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Kudzai Mutisi, Baraka Celestin Sempuga & Mabatho Moreroa

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A review of current practices and the feasibility of anaerobic digestion of biochar infused abattoir effluent

Kudzai Mutisi¹ (50135082@mylife.unisa.ac.za), Baraka Celestin Sempuga¹ (sempubc@unisa.ac.za), Mabatho Moreroa^{1*} (emorerm@unisa.ac.za)

¹ Institute for Catalysis and Energy Solutions, College of Science Engineering and Technology, University of South Africa, Florida Park, Roodepoort, South Africa.

*Corresponding author

Abstract

Anaerobic digestion (AD) of abattoir effluents offers a sustainable method for treating high-strength wastewater, simultaneously generating biogas and organic fertilisers. However, inhibitors such as ammonia, long-chain fatty acids, and volatile fatty acids often disrupt process stability and limit biogas production. Biochar, a carbon-dense byproduct of biomass pyrolysis, has proven to be an efficacious additive in addressing these issues by adsorbing inhibitory substances, regulating pH, enhancing microbe adhesion, and fostering direct interspecies electron transfer. This paper consolidates contemporary insights on the AD of abattoir effluent, the processes of biochar's influence in AD systems, and the effects of feedstock type, pyrolysis parameters, and reactor design on system performance. The review emphasises the potential of biochar as an addition to the AD in abattoir effluents, which are noted for their elevated protein and fat content. We analyse technological, economic, and environmental factors; identify research deficiencies concerning standardisation, long-term impacts, and scalable implementation; and suggest future pathways to enhance biochar-assisted AD in abattoir wastewater. The review highlights biochar's contributions to improving biogas production, stabilising microbial populations, and promoting circular economic goals.

Keywords: biogas, sustainable development goals, waste management, resource recovery.

1. Introduction

The ever-increasing consumption of meat, coupled with rapid urbanisation and increased population densities, has led to the widespread establishment of abattoirs (also known as slaughterhouses), especially in urban and peri urban areas. For instance, in India, there are more than 1000 large-scale abattoirs that produce large quantities of effluent (also known as wastewater) with a devastating impact on the environment if not managed well (Aziz et al., 2022). In Australia, large-scale abattoirs produce more than 1000 m³ of wastewater per day (Gautam et al., 2024). The process of turning biowaste into renewable energy is gaining momentum worldwide as a sustainable way to manage waste from human populations and meet the energy needs of modern economies (Mudzanani et al., 2022). The anaerobic digestion (AD) of organic waste, like wastewater from abattoirs, offers a way to manage waste sustainably while also producing biogas and organic fertilisers. Abattoir effluents contain proteins, fats, and carbohydrates and hence have significant biogas production potential due to the high organic

content (Ahmad, 2024). However, challenges such as ammonia (NH_3) toxicity, the production of long-chain fatty acids (LCFAs), and the production of volatile fatty acids (VFA) can inhibit and destabilise the AD process, thereby reducing methane (CH_4) yields (Atchala et al., 2025). Biochar, a carbon-rich material obtained from the pyrolysis of biomass, has emerged as a promising additive to enhance biogas production (Zeynali et al., 2024). Biochar has a porous structure, offers excellent adsorbent potential for inhibitory substances, and promotes microbial growth (Khoei et al., 2021).

The environmental burden posed by untreated abattoir effluents extends far beyond a localised nuisance; it manifests as a severe ecological and public health threat. Discharge of these protein- and lipid-rich waste streams generates noxious odours and attracts disease vectors like flies, worsening sanitation problems for nearby communities (Gutu et al., 2021; Kothari et al., 2024). In aquatic ecosystems, abattoir effluents promote massive eutrophication, depleting dissolved oxygen and triggering algal blooms that suffocate aquatic life (Nandomah & Tetteh, 2023; Ragasri & Sabumon, 2023). Conventional AD systems, touted as sustainable solutions for energy recovery, often fail to cope with the complex inhibitory profile of abattoir wastewater. This results in chronic process instability, suboptimal CH_4 yields, and persistent non-compliance with environmental discharge standards (Atchala et al., 2025; Bingo et al., 2021).

Despite biochar's demonstrated benefits, critical knowledge gaps prevent its standardised application in some AD systems. First, the variability in biochar's physicochemical properties emanating from variability in feedstock and pyrolysis conditions complicates performance predictability across substrates (Wu et al., 2022; Huang et al., 2023). For instance, high-temperature biochar ($>700^\circ\text{C}$) may reduce CH_4 yields due to high inert carbon content, while low-temperature variants ($<500^\circ\text{C}$) excel in adsorption but lack conductivity (Chen et al., 2022). Second, optimal dosages remain context-specific, with overdosing (>8 g/L) risking system inhibition through reduced reactor volume or toxic compound release (Feng et al., 2025). Third, long-term impacts, such as biochar's inert accumulation in digestate and its effects on soil ecosystems post-application, require rigorous lifecycle assessments (Huang et al., 2023; Afshar & Mofetta, 2024). Finally, economic barriers, including high production costs and fragmented supply chains, highlight the need to develop scalable, cost-effective models that integrate decentralised biochar production with existing waste management infrastructure (Campion et al., 2023).

The core challenge lies in the biochemical composition of abattoir effluent. NH_3 originating from rapid protein degradation (exceeding 1,400 mg/L in some effluents) directly inhibits methanogens by disrupting intracellular pH and enzymatic functions essential for CH_4 synthesis (Rajagopal, 2025; Khoei et al., 2021). During AD of abattoir effluents, by-products of lipid hydrolysis such as VFAs and LCFAs accumulate to saturating levels, thus overwhelming conventional AD systems and causing acute digester acidification and process collapse (Elsamadony et al., 2021; Liu et al., 2021). The impact of these primary inhibitors is compounded by on-farm contaminants that include residual antibiotics,

disinfectants, heavy metals, and high-salinity effluents from cleaning processes (Ibigbami et al., 2023; Kothari et al., 2024).

