Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Effect of different Biochars on Anaerobic Digestion of Organic Solid Waste: A Review

Hawra Hassan Ataa[1], Zaidun Naji Abudi [2], Salam Salman Chiad Alharishawi [3]

[1]Environmental Engineering Department, College of Engineering, Mustansiryiah University, Baghdad, Iraq.

[2,3]Mustansiryiah University, College of Engineering, Baghdad, Iraq.

ARTICLE INFO

Article history:
Received 17 August 2025
Revised 17 August 2025
Accepted 27 August 2025
Available online 14 September 2025

Keywords:
Anaerobic digestion
Biogas
Biochar
Methane
organic waste

ABSTRACT

More kitchen waste adds big issues for the earth due to the gas from trash heaps. A way to fix this is by changing waste into gas with biochar. This study looks at how biochar (from sewers & plants) can help turn more kitchen waste into gas.

This paper checks out how biochar aids in making gas from kitchen waste. It sees how sewers' sludge & plant bits boost the process. As kitchen waste & gas from trash grow, turning this waste into gas is key

Anaerobic digestion offers a sustainable solution by converting organic waste into biogas. The study aims to evaluate how different types of biochar improve biogas production, contributing to more efficient waste management practices.

1. Introduction

Anaerobic Digestion of Organic Solid Waste

1.1. Kitchen Waste & its Bad Effects

All the trash from our kitchens, like old food, scraps, & other waste, is a big earth issue due to its huge size & fast rise. New stats show that about 1.6 billion tons of food is thrown out each year around the world. This piles up big problems like more dirt & less power [1].

Bad handling of this trash may let out harsh gases, like methane, that get into the air when waste breaks down with no air in dumps [2].

Food waste breaks down fast, as it is made of stuff that can rot quickly. Yet, changes in what we eat & the time of year make it tough to deal with [5]. Such changes can mess up the steps to turn waste into gas, making it hard to get good gas from trash. Effective management strategies are essential for addressing the environmental impacts and resource recovery potential related to kitchen waste. The adoption of advanced pre-treatment techniques, improvements in source sorting practices and a greater focus on recycling are critical measures aimed at reducing methane emissions while enhancing energy generation potential through anaerobic digestion [5] for additional insights.

1.2. Importance of biogas production from anaerobic digestion

The production of biogas through anaerobic digestion is crucial for kitchen waste management and offers a sustainable solution to food waste, which contributes to significant environmental harm. Approximately 1.6 billion tons of food is wasted annually worldwide, leading to increased carbon emissions from poor disposal methods. Anaerobic digestion

Corresponding author E-mail address: hawarhassan87@uomustansiriyah.edu.iq
https://doi.org/10.61268/7wgh1y82

effectively converts organic waste into biogas, primarily methane, serving as a renewable energy source [5]. Biogas production also reduces reliance on fossil fuels and lowers carbon emissions associated with traditional energy sources [6]. Anaerobic digestion systems can process various organic materials, including kitchen scraps, demonstrating their efficiency and adaptability. Co-digestion techniques allow for the simultaneous processing of different organic wastes, increasing overall biogas output by optimizing nutrient balance for microorganisms [14]. Additionally, anaerobic digestion contributes to nutrient cycling by producing digestate, a valuable fertilizer byproduct [4]. This recovery and recycling of nutrients support agricultural practices and advance sustainable environmental goals. In summary, biogas production through anaerobic digestion addresses food waste issues while providing a cleaner energy alternative that mitigates environmental impacts and promotes resource recovery.

Fig.1 An anaerobic digestion plant with biochar addition from digestate pyrolysis. (source: reference [4].

1.3. Challenges in managing kitchen waste effectively

The management of kitchen waste faces significant challenges that hinder anaerobic digestion effectiveness. A primary issue is the inconsistency in kitchen waste composition, which varies with seasonal diets and local culinary habits. This variability complicates treatment processes, as different organic materials require specific handling to optimize biogas production. Additionally, kitchen waste often contains biodegradable substances mixed with inert items like plastics, creating hurdles for efficient digestion. The presence of non-organic elements can disrupt the digestion process, leading to reduced gas [5]. Moreover, inert materials such as disposable tableware introduce practical complications, increasing operational costs related to sorting and preprocessing [5]. While some plastics may aid initial fermentation stages, they ultimately inhibit methanogenic bacteria crucial for effective biogas production [5]. Issues like foaming and acidification during digestion can cause ammonia inhibition, further reducing biogas yield and compromising system stability [18]. These technical challenges underscore the need for enhanced pre-treatment techniques and co-digestion strategies to overcome barriers and optimize resource recovery from kitchen waste. Innovative solutions, such as advanced separation methods for non-biodegradable materials before anaerobic processing, are essential for improving biogas output and advancing sustainable practices in kitchen waste management systems.

