanomaterial-based strategies that can maximize biogas yields without compromising the integrity of the surrounding ecosystem (Khan *et al*., 2022) [33], Researchers have explored the use of inherently biodegradable nanomaterials, such as those derived from natural sources, which can minimize the environmental impact of nano-enabled biogas production. As the field of nano-enabled biogas production continues to evolve, a balanced approach that considers both the environmental implications and the scalability of these technologies will be crucial in realizing the full potential of this renewable energy source.

Conclusions

Biogas production through anaerobic digestion has emerged as a promising technique for managing food waste and municipal solid waste (MSW), offering dual benefits of waste reduction and renewable energy generation. However, the widespread adoption of this technology faces several operational challenges have limited the widespread application of this technique. By optimizing feedstock selection, improving anaerobic digestion processes, and implementing cutting-edge technologies, we can significantly boost biogas yields and quality. This not only addresses waste management challenges but also provides a reliable, clean energy source to meet growing global demands. As we continue to innovate and scale up biogas production, we pave the way for a more circular economy, reduced greenhouse gas emissions, and greater energy independence. The ongoing advancements in biogas technology underscore its potential as a key player in the renewable energy landscape, contributing significantly to our transition towards a more sustainable and resilient world.

Conflict of Interest

The authors have no conflict of interest.

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