Even though biochar showed promise for enhancing the AD of various substrates, there are knowledge gaps regarding its application in abattoir wastewater. First, although biochar can adsorb complex mixtures such as LCFAs and antibiotics and even promote DIET under NH_3 stress, its effectiveness in lipid- and protein-rich abattoir wastewater has not yet been explored (Ma et al., 2023). Second, the optimal biochar dosage for the AD of abattoir wastewater remains unknown and difficult to determine due to the wide variation in the composition abattoir effluents (pH 5–8.9, COD 1,100–20,000 mg/L) that influences cost-efficiency and process performance (Ragasri & Sabumon, 2023). Lastly, there is a lack of techno-economic models for large-scale implementation of biochar in AD projects.

Traditional AD, while theoretically sustainable, usually fails due to the biochemical assault unique to abattoir effluents. The wastewater's high protein and lipid content triggers self-sabotaging inhibition due to NH_3 toxicity disrupting methanogen metabolism (Rajagopal, 2025), LCFAs forming impermeable layers that block mass transfer and induce acidification (Elsamadony et al., 2021), and VFAs accumulating to reduce pH below 6.0 (Liu et al., 2022). Abattoir effluents also contain inhibitory on-farm contaminants such as antibiotics, disinfectants, and heavy metals that persist through treatment (Kothari et al., 2024). Consequently, most digesters operate below their CH_4 potential and produce effluent that fails to meet discharge regulations (Aziz et al., 2022).

Recent studies have indicated that biochar can adsorb NH_3 , immobilise inhibitory chemicals, facilitate DIET, and support vital methanogens such as *Methanobacterium* (Khoei et al., 2021; Batta et al., 2023). Nevertheless, significant research deficiencies impede its extensive application as an addition in the AD of abattoir effluents. There are knowledge gaps about biochar's efficacy under elevated NH_3 stress (Tripathi et al., 2025). The appropriate biochar dosage for abattoir effluents remains indeterminate due to significant variability in both composition and quantity, possibly making it context specific. Additionally, scalability obstacles emerge from fragmented supply chains and the lack of comprehensive techno-economic models (Campion et al., 2023). This evaluation will be crucial in advancing the attainment of Sustainable Development Goals (SDGs) 6 (clean water and sanitation), 7 (affordable and clean energy), 11 (sustainable communities), and 13 (climate action) (United Nations, 2025). This synthesis is both an intellectual need and an environmental obligation. The objective of this review is to objectively assess the capacity of biochar to improve the stability and efficiency of AD systems that process protein- and lipid-rich slaughterhouse effluents, focusing on performance mechanisms, operational optimisation, and scalability.

2. Methodology

This review used a structured narrative synthesis to summarise evidence on prospects for biochar-assisted AD for abattoir wastewater and other comparable high-protein/high-lipid substrates. A targeted literature search was conducted in major scholarly databases (Springer Nature, ScienceDirect, ResearchGate, and Google Scholar) using combinations of keywords related to abattoir/slaughterhouse wastewater, AD/biogas/CH₄, and biochar/carbonaceous additives/DIET/inhibition. Reference lists of key articles were also screened to identify additional studies.

Studies were included if they were recent (from 2019 onwards) and reported AD performance outcomes with biochar amendments (CH₄ content, biogas yields, and stability indicators such as pH, VFAs, alkalinity, or NH₃) and described biochar production conditions and properties sufficiently for interpretation. Studies without primary data, without clear methods, or not relevant to AD were excluded.

Data were extracted on substrate characteristics, reactor configuration and operating conditions (temperature, organic loading rate, retention time), biochar feedstock and pyrolysis conditions, biochar dose, and key outcomes (CH₄/biogas, inhibition mitigation, and microbial or mechanistic evidence). Due to high methodological and reporting heterogeneity across studies, findings were synthesised qualitatively (not meta-analysed) and organised by recurring themes: inhibition control (NH₃, VFAs, and LCFAs), process stability, electron transfer effects, and scale-up/techno-economic implications.

3. Challenges and opportunities of anaerobic digesters of abattoir effluents

3.1 Challenges posed by abattoir effluents

Abattoirs produce wastewater that varies in composition from one abattoir to another. Each abattoir experiences substantial time-based fluctuations in both the composition and quantity of wastewater, making it difficult to standardise treatment and management (Kothari et al., 2024). The general characteristics of some abattoir effluents are summarised in Table 1.

Table 1: General characteristics of some abattoir effluents (Ragasri & Sabumon, 2023)

Parameters	Pig wastewater	Cattle wastewater	Rendering wastewater
pH	7.2-8.9	5-7.8	-
COD (mg/L)	7963-20000	1100-15000	4000-15000
BOD (mg/L)	200-2055	600-3900	4000-10000
TN (mg/L)	340-1434	50-840	500-1700
TKN (mg/L)	-	40-700	-

BOD: Biological oxygen demand; COD: Chemical oxygen demand; TKN: Total Kjeldahl Nitrogen; TN: Total nitrogen.

Abattoir effluents pose challenges because of their complex composition. Generally, abattoir effluents contain oils and fats, proteins, fibres, blood, pathogenic microorganisms, meat extracts, rumen content, nutrients, detergents, pharmaceuticals, and heavy metals (Ibigbami et al., 2023, Nandomah & Tetteh, 2023). The discharge of untreated abattoir waste into water bodies creates serious public health and environmental risks (Nandomah & Tetteh, 2023; Kothari et al., 2024). Worldwide, local and national governments impose strict regulations on the discharge of abattoir effluents (Gutu et al., 2021). AD is one of the most effective methods used to treat abattoir effluents to meet the regulatory standards before discharge into the environment (Kothari et al., 2024), because if left untreated, abattoir effluents are a real threat to both modern living standards and the preservation of the natural environment. Abattoir wastewater, when discharged into water bodies, promotes algal growth and eutrophication, ultimately leading to the deaths of aquatic species (Gutu et al., 2021). The AD of abattoir effluents does not only provide much-needed biogas, but it simultaneously serves as an effective environmental conservation strategy (Bingo et al., 2021).