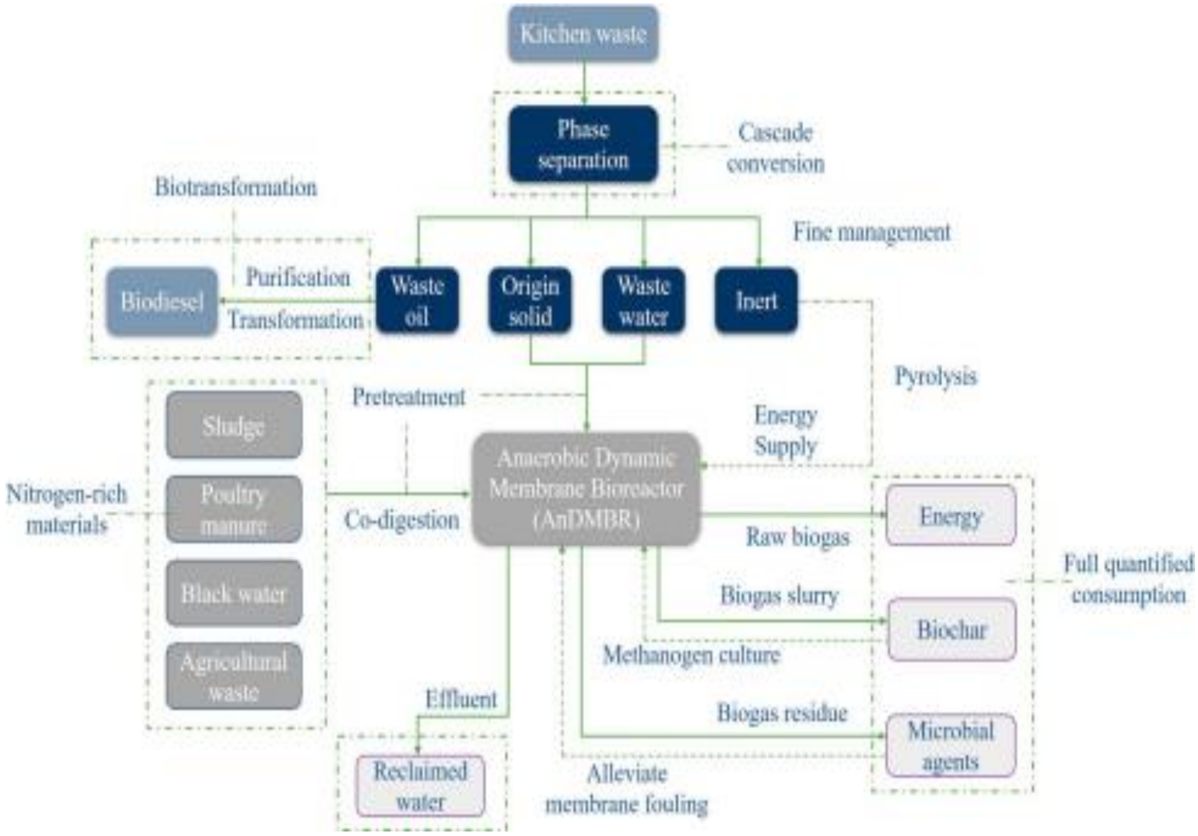

Figure 2: Proposed full quantitative model for recycling kitchen waste [5].

2. Biochar: Definition and Types

2.1. What is biochar?

Biochar, a carbon-dense substance, is created through the pyrolysis of biomass under high temperatures and limited oxygen. This thermochemical transformation disassembles organic materials into a stable solid that boasts an array of advantageous properties for environmental use. One of biochar's remarkable features is its highly porous architecture, which provides an expansive specific surface area (SSA), enabling it to effectively adsorb various ions and compounds. This versatile material can be derived from different feedstocks, including plant sources such as wood and agricultural byproducts, as well as manure-derived inputs.

Like sewage sludge and poultry litter. The Characteristics of the final biochar are significantly shaped by both the nature of the feedstock employed and the conditions of pyrolysis—factors like temperature and duration play key roles in determining its chemical makeup and physical properties. The multifaceted contributions of biochar to enhancing anaerobic digestion processes have drawn increasing interest. It serves not just as a nutrient carrier; it also stimulates microbial activity by offering a conducive environment for the microbial communities engaged in anaerobic digestion. According to [20], biochar’s distinctive qualities—including its pH buffering ability, extensive porosity, and potential for electron transfer—are vital for boosting biogas production efficiency during anaerobic digestion.

Furthermore, biochar can alleviate challenges typically encountered in the anaerobic digestion process, such as the buildup of volatile fatty acids (VFAs) that may impede methane oogenesis. By supplying surfaces conducive to microbial colonization and facilitating direct interspecies electron transfer (DIET), biochar aids in the more efficient conversion of organic waste into biogas while also playing a role in broader waste management initiatives focused on sustainability and resource recovery.