Harnessing the biogas potential of abattoir effluents involves overcoming several biochemical and operational challenges associated with their composition, particularly the inhibitory effects of NH_3 , VFAs, and LFCAs (Atchala et al., 2025). Abattoir effluents are rich in proteins, which, during AD, are broken down into amino acids and subsequently degraded into NH_3 (Soja et al., 2023). At low concentrations, NH_3 serves as a nitrogen source for microbial growth, but it becomes toxic and inhibitory at higher levels. Excessive NH_3 interferes with methanogenic microorganisms by changing intracellular pH and disrupting enzymatic functions necessary for CH_4 production (Khoei et al., 2021). The inhibitory effect of NH_3 can destabilise the AD process, leading to reduced CH_4 yields and, in severe cases, digester failure (Hanum et al., 2022; Ihoeghian et al., 2023). Striking a balance between maintaining NH_3 levels conducive for microbial activity and avoiding inhibition is an enormous challenge when treating protein-rich substances such as abattoir effluents (Rajagopal, 2025).

The fats in abattoir wastewater are responsible for creating and promoting an inhibitory environment during the AD process. Fats are hydrolysed into VFAs (carboxylic acids containing 2 to 8 carbon atoms), which can inhibit microbial activity during the AD process (Batta et al., 2023). The accumulation of VFAs during AD triggers a marked drop in pH, thus creating a hostile environment for methanogens and methanogenesis (Cao et al., 2025). The optimum pH for methanogenesis ranges from 6.6 to 7.8 (Fu et al., 2021).

Besides VFAs, LFCAs formed during the hydrolysis of lipids in abattoir effluents strongly inhibit the AD process (Wenjing et al., 2022). LCFAs form layers that impede mass transfer, reduce microbial contact with substrates, and can physically clog the system, leading to a reduction in digester efficiency or even total failure (Elsamadony et al., 2021). The management of LCFAs is, therefore,

vital for sustaining stable operation in digesters processing substrates with high fat, oil, and grease levels (Liu et al., 2021).

3.2 Opportunities

Although the AD of abattoir effluents presents biochemical challenges, their high organic content offers attractive opportunities for biogas production (Atchala et al., 2025). The elevated COD and BOD levels of abattoir wastewater make it an energy-rich feedstock for biogas reactors, with the potential to produce significant quantities of biogas under favourable conditions (Gutu et al., 2021). Biogas, a homogeneous mixture primarily composed of CH₄ and carbon dioxide, is a renewable energy source that can reduce reliance on fossil fuels and support the achievement of the United Nations SDGs 6, 7, 11, and 13 (Gustafsson et al., 2022; Kabeyi & Olanrewaju, 2022). Moreover, the AD of abattoir wastewater aligns with the principles of a circular economy by converting waste into energy and a nutrient-rich digestate (Havukainen & Dace, 2023).

The organic richness of abattoir effluents manifests as high levels of COD and BOD, indicating their suitability as a feedstock for AD (Gutu et al., 2021). A study by Aziz et al. (2022) demonstrated the high potential of abattoir effluents as feedstock for biogas production. The researchers achieved an average biogas production of 17.3 L/day with CH₄ content exceeding 70% at an organic loading rate of 7.8–9.8 kg COD/m³d⁻¹. Their techno-economic analysis concluded that potential electricity savings from this production were 52%. Therefore, abattoirs can significantly reduce their energy costs, generate income by selling digestate, and promote a sustainable circular economy by exploiting the biogas potential of abattoir wastewater (Habchi et al., 2024).

4. Current practices in anaerobic digestion of abattoir wastewater

The complex composition and elevated risk of inhibition in the AD of abattoir effluents have spurred the development of numerous advanced methods and strategies to enhance the efficiency of abattoir wastewater treatment (Atchala et al., 2025). Gutu et al. (2021) recommended a multi-integrated systems approach to the AD of abattoir effluents to address the process inhibition caused by temperature fluctuations, pH fluctuations, and the accumulation of VFAs. Bingo et al. (2021) evaluated the effectiveness of an integrated multi-stage system for the treatment of poultry abattoir wastewater. They suggested the use of aerobic treatment as a post-treatment method for AD effluent.

A study by Tong et al. (2023) employed the upgraded anaerobic–aerobic abattoir wastewater treatment process with a supernatant recycle ratio of 300% to the second aerobic compartment at a dissolved oxygen concentration of 4.64–4.90 mg L⁻¹. This process managed to maintain COD removal efficiencies between 95.94% and 98.14% as the organic loading rate increased from 500 to 2 000 g COD m⁻³ d⁻¹. Most importantly, it achieved its minimum effluent total nitrogen concentration at 1 500 g COD m⁻³ d⁻¹, all within the limits set by China's discharge standards. The combined anaerobic–aerobic batch reactor system treating

abattoir wastewater first achieved 25% BOD, 62% COD, 42% TKN and 9% phosphate removal over 30 days of anaerobic operation, which then improved to 94% BOD, 69% COD and 93% TKN removal following the aerobic stage. Even though phosphate removal remained variable, the study demonstrated the enhanced efficacy of adding an aerobic post-treatment stage (Nassar et al., 2022). A study by Liu et al. (2022) concluded that the combined anaerobic-aerobic treatment of abattoir wastewater could easily achieve energy self-sufficiency.

The main challenge of using abattoir effluents as feedstock for AD stems from the high protein content and a very high concentration of VFAs, which limits the biogas yield (Soja et al., 2023). To optimise the AD of abattoir wastewater, other researchers like Agabo-García et al. (2022) suggested co-digestion as a viable solution. Agabo-García et al. (2022) concluded that the co-digestion of abattoir wastewater with other substrates, such as activated sludge, can dilute inhibitory compounds, thus increasing biogas production. The co-digestion of abattoir wastewater with sugar press mud, for instance, achieves a high CH₄ yield, increases COD and BOD removal, and reinforces process stability (Anyango et al., 2022). Another study by Bist et al. (2024) concluded that the co-digestion of poultry slaughterhouse waste (SHW) with chicken litter (CL) significantly enhances biogas yield and waste stabilisation, with optimal performance observed at SHW:CL ratios between 1:1 and 1:4.

Pretreatment methods, such as thermal or chemical processes, can break down complex fats and proteins into more digestible forms. The overall aim of pre-treating abattoir effluents is to reduce the risk of inhibition (Atchala et al., 2025). Advanced reactor designs, including phased digestion systems or reactors equipped with NH₃-stripping units, can also enhance the robustness and efficiency of the AD process (Gutu et al., 2021; Ning et al., 2023).

The use of additives to enhance the AD of abattoir wastewater is an entrenched contemporary practice. An investigation by Thakur et al. (2023) revealed that applying abiotic stress factors such as salinity, micro aeration, micronutrients, and antibiotics can significantly enhance biowaste digestibility and CH₄ production in AD, but further research is needed to optimise and understand their combined effects. Bioaugmentation through the addition of microbial consortia to AD systems is an effective strategy in reducing NH₃ inhibition during the digestion of abattoir wastewater (Wang et al., 2023).

Table 2: Summary of the technologies explored by different researchers for AD of abattoir effluent

Substrate	Key Finding	Technology Explored	Reference
Abattoir effluent	COD removal efficiency of 95.94% to 98.14%	Upgraded anaerobic-aerobic digestion	Tong et al. (2023)
Abattoir effluent	Treated effluent is most likely to	Multi-integrated systems to mitigate	Gutu et al. (2021)

	meet discharge standards.	temperature, pH and VFA fluctuations	
Poultry abattoir wastewater	98% COD removal efficiency	Integrated multi-stage treatment system.	Bingo et al. (2021)
Abattoir wastewater	Energy self-sufficiency achieved.	Combined anaerobic-aerobic treatment.	Liu et al. (2022)
Abattoir wastewater co-digested with sludge	Biomethane production of 0.3 L/g COD _{t_{initial}}	Co-digestion with agricultural residues or municipal organic waste.	Agabo-García et al. (2022)
Abattoir wastewater + sugar press mud	59% increase in methane yield compared to control.	Co-digestion with sugar press mud; improved COD/BOD removal and stability.	Anyango et al. (2022)
Abattoir effluents	Biogas production increased by 24% compared with the control.	Thermal or chemical pretreatment prior to digestion.	Atchala et al. (2025)
Abattoir effluent	Antibiotic augmentation increased biomethane yield by 46%.	Applied abiotic stress factors to increase digestibility of biowaste.	Thakur et al. (2023)
Abattoir effluent	A syntrophic microbial consortium restored AD performance in 21 days.	Bioaugmentation with tailored microbial consortia.	Wang et al. (2023)

5. Biochar: Production, environmental impacts, properties, and applications in biogas production

5.1. Production, environmental impacts, and properties

The physicochemical properties of biochar are highly variable and largely depend on factors such as the type of feedstock used and the production conditions, such as temperature, pressure, heating rate, and residence time (Díaz et al., 2024).

These factors influence the structural, chemical, and functional characteristics of biochar, making it a versatile material with numerous applications (Ganesapillai et al., 2023). Figure 1 denotes the production process for biochar.

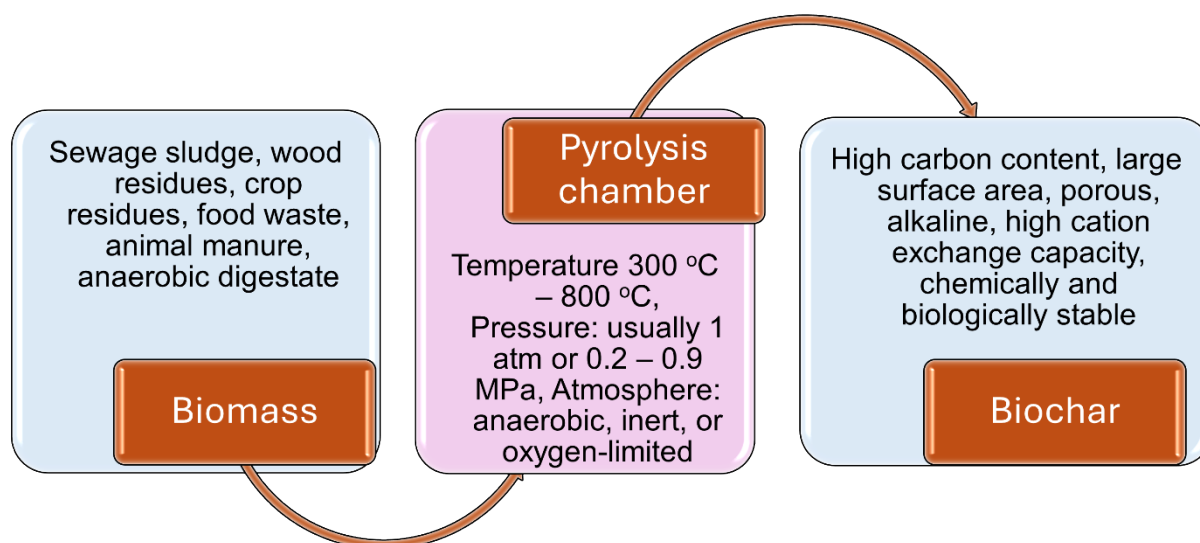


Figure 1: The biochar production process

Biochar production can deliver net climate and waste-management benefits when biomass residues are converted to biochar via pyrolysis rather than openly burned or left to decay. Life-cycle studies show that, if the process captures stable carbon in biochar and uses co-products such as syngas and bio-oil for heating or electricity generation, the overall greenhouse gas footprint will diminish (Xia et al., 2024; Li et al., 2024). Using agricultural residues as feedstock prevents field-burning emissions and reduce pressure on landfills, while the resulting biochar can support nutrient cycling and lower downstream emissions from soil management (Patel & Panwar, 2023). However, the extent of the benefits is highly dependent on feedstock logistics, moisture content, and pyrolysis efficiency. The environmental benefits are maximised when modern, energy-integrated plants are used instead of small, inefficient kilns (Li et al., 2024).