2.2. Different types of biochar used in studies Biochar.

A carbon-rich substance generated through the pyrolysis of organic materials has been the focus of numerous studies due to its potential to enhance anaerobic digestion (AD). Among the biochar receiving significant attention are those derived from sewage sludge and plant residues. Sewage sludge biochar, which arises from the pyrolysis of dewatered sewage sludge—a byproduct of wastewater treatment—boasts distinctive characteristics that
can favorably affect microbial activity in AD sstems. Its high nitrogen and sulfur content are vital for fostering microbial growth. Research suggests that integrating sewage sludge biochar into AD setups can substantially elevate biogas production, particularly with easily degradable substrates such as sodium acetate [17]. Conversely, plant residues biochar, obtained from a variety of biomass sources like corn straw or hardwoods, generally showcases a greater specific surface area and enhanced porosity compared to its sewage sludge counterpart. These attributes promote superior microbial colonization and improve electron transfer mechanisms during methane generation [10]. For example, comparative studies have indicated that wood-derived biochar often leads to elevated methane production rates due to its fine aromatic structures and lower ash content [20]. Nevertheless, while plant residue biochar can enhance the digestibility and methane yield from organic waste, it might fall short on the alkalinity front that manure or sludge-based biochar provides to counteract acidification issues during digestion. The differences in properties between these two varieties of biochar underscore the necessity for careful selection based on specific waste characteristics to optimize anaerobic digestion outcomes. Moreover, both types play distinct roles in supporting microbial communities and influencing nutrient availability throughout the digestion process.

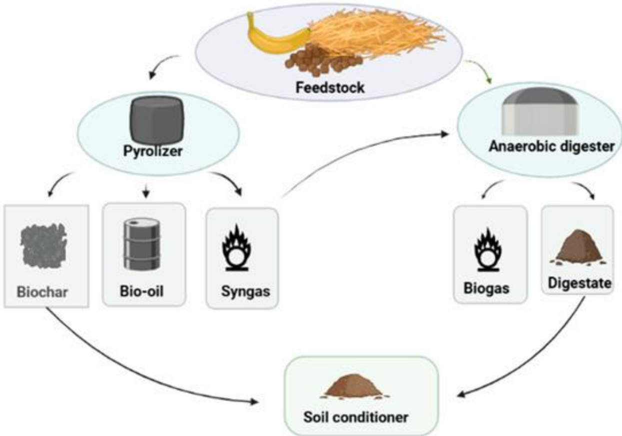

Figure 3: Synergistic relationship between pyrolysis and anaerobic digestion [10].

3. Mechanism of Biochar in Enhancing Anaerobic Digestion

3.1. Role of biochar in microbial activity

Improvement Biochar has gained attention for enhancing microbial activity in anaerobic digestion (AD). By integrating biochar, a conducive environment is created for beneficial microorganisms that break down organic matter. Its porous structure promotes the adhesion and colonization of diverse microbial consortia, improving biomass degradation efficiency [10]. This increase in microbial density can expedite methanogens, crucial for optimizing biogas production from organic waste. Additionally, biochar enhances electron transfer conditions in digesters, acting as a conductive medium that facilitates direct interspecies electron transfer (DIET) among microbial groups involved in digestion. This mechanism can significantly elevate methane production rates (Exploring the Potential of Biochar for Improving Anaerobic Digestion, 2025)[8]. Biochar also mitigates toxic compounds while maintaining favourable digester environments, supporting microbial health and activity.

The characteristics of biochar—such as its ability to buffer pH levels and its functional Groups are key in shaping microbial communities. By promoting certain functional microbes essential for volatile fatty acid (VFA) conversion, biochar helps sustain balanced microbial ecosystems during AD fluctuations [20]. Moreover, the variety of biochar from different feedstock materials influences metabolic pathways critical for effective methane production. In summary, incorporating biochar into AD systems effectively boosts biogas yields and fine-tunes microbial community dynamics, ensuring robust digestibility and resilience against disturbances.

3.2. Effects on nutrient availability for microbial growth

Biochar enhances nutrient availability for microbial proliferation during anaerobic digestion through various mechanisms. It acts as a stabilizing agent that optimizes the physical and chemical environments within the digester, crucial for fostering microbial activity. A key advantage of biochar is its capacity to retain moisture and essential nutrients such as nitrogen, phosphorus, and potassium, preventing their leaching and ensuring accessibility for microbes involved in biogas production. Additionally, biochar's porous structure increases its surface area, providing an ideal habitat for beneficial microbes. This characteristic facilitates microbial colonization and accelerates growth rates by enhancing interspecies electron transfer, vital for efficient interaction among microorganisms during anaerobic digestion. Biochar also helps mitigate the impact of inhibitory substances that could hinder microbial performance. Research indicates that incorporating biochar can elevate volatile fatty acids (VFAs) levels, important substrates for methanogenic microorganisms. Increased VFA concentrations invigorate microbial activity, enhancing biogas production efficiency (as elaborated in (Capone et al., 2023, page 6)[12]). Furthermore, biochar’s buffering capacity stabilizes pH levels in the digestate, reducing fluctuations that could negatively affect microbial communities [7]. In conclusion, integrating biochar into anaerobic digestion systems enhances nutrient availability and creates conditions favourable for microbial growth and activity, resulting in improved biogas yields and digestive stability.

4. Recent Studies on Biochar and Anaerobic Digestion

4.1. Overview of key research findings from Recent studies

Recent investigations highlight the significant role of biochar in enhancing anaerobic digestion (AD) processes. Incorporating biochar has shown notable increases in methane production, with some studies reporting biogas yield boosts of over 46% when using biochar from biogas residue compared to controls. These improvements are linked to mechanisms like increased microbial activity and reduced toxicity from inhibitors such as ammonia, which occur during organic waste digestion. Engineered biochar can effectively adsorb these inhibitors, promoting more stable AD [13].