Adverse environmental impacts arise mainly from pyrolysis emissions, contaminated feedstocks, and poor process control during biochar production. Pyrolysis can release particulate matter, carbon monoxide, nitrogen oxides, and organic vapours. Without a gas cleaning system, air pollution may cancel the climate gains, and biochar dust can be resuspended during handling and transport (Ravi et al., 2020). Pollutants can also be built into the biochar. For example, polycyclic aromatic hydrocarbons (PAHs) form under certain temperatures between 400 °C and 700 °C, and their concentrations depends on feedstock and operating conditions (Li et al., 2023; Sia et al., 2025). If waste streams containing metals or persistent contaminants are used, some impurities can concentrate in biochar or leach from production residues, creating soil and water-quality risks (Dong et al., 2025). Life-cycle assessments indicate that there are trade-offs such as increased electricity usage, auxiliary fuels, and transport emissions which can be significantly high for systems with long supply chains or inefficient reactors (Xia et al., 2024).

Generally, biochar has an unusually large surface area and high porosity, which enhance its effectiveness as an adsorbent for various contaminants, including heavy metals, organic pollutants, and nutrients (You et al., 2024). The adsorption properties of biochar are further enhanced by the presence of diverse functional groups, such as carboxyl, hydroxyl, and carbonyl groups, on its surface (Li et al., 2025). The functional groups on the biochar surface significantly increase its affinity for binding different compounds and chemical species (Krysanova et al., 2022). Figure 2a – 2c shows the surface of different types of biochar magnified by a scanning electron microscope (SEM).

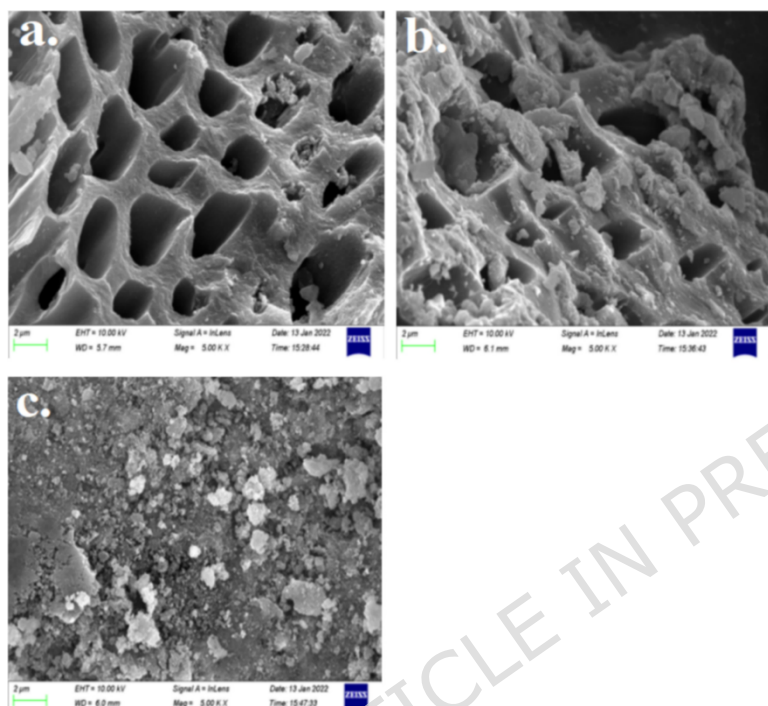


Figure 2: The surface of biochar as seen under an SEM. a) rice straw biochar, b) rice straw magnetic biochar, c) rice straw hydrothermal magnetic biochar (Wang et al., 2026)

Biochar is alkaline in nature, a characteristic that contributes to its ability to buffer pH in various systems, including anaerobic digesters (Ihoeghian et al., 2023). The pH of biochar ranges from 7.1 to 10.5 (George, 2022). The addition of biochar to soils and AD systems has the effect of stabilising the pH and thus promoting a friendly environment for sustainable microbial activity (You et al., 2024). Arwenyo et al. (2023) revealed the strong buffering capacity of biochar when applied to acidic soils and other acidic environments. In AD systems, the buffering capacity of biochar is particularly useful when processing acidic feedstocks, as it mitigates the risk of process failure caused by acidification (Nie et al., 2024).

Another key property of biochar is its high cation exchange capacity (CEC) (Dike et al., 2021). The high CEC of biochar enhances its ability to adsorb and release essential nutrients such as ammonium, phosphate, and potassium (Meier et al., 2025). It is this nutrient-holding capacity that supports microbial growth in anaerobic digesters and promotes nutrient retention in agricultural soils when biochar is applied as a soil amendment (Bao et al., 2024). The effective retention

of ammonium and phosphate, for instance, is beneficial in reducing nutrient losses to the environment, thus contributing to sustainable nutrient management practices. Biochar's ability to adsorb and immobilise heavy metals and other pollutants reduces the toxicity of digestate, making it safer for use as a fertiliser (Huang et al., 2023).