Research also shows that biochar mitigates the negative effects of high ammonia levels and aids in digesting volatile fatty acids (VFAs), essential for methanogens. Various biochar types, derived from different feedstocks through pyrolysis and hydrothermal carbonization, exhibit distinct characteristics influencing their effectiveness in AD systems [3]. For example, biochar from rice husks enhances cumulative methane yields by 36.75% during mesophilic digestion, underscoring the benefits of selecting specific feedstocks for optimizing biogas production [18].

Evaluations have emphasized the economic viability and environmental benefits of using biochar in AD systems. Increased methane production aids energy recovery and reduces greenhouse gas emissions [9], while improving system efficiency and stability to address waste management and pollutant removal challenges [7]. The positive outcomes associated with biochar suggest its potential as an additive for sustainable waste management and renewable energy generation.

4.2. Comparison between sewage sludge and plant residue biochar effects on biogas production

The effects of sewage sludge biochar and plant residue biochar on biogas production show notable differences in anaerobic digestion processes. Sewage sludge biochar, particularly from biogas residues, significantly enhances methane output when combined with food waste, yielding up to 432.2 mL of methane per gram of volatile solids, surpassing coconut shell or corn Stover biochar [2]. This performance may be linked to its structural attributes and increased microbial activity, as it contains electroactive microorganisms that aid methanogens.

In contrast, the influence of plant residue biochar varies based on their properties and preparation methods. For instance, pine sawdust biochar can increase methane production by 41.6% when added to carbohydrate-rich food waste [19]. This is likely due to its ability to foster microbial colonization and adsorb inhibitors in the digestant. Research also suggests that different plant residue biochar can selectively impact microbial communities in anaerobic digesters, enriching populations of Methanosarcina while potentially suppressing Methanobacterium [24]. The varying outcomes highlight the need for further research comparing sewage sludge and plant-derived biochar under controlled conditions. Overall, both types contribute positively to biogas production, with efficiency depending on source material and characteristics.

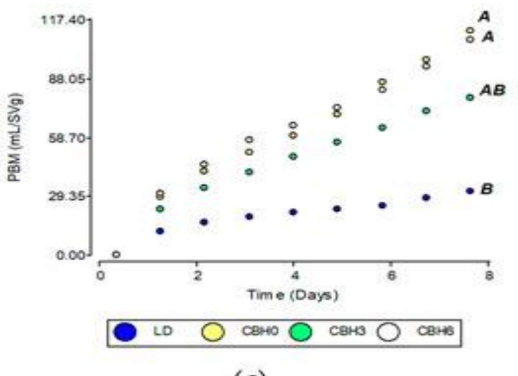

Figure 4: Effect of the PBM of biochar at different temperatures and three different concentrations (0 g/L, 3.33 g/L, and 6.67 g/L) on the anaerobic co-digestion of untreated sludge and leachate from municipal organic waste: (a) effect of BL biochar; (b) effect of BM biochar; (c) effect of BH biochar. (source: reference[22].

5. Benefits of Using Biochar in Anaerobic Digestion Process

5.1. Enhanced biogas yield compared to traditional methods

The integration of biochar into anaerobic digestion (AD) systems significantly enhances biogas production compared to conventional methods. Research shows that adding biochar creates a favourable environment for microbial populations essential for decomposing organic matter and generating methane. For example, biogas residue biochar resulted in a 46.2% increase in methane output, averaging 432.2 mL per gram of volatile solids per day [2].

Biochar boosts gas production through its porous structure, which enables microbial colonization and promotes methanogenic archaea crucial for biogas transformation [4]. It also enhances biochemical reactions by facilitating electron transfer, leading to faster degradation rates and higher quality methane (Exploring the Potential of Biochar for Improving Anaerobic Digestion, 2025)[8]. Additionally, biochar reduces hydrogen sulphide concentrations in biogas, improving emission cleanliness and overall system efficiency. Targeted studies have observed increased methane yields from food waste with various biochar types. For instance, pine sawdust biochar at 8.3 g/L improved methane production by 41.6% in aqueous carbohydrate food waste mixtures [19]. Similarly, rice husk biochar showed significant improvements in cumulative methane yields during mesophilic anaerobic digestion processes [18].

These findings underscore biochar's potential to enhance biogas generation and optimize waste management practices, reducing environmental impacts associated with traditional disposal methods.

5.2. Reduction in methane emissions during An aerobic digestion process

The use of biochar in anaerobic digestion methods has been found to significantly reduce methane emissions, a potent greenhouse gas that plays a major role in climate change. By enhancing microbial activity and creating a more favourable environment for methanogenic archaea, biochar facilitates a more efficient conversion of organic waste into methane. Research suggests that the addition of biochar improves the breakdown of volatile fatty acids (VFAs), which are crucial precursors for methane production. For example, studies indicate that certain types of biochar can alleviate acid inhibition and enhance the degradation of long-chain fatty acids, directly correlating with increased methane yields [15]. Additionally, the porous structure of biochar provides an improved habitat for microbes and supports interspecies electron transfer between syntrophic bacteria and methanogens, thus boosting the efficiency of methane production (according to [2]. This is important because maintaining a diverse microbial community is vital for optimal digestion performance. However, exceeding specific dosage limits can disrupt microbial activity due to toxicity from excessive alkali metals or disturbances within microbial networks [10].

Furthermore, using biogas residues as feedstock for biochar production fosters a circular economy within anaerobic digestion systems. Biochar derived from residues has demonstrated superior properties compared to other types, such as enhanced cation exchange capacity and better nutrient availability [1]. This recycling method not only reduces overall greenhouse gas emissions but also helps mitigate environmental pollution linked to waste disposal. Consequently, reducing methane emissions through improved anaerobic digestion supported by biochar presents a promising strategy for optimizing energy recovery from organic waste while tackling environmental management issues.

6. Challenges and Limitations in Using Biochar for Anaerobic Digestion

6.1. Variability in biochar properties depending on feedstock and pyrolysis conditions

The characteristics of biochar can fluctuate considerably depending on the selected feedstock and the pyrolysis conditions employed during its creation. This inconsistency results in varied physicochemical traits that can impact the effectiveness of anaerobic digestion (AD). For example, feedstocks such as agricultural byproducts, timber waste, and municipal refuse yield biochar with unique surface areas, porosities, and functional groups. These variations consequently affect microbial interactions and nutrient dynamics within the AD framework [23]. The temperature at which pyrolysis occurs is another vital element; elevated temperatures typically enhance the stability of biochar while lowering its volatile matter content, although they may also reduce surface area [15]. Different types of biochar display diverse adsorption capacities for nutrients and inhibitory substances, which can affect biogas production results. Studies demonstrate that certain biochars can boost methanogens by providing essential surfaces for microbial colonization or by promoting electron transfer among various microbial populations [16].

However, excessively high amounts of particular biochar can induce toxic effects due to their chemical makeup or high alkalinity levels, ultimately undermining the microbial diversity necessary for efficient digestion processes [10]. Additionally, pre-treatment strategies aimed at enhancing feedstock quality before pyrolysis can significantly shape the final properties of biochar. For instance, pre-processing sewage sludge prior to pyrolysis increases its adsorption capacity while diminishing harmful contaminants [23]. The challenge remains in standardizing biochar applications across different substrates and AD systems since each pairing may produce distinct outcomes depending on these variable factors.

6.2. Potential inhibitory effects on certain microbial communities

The integration of biochar into anaerobic digestion processes can lead to various inhibitory effects on specific microbial populations. While there are advantages to boosting biogas production, the presence of biochar may also pose obstacles that disrupt microbial dynamics. The varying physicochemical characteristics of biochar, influenced by the type of feedstock and pyrolysis conditions, can adversely affect the composition and functionality of microbial communities. For example, certain biochar might contain elevated levels of toxic substances or heavy metals, potentially hindering crucial microorganisms needed for efficient anaerobic digestion [11]. Furthermore, excessive application of biochar has been observed to prolong lag phases and diminish overall methane yields due to competition among microbial species. High concentrations of biochar can also increase the adsorption of volatile fatty acids and ammonia nitrogen—key components for methanogenic activity [18]. This situation could lead to a scenario where beneficial microorganisms are outmatched or inhibited by those that flourish in the altered conditions brought about by the inclusion of biochar.

An additional consideration is the potential shifts in interspecies electron transfer dynamics instigated by different types of biochar. While some research indicates that specific biochar can enhance direct interspecies electron transfer (DIET) among microbes [2], other findings suggest that certain varieties may fail to facilitate the necessary interactions between methanogens and fermentative bacteria effectively.

Therefore, although incorporating biochar into anaerobic digestion systems offers promising prospects for enhancing biogas production, it is essential to thoughtfully assess both the selection and quantity of biochar utilized to prevent detrimental effects on microbial communities that are fundamentally important to the digestion process.

7. Recommendations for Future Research Directions

7.1. Need for standardized testing protocols for biochar applications in anaerobic digestion

The incorporation of biochar into anaerobic digestion processes has garnered significant interest due to its potential advantages; however, the lack of standardized testing protocols presents a considerable obstacle to its wider application. Currently, the effectiveness of biochar in enhancing anaerobic digestion is influenced by several factors, including the feedstock used for its production and the specific pyrolysis conditions experienced. [10], variations in these parameters can result in inconsistent outcomes regarding methane generation and overall system stability. Without a unified framework for testing and assessing biochar, drawing reliable conclusions about its efficacy across different scenarios becomes quite challenging. To address this issue, there is an urgent need to develop standardized methodologies that can reliably evaluate the properties and effects of biochar within anaerobic digestion contexts. Such protocols would enable comparative research and allow scientists to identify optimal conditions for various types of biochar. Moreover, as highlighted in [7], it is vital to understand how distinct characteristics—such as particle size, surface area, and functional groups—affect microbial activity and biogas production. Standardized assessments could also include factors such as nutrient release profiles or inhibitory impacts on microbial populations. Furthermore, establishing uniform testing protocols may also clarify the mechanistic pathways through which biochar influences outcomes in anaerobic digestion. For example, investigating how biochar improves buffering capacity or facilitates direct interspecies electron transfer could provide insights into strategies for increasing biogas yields [9].