5.2. Applications of biochar

Biochar has been widely studied for its applications in environmental management, particularly in soil remediation and climate change mitigation (Boughattas et al., 2025). When applied to soil, biochar improves water retention, nutrient availability, and nutrient retention and mitigates soil acidity (Arwenyo et al., 2023; Antonangelo et al., 2021; Bao et al., 2024).

In water and wastewater treatment, biochar is mostly used as an adsorbent for removing contaminants such as heavy metals, nutrients, and organic pollutants (Olugbenga et al., 2024). In this regard, engineered biochar with a higher surface area, stronger adsorption capacity, and various surface functional groups is preferred over pristine biochar (Wang et al., 2021). Biochar was found to be highly effective in removing dyes, cytotoxins, radioactive materials, antibiotics, humic acid, microplastics, and other emerging contaminants from polluted waters (Tripathi et al., 2025).

Researchers (Kumar et al., 2021) have extensively explored the effectiveness of biochar as an additive to enhance the AD of various substrates. Multiple studies have shown that the addition of biochar can increase CH₄ production, reduce process lag, enhance process stability, improve digestate quality, and increase microbial activity (He et al., 2023; Ninget al., 2023; Shen et al., 2021; Nie et al., 2024). During AD, biochar provides a surface for microbial attachment and adsorbs inhibitory substances such as NH₃ (Khoei et al., 2021).

5.3. Biochar and anaerobic digestion

5.3.1. Effects on biogas production

Biochar is well documented as an additive that enhances biogas production during AD. Awode et al. (2022) studied the effect of biochar on biogas yield during the AD of poultry droppings. The results show that a 10 w/w% biochar increased biogas yield by 26% and 24% during the AD of layer wastes and broiler wastes, respectively. Table 3 summarises the effect of biochar on biogas yield during the AD of various substrates.

Table 3: Effect of biochar during AD of various substrates

Researchers	Year	Summary of Findings
Awode et al.	2022	A 10% w/w addition of biochar increased biogas yield by 26% for layer wastes and by 24% for broiler wastes during AD.
Yin et al.	2019	Biochar in microbial electrolysis cells increased production by 24.7%, VS removal by 17.9%,

		enhanced hydrolysis & acidogenesis rates, and promoted DIET.
Li et al.	2022	Biogas residue biochar increased CH ₄ yield by 10.5%; VFA concentration rose by 19.3%; and acetate/valerate proportions improved, indicating enhanced VFA degradation.
Batta et al.	2023	In AD of APC, biochar led to an 83% increase in biogas production, higher CH ₄ content, and adsorbed phenolic inhibitors at 39.77 mg phenol/g biochar.
Khoei et al.	2021	Triturated biochar in thermophilic AD of acidified sludge increased the CH ₄ production rate by 20–94% and promoted VFA turnover, ammonia adsorption, alkalinity, and DIET.
Kulabako et al.	2025	In cow dung-water hyacinth AD, 2% wood biochar increased CH ₄ production by 76.8%, while 2% faecal sludge biochar resulted in a 94% increase; mixed substrates experienced increases of 20–37%.
Ning et al.	2023	Adding 10 g/L biochar in two-stage AD raised CH ₄ yield by 7% (237 L/kg VS) and achieved the highest energy yield of 8.5 MJ/kg VS by stabilising hydrolysis and digestion.
Sugiartha et al.	2021	Raw biochar increased cumulative CH ₄ yield by 46.9% and daily rate by 43%; leached biochar showed smaller gains, indicating the role of minerals in boosting performance.
Feng et al.	2025	A 5 g/L dosage of biochar increased CH ₄ production by 196.5%, while an excessive dosage of 8 g/L reduced the benefits.
Ding et al.	2024	Biochar effects varied by inoculum: it increased CH ₄ by 20.3–38.7% for peptone-swine inoculum (CPI) seeds but reduced it by 5.3–23.1% for swine manure inoculum (SMI); it enhanced VFA accumulation, ammonia mitigation, and microbial growth.

Yin et al. (2019) studied the effect of biochar in microbial electrolysis cells and noted a 24.7% increase in CH₄ production while volatile solids removal efficiency increased by 17.9%. In this study, biochar improved the process by increasing the rate of the hydrolysis and acidogenesis stages. Moreover, the research revealed

that biochar promoted DIET, which is crucial in biomethane production and leads to a reduction of process lag.

Li et al. (2022) investigated the impact of biochar on CH₄ production during the AD of kitchen waste. The study indicated that biochar derived from biogas residue increased the CH₄ yield by 10.5%. The highest VFA concentration was 19.3% greater than the VFA concentration in the system that did not contain biochar. In addition, the percentage of acetate and valerate was 25.3% and 12.8%, while it was 16.3% and 22.0% in the control. The findings of this study suggested that biochar promoted the degradation of VFAs.

Batta et al. (2023) studied the effect of biochar on the AD of aqueous pyrolysis condensate (APC). The results indicated that the addition of biochar led to an 83% increase in cumulative biogas production and a significant increase in CH₄ content at the highest APC loading. Overall, the biochar mitigated the inhibitory effect of phenolic components by adsorbing these inhibitors at a rate of 39.77 mg of phenol per gram of biochar.

Triturated biochar increased the CH₄ production rate during the thermophilic AD of acidified sludge by 20–94% (Khoei et al., 2021). The study by Khoei et al. (2021) also confirmed the impact of biochar in promoting VFA production and consumption, adsorbing NH₃, increasing the alkalinity of the system, and facilitating the DIET.

Kulabako et al. (2025) investigated the impact of wood and faecal sludge biochar on biogas production from the AD of water hyacinth. Laboratory-scale experiments using cow dung infused with 2% wood biochar led to a 76.8% increase in CH₄ production, while 2% faecal sludge biochar increased CH₄ production by 94%. When 2% wood biochar was added to a 50% cow dung – 50% water hyacinth mixture, CH₄ production increased by 20%, while the addition of 2% faecal sludge biochar increased CH₄ production by 37%.

Feng et al. (2025) demonstrated that biochar addition effectively overcomes oil-related inhibition in food wastewater AD. Using synthetic wastewater containing sodium oleate (4 g/L; initial COD 5000 mg/L), they found that oleate suppressed cumulative CH₄ yield by 36.61%. However, adding 5 g/L biochar substantially enhanced CH₄ production (196.50% increase), facilitated oleate biodegradation, and enriched functional microbes like the phyla *Thermotogae* and *Bacteroidetes*, and the hydrogenotrophic methanogens *Methanoculleus* and *Methanosarcina*, promoting hydrogenotrophic methanogenesis. Increasing biochar to 8 g/L reduced benefits, likely due to excessive adsorption of essential intermediates, such as VFAs, hindering methanogenesis (Feng et al., 2025).

Ning et al. (2023) found that adding biochar to two-stage AD improved biomethane production by enhancing hydrolysis and stabilising the digestion process. The highest CH₄ yield (237 L/kg VS) was observed in the second-stage digester with a 10 g/L biochar dosage, representing a 7% increase compared to digestion without biochar. Overall, biochar supplementation was shown to enhance gaseous biofuel production, with the highest energy yield of 8.5 MJ/kg VS achieved in two-stage digestion (Ning et al., 2023).

A study by Sugiarto et al. (2021) demonstrated that biochar, particularly raw biochar, significantly enhanced CH₄ production during AD, increasing cumulative CH₄ yield (YM) by 46.9% and daily production rate (RM) by 43.0% compared to the control. Leached biochar, with reduced mineral content, showed lesser improvements (33.2% YM, 18.2% RM), indicating that minerals, especially iron, play a key role in boosting CH₄ production by enhancing VFA degradation and enriching microbial groups such as the class *Clostridia* and *acetoclastic* methanogens like the genus *Methanosaeta*.

During an investigation by Ding et al. (2024), it was found that biochar influenced AD performance differently depending on the inoculum source, with CH₄ yields from cellulose- CPI seeds being 20.3–38.7% higher than SMI seeds without biochar, while biochar addition reduced CH₄ yields by 5.3% and 23.1% for CPI and SMI, respectively. Despite this reduction, biochar enhanced VFA accumulation, mitigated NH₃ inhibition, and improved organic degradation by increasing soluble COD breakdown. Microbial analysis revealed that biochar facilitated the growth of key bacterial phyla and orders such as *Bacteroidetes* and *Clostridiales* and enriched hydrogenotrophic methanogens like *Methanobrevibacter* and *Methanobacterium*, contributing to overall system stability and efficiency in organic waste treatment.

5.3.2. Mechanisms of Action

AD is a biological process wherein microorganisms decompose biomass in an oxygen-free environment, generating biogas as a valuable renewable energy resource. Biochar has garnered significant interest for its capacity to enhance AD owing to its physical, chemical, and biological attributes. Biochar improves biogas generation by the adsorption of inhibitory chemicals, promotion of DIET, presence of surface functional groups, and modification of microbial populations. These mechanisms enhance the efficiency and stability of the digesting process, hence augmenting CH₄ yields and process resilience.

A principal advantage of biochar in AD is its extensive surface area and porous architecture, enabling it to adsorb and immobilise inhibitory substances such as NH₃, VFAs, and heavy metals (Gotore et al., 2025). Elevated levels of NH₃ are detrimental to methanogens, the bacteria that facilitate CH₄ synthesis. Through the adsorption of NH₃, biochar sustains a conducive microbial habitat and mitigates the suppression of methanogenesis (Li et al., 2021). Likewise, VFAs as intermediates in AD, can accumulate and decrease pH, thereby reducing microbial activity. Biochar's buffering capacity neutralises excess acids, ensuring a steady pH environment conducive to efficient digestion (Kumar et al., 2021). Moreover, biochar possesses the capacity to absorb heavy metals, including copper, zinc, and lead, which may disrupt microbial metabolism. By alleviating these inhibitory effects, biochar augments microbial activity and boosts biogas generation (Sharma & Suthar, 2021). Biochar improves AD by serving as an electron mediator, promoting DIET among microbial populations. In anaerobic systems, electron transport is essential for the degradation of organic matter, especially in syntrophic interactions between bacteria and methanogens (Ihoeghian et al., 2023). Conventional interspecies electron transfer depends on hydrogen or

formate as intermediates, potentially constraining reaction efficiency. The conductive qualities of biochar facilitate direct electron transmission between syntrophic bacteria and methanogens, hence enhancing fatty acid breakdown and augmenting CH₄ generation (Khalid et al., 2022). DIET is especially advantageous in digesters with elevated organic loads, as the buildup of intermediates may result in process instability. Research indicates that the incorporation of biochar markedly increases CH₄ production and diminishes the lag phase of digestion by enhancing electron transfer efficiency (Khoei et al., 2021).

The surface chemistry of biochar is essential in influencing the AD process. Biochar comprises many functional groups, such as carboxyl, hydroxyl, and carbonyl groups, capable of interacting with chemical substances and microbial organisms (Pan et al., 2022). These functional groups act as binding sites for organic molecules and vital nutrients, enhancing their bioavailability for microbial absorption (Zeynali et al., 2024). Moreover, biochar can adsorb long-chain fatty acids, which are hazardous intermediates generated during lipid decomposition. Biochar safeguards microbial populations from toxicity by inhibiting the buildup of long-chain fatty acids, hence facilitating a more efficient digesting process (Li et al., 2021). Moreover, the CEC of biochar facilitates the retention and progressive release of vital nutrients, including ammonium, phosphate, and potassium, thus maintaining a consistent supply for microbial proliferation (Ning et al., 2023).