In conclusion, the creation of standardized testing processes is essential not only for advancing academic research but also for promoting practical applications of biochar in anaerobic digestion systems.

7.2. Exploration of alternative feedstocks for biochar production tailored to specific waste types

Investigating alternative feedstocks for biochar generation is essential for enhancing anaerobic digestion efficiency. Diverse organic materials like agricultural by-products, food scraps, and wastewater sludge can be converted into biochar, each contributing unique properties. The temperature and conditions during pyrolysis significantly influence the biochar's characteristics, affecting its performance in anaerobic digestion [10]. Engineered biochar can specifically target inhibitors present in various organic waste streams. By modifying the surface functional groups of biochar, their ability to adsorb substances like ammonia or limonene compounds that hinder microbial activity can be improved [13]. This approach not only increases biogas production rates but also reduces lag phases typically associated with these processes.

Using waste materials such as used coffee grounds or citrus peels broadens the range of feedstock while addressing waste disposal challenges [16]. Optimizing pyrolysis conditions for these sources can yield biochar that enhances methane output and mitigates operational difficulties common with conventional substrates.

Additionally, analysing different biochars from various feedstocks reveals their distinct impacts on microbial ecosystems within digesters. Understanding these effects is vital for selecting the most suitable biochar for specific organic waste compositions [3]. This relationship between biochar attributes and feedstock varieties fosters greater process efficacy and promotes sustainable practices in organic waste management.

8. Practical Applications and Implications for Waste Management Policies

8.1. Integration of biochar use into municipal solid waste management strategies

Incorporating biochar into municipal solid waste management enhances both efficiency and sustainability. Utilizing biochar from organic waste helps local governments address environmental issues linked to landfills and greenhouse gas emissions. Evidence shows that integrating biochar in anaerobic digestion boosts microbial activity, leading to increased biogas production [8]. Biochar also aids in nutrient recycling and pollutant reduction, improving the quality of digestate and creating valuable outputs like organic fertilizers and soil amendments for agriculture [5]. This circular economy approach not only promotes sustainable farming but also reduces food waste through better resource recovery and waste management. Moreover, municipalities incorporating biochar may experience lower operational costs for waste treatment facilities. Producing biochar from digestate using renewable energy, such as methane combustion in biogas plants, ensures consistent product quality while keeping expenses down [9].

However, successful integration of biochar requires careful planning regarding feedstock selection and compliance with regulatory standards. Municipalities must establish guidelines for biochar production techniques and evaluate their environmental impact, considering how different feedstocks affect biochar properties and performance in anaerobic digestion [16]. With thoughtful implementation, biochar can effectively enhance solid waste management strategies and support sustainability goals.

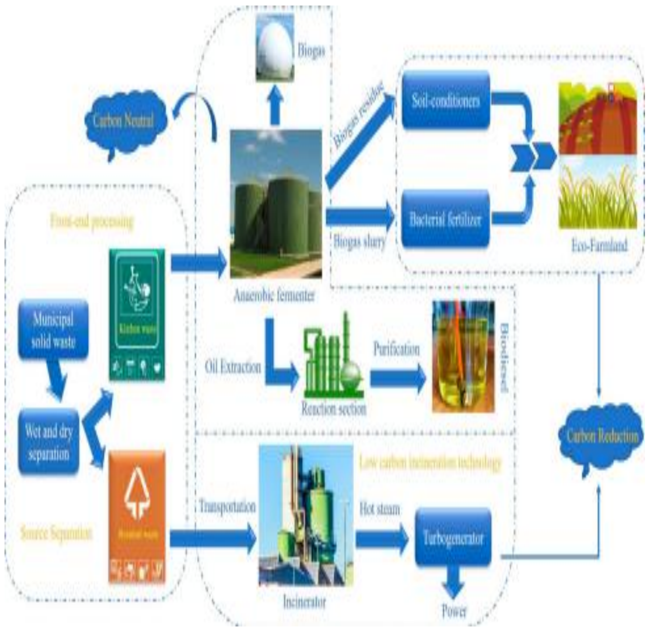

Figure 5: Optimization of the energy supply chain layout for anaerobic digestion of kitchen waste based on source separation and carbon reduction [5].

8.2. Potential economic benefits for local communities through biogas production

The generation of biogas through anaerobic digestion offers significant financial benefits for local communities. By converting organic waste into biogas, communities can reduce waste management issues and promote renewable energy production. Utilizing materials like kitchen scraps and agricultural byproducts decreases landfill dependency while lowering waste disposal costs. The versatile biogas can generate electricity, provide heating, or be refined into bio methane for transportation or integration into the natural gas system. Local biogas facilities also foster job growth in various sectors, from construction to operation. As noted in [6], biogas initiatives have positively influenced employment in countries such as Germany by broadening job opportunities associated with organic waste management. In addition to economic advantages, biogas production contributes to environmental sustainability by reducing greenhouse gas emissions linked to traditional waste disposal. Communities adopting anaerobic digestion can achieve smaller carbon footprints and improved air quality by decreasing methane emissions released from organic material breakdown in landfills. Incorporating biochar with anaerobic digestion enhances methane output and process efficiency [9]. This synergy optimizes resource recovery, aligning with circular economy principles. Ultimately, investing in biogas systems addresses waste management challenges while empowering local economies and promoting sustainable development for current and future generations.

Table 1:Energy conservation and emissionreduction capabilities[6]

Treatments	1 L Biogas Production (mL/g VS)	1 t Biogas Production (m^3)	Biogas CO_2 Emissions (t)	Standard Coal (kg)	Coal CO_2 Emissions (t)	Emission Reductions (kg)
Blank	77.60	46.98	54.65	33.54	63.78	9.12
Humus composites 5 g/L	116.88	70.76	82.32	50.52	96.06	13.74
Humus composites 10 g/L	53.72	32.52	37.83	23.22	44.15	6.32

9. Conclusion

9.1. Summary of key findings on the role of different biochars in enhancing biogas production from kitchen waste

Incorporating various biochar types into anaerobic digestion (AD) processes significantly enhances biogas yields from kitchen waste. Research indicates that biochar improves methane production by promoting microbial activity, stabilizing pH levels, and enhancing nutrient availability. For example, rice husk biochar (RHB550) can increase methane output by up to 36.75% compared to control samples, aiding in volatile fatty acid oxidation and process stability [18]. The feedstock used for biochar production is crucial in determining its properties and effects on AD efficiency. Biochar from fruitwood paralyzed at 550°C led to a 69% increase in methane yield during chicken manure digestion [16]. This highlights how variations in pyrolysis conditions and feedstock type can create tailored biochar for optimal biogas production. Co-digestion practices, which combine kitchen waste with complementary substrates, further enhance biogas production. The interaction between different biochars and co-substrates improves buffering capacity, reducing ammonia's inhibitory effects and increasing microbial efficiency. For instance, thermophilic conditions with biogas residue biochar yielded approximately 46.2% more methane daily than inert materials [2].

Overall, utilizing diverse biochar types not only boosts methane yields but also aids in nutrient management and pH stability during anaerobic digestion, maximizing biogas output from kitchen waste.

9.2. Final thoughts on sustainable waste management practices through anaerobic digestion with biochar use

The infusion of biochar into anaerobic digestion represents a significant advancement in sustainable waste management. By utilizing biochar from organic refuse like kitchen scraps, biogas output can be increased while addressing environmental issues related to organic waste disposal. Biochar enhances microbial activity and promotes interactions among diverse microbial populations, which boosts methane yields [1], [22].

This approach aligns with circular economy principles, turning waste into valuable resources for energy generation and soil improvement. Creating biochar from biogas residue supports recycling and reduces pollution linked to untreated organic materials. The unique properties of biochar, such as its porous structure and adsorption capabilities, significantly enhance the efficiency of anaerobic digestion [21].

Moreover, increased biogas production can lower greenhouse gas emissions compared to traditional waste management practices [4]. The nutrient availability from biogas slurry benefits agricultural efforts, fostering an ecosystem that minimizes waste and optimizes resources. This strategy also encourages community engagement through local energy initiatives and offers economic benefits by reducing dependence on fossil fuels. Future research should focus on refining feedstock selection and pyrolysis parameters to maximize biochar's advantages and ensure compatibility with various organic substrates [3], [9]. Biochar-enhanced anaerobic digestion could play a vital role in sustainable waste management.

References

[1] H. Liu, X. Wang, Y. Fang, W. Lai, S. Xu, and E. Lichtfouse, “Enhancing thermophilic anaerobic co-digestion of sewage sludge and food waste with biogas residue biochar,” *Renew. Energy*, vol. 188, pp. 465–475, 2022.

[2] Q. Meng, H. Liu, H. Zhang, S. Xu, E. Lichtfouse, and Y. Yun, “Anaerobic digestion and recycling of kitchen waste: a review,” *Environ. Chem. Lett.*, vol. 20, no. 3, pp. 1745–1762, June 2022, doi: 10.1007/s10311-022-01408-x.

[3] K. Zhao, Q. Wei, M. Bai, and M. Shen, “Study on the Environmental Impact and Benefits of Incorporating Humus Composites in Anaerobic Co-Digestion Treatment,” *Toxics*, vol. 12, no. 5, p. 360, 2024.

[4] S. Taylor, “Anaerobic Digestion at Western Washington University,” 2023, Accessed: Sept. 07, 2025. [Online]. Available: https://cedar.wwu.edu/wwu_honors/664/

[5] Mariappan I. *et al.*, “Exploring Cutting-Edge Approaches in Anaerobic Digestion and Anaerobic Digestate Management,” *ChemBioEng Rev.*, vol. 11, no. 3, pp. 573–594, June 2024, doi: 10.1002/cben.202300063.

[6] D. Ovi *et al.*, “Effect of rice husk and palm tree-based biochar addition on the anaerobic digestion of food waste/sludge,” *Fuel*, vol. 315, p. 123188, 2022.

[7] Z.-F. Wu *et al.*, “Effects of biochars derived from different feedstocks and pyrolysis temperatures on the anaerobic digestion of kitchen waste,” *Renew. Energy*, vol. 230, p. 120833, 2024.