Biochar markedly affects the makeup and functionality of microbial populations engaged in AD. The porous structure offers an extensive surface area for microbial adhesion, which facilitates biofilm development and augments microbial colonisation. Biofilms on biochar particles shield microorganisms from environmental stress and enhance substrate breakdown efficiency (Awode et al., 2022). Furthermore, biochar has demonstrated the ability to selectively enhance essential microbial communities that facilitate AD. Research demonstrates that the incorporation of biochar enhances the prevalence of essential bacterial taxa, specifically the phylum *Bacteroidetes* and the order *Clostridiales*, which are integral to hydrolysis and acidogenesis (Khoei et al., 2021). Furthermore, biochar enhances the proliferation of hydrogenotrophic methanogens, including *Methanobrevibacter* and *Methanobacterium*, which utilise hydrogen for CH₄ synthesis (Pant & Rai, 2021).

5.3.3. Factors influencing biochar effectiveness

The effectiveness of biochar as an additive in AD systems is affected by various intricate parameters, including feedstock type, biochar dosage, reactor conditions, physicochemical qualities of biochar, and substrate features. This amalgamation of elements dictates biochar's efficacy in enhancing CH₄ synthesis, stabilising microbial populations, and alleviating inhibitory chemicals. The biomass used for biochar production significantly affects its structural and functional characteristics.

Feedstocks, including woody biomass, agricultural leftovers, and animal dung, produce biochar, which is characterised by unique surface areas, porosity, and

chemical compositions. Biochar produced from woody biomass, such as cedar or pine, generally has more porosity and surface area than biochar sourced from agricultural leftovers, like rice husk or wheat straw, owing to variations in lignin and cellulose composition (Wenjing et al., 2022). A study comparing cow manure biochar (pyrolysed at 400°C) and mushroom bran biochar (pyrolysed at 550°C) revealed that CH₄ generation rose by 81.30% and 77.59%, respectively, relative to control systems devoid of biochar (Pan et al., 2022). Nonetheless, the same study observed that biochar's specific surface area and porosity, although favourably associated with pyrolysis temperature, did not have a direct correlation with biogas generation. The quantity of biochar is a crucial factor influencing its effect on AD. Moderate doses have demonstrated the ability to augment CH₄ production, diminish lag phases, and stabilise pH (Ning et al., 2023).

A study utilising glucose as the exclusive carbon source revealed that a biochar dosage of 8 g/L enhanced cumulative CH₄ generation to 390.33 mL CH₄/g-VS, in contrast to 135.06 mL CH₄/g-VS in non-amended reactors (Świechowski et al., 2024). Research conducted by Shi et al. (2022) has shown that the incorporation of an appropriate biochar dosage (0.60 g/gVS oily sludge) markedly enhanced CH₄ generation during the mesophilic digestion of oily sludge, elevating the yield to 138.41 mL/gVS, a 219% increase compared to the control group. Biochar improved hydrolysis, acidogenesis, and acetogenesis, while promoting microbial enrichment and the activation of functional genes. Excessive biochar (>4.80 g/gVS OS) adversely affected methanogenic efficiency, resulting in a 32.5% reduction and an increase in the lag phase by 5.72 hours. In a distinct study conducted by Feng et al. (2025), the researchers discovered that the incorporation of 5 g/L of biochar markedly enhanced CH₄ yield during AD of food wastewater, increasing production by 196.50%. However, elevated dosages (8 g/L) diminished this advantage due to excessive adsorption of LFCAs and VFAs, which impeded methanogenesis.

The ideal dosage is contingent upon the physicochemical features of biochar. Conductive biochars, characterised by elevated electrical conductivity, necessitate reduced dosages to promote DIET, whereas adsorbent biochars, which possess a high porosity, may require increased dosages to alleviate ammonia or VFAs (Chen et al., 2023). A balance must be achieved to prevent system overload while guaranteeing adequate surface area for microbial contact. Operational characteristics significantly influence the efficacy of biochar in AD. Thermophilic temperatures (45–60°C) enhance DIET but necessitate biochar pyrolysis below 700°C to prevent the creation of inert carbon. Wood biochar created at 950°C decreased CH₄ yield by 52%, whereas biochar produced at 400°C increased it by 40% (Chen et al., 2022). Biochar's intrinsic alkalinity mitigates acidic pH fluctuations caused by VFAs, hence stabilising methanogen activity. Elevated organic loading rates (>3.5 gVS/L/day) are alleviated by biochar's adsorption of VFAs and ammonia, but prolonged hydraulic retention durations (>20 days) improve nutrient retention (Ning et al., 2023). The effectiveness of biochar depends on its inherent characteristics, such as a high surface area (>74 m²/g) and mesoporosity (2–50 nm), which optimise inhibitor adsorption, whereas graphitic carbon facilitates DIET between syntrophs and methanogens (Kumar et al., 2021; Li et al., 2021). Reduced pyrolysis temperatures (400–550°C) maintain

functional groups for adsorption, while elevated temperatures ($>600^{\circ}\text{C}$) enhance conductivity at the expense of adsorption capacity. The organic substrate's composition determines biochar's function in AD. For substrates rich in lignocellulose, such as agricultural waste, biochar with elevated porosity is advantageous due to its ability to adsorb phenolic inhibitors and offer a conducive surface for hydrolytic bacteria, hence enhancing the degradation of complicated polymers (Kundu et al., 2023). Conversely, protein-rich substrates such as slaughterhouse waste benefit from biochar's significant NH_3 adsorption capability, which mitigates the inhibition of methanogens and sustains process stability (Lü et al., 2021). Lipid-rich substrates, such as food waste, typically produce hazardous long-chain fatty acids during breakdown. In this instance, biochar is essential since it immobilises these chemicals on its surface, thus reducing LCFA toxicity and promoting CH_4 synthesis (Chen et al., 2023).

6. Prospects for biochar-amended anaerobic digestion of abattoir effluents

6.1. Specific challenges