[8] A. K. Thakur, “Effect of sludge biochar as an additive in thermophilic anaerobic digestion,” 2024, Accessed: Aug. 29, 2025. [Online]. Available: https://odr.chalmers.se/bitstreams/088e0544-6013-4f74-a4d4-2a24fa5fea7d/download

[9] M. Manga, C. Aragón-Briceño, P. Boutikos, S. Semiyaga, O. Olabinjo, and C. C. Muoghalu, “Biochar and its potential application for the improvement of the anaerobic digestion process: a critical review,” *Energies*, vol. 16, no. 10, p. 4051, 2023.

[10] W. Zhao, H. Yang, S. He, Q. Zhao, and L. Wei, “A review of biochar in anaerobic digestion to improve biogas production: performances, mechanisms and economic assessments,” *Bioresour. Technol.*, vol. 341, p. 125797, 2021.

[11] H. Bandara and S. Janaranjana, “Exploring the Potential of Biochar in Enhancing U.S. Agriculture,” *Reg. Sci. Environ. Econ.*, vol. 2, no. 3, p. 23, Sept. 2025, doi: 10.3390/rsee2030023.

[12] A. Capone, S. Borowski, E. Sobolewska, L. Zaccariello, and B. Morrone, “Biochar and Hydrochar Impact on the Anaerobic Digestion Process of Sewage Sludge,” *Chem. Eng. Trans.*, vol. 109, pp. 259–264, 2024.

[13] L. Chen *et al.*, “Biochar application in anaerobic digestion: Performances, mechanisms, environmental assessment and circular economy,” *Resour. Conserv. Recycl.*, vol. 188, p. 106720, 2023.

[14] M. Rowan *et al.*, “Anaerobic co-digestion of food waste and agricultural residues: An overview of feedstock properties and the impact of biochar addition,” *Digit. Chem. Eng.*, vol. 4, p. 100046, 2022.

[15] J. Mumme, F. Srocke, K. Heeg, and M. Werner, “Use of biochars in anaerobic digestion,” *Bioresour. Technol.*, vol. 164, pp. 189–197, 2014.

[16] C. W. Wambugu, E. R. Rene, J. Van de Vossenberg, C. Dupont, and E. D. Van

Hullebusch, "Role of biochar in anaerobic digestion based biorefinery for food waste," *Front. Energy Res.*, vol. 7, p. 14, 2019.

[17] M. Zhang, J. Li, Y. Wang, and C. Yang, "Impacts of different biochar types on the anaerobic digestion of sewage sludge," *RSC Adv.*, vol. 9, no. 72, pp. 42375–42386, 2019.

[18] W. G. Wang GaoJun, L. Q. Li Qian, M. Dzakpasu, G. X. Gao Xin, Y. C. Yuwen ChaoSui, and X. C. Wang, "Impacts of different biochar types on hydrogen production promotion during fermentative co-digestion of food wastes and dewatered sewage sludge.," 2018, Accessed: Aug. 29, 2025. [Online]. Available: https://www.cabidigitallibrary.org/doi/full/10.5555/20193003963

[19] A. Ahmad *et al.*, "Effect of sewage sludge biochar on the soil nutrient, microbial abundance, and plant biomass: A sustainable approach towards mitigation of solid waste," *Chemosphere*, vol. 287, p. 132112, 2022.

[20] J. Pan, J. Ma, X. Liu, L. Zhai, X. Ouyang, and H. Liu, "Effects of different types of biochar on the anaerobic digestion of chicken manure," *Bioresour. Technol.*, vol. 275, pp. 258–265, 2019.

[21] P. Devi and C. Eskicioglu, "Effects of biochar on anaerobic digestion: a review," *Environ. Chem. Lett.*, vol. 22, no. 6, pp. 2845–2886, Dec. 2024, doi: 10.1007/s10311-024-01766-8.

[22] W. Zhao, H. Yang, S. He, Q. Zhao, and L. Wei, "A review of biochar in anaerobic digestion to improve biogas production: performances, mechanisms and economic assessments," *Bioresour. Technol.*, vol. 341, p. 125797, 2021.

[23] J. Pan, J. Ma, X. Liu, L. Zhai, X. Ouyang, and H. Liu, "Effects of different types of biochar on the anaerobic digestion of chicken manure," *Bioresour. Technol.*, vol. 275, pp. 258–265, 2019.

[24] J. Ramírez, E. Deago, and A. M. C. James Rivas, "Effect of biochar on anaerobic co-digestion of untreated sewage sludge with municipal organic waste under mesophilic conditions," *Energies*, vol. 17, no. 10, p. 2393, 2024.

[25] M. A. Rahman, R. Shahazi, S. N. B. Nova, M. R. Uddin, M. S. Hossain, and A. Yousuf, "Biogas production from anaerobic co-digestion using kitchen waste and poultry manure as substrate—part 1: substrate ratio and effect of temperature," *Biomass Convers. Biorefinery*, vol. 13, no. 8, pp. 6635–6645, June 2023, doi: 10.1007/s13399-021-01604-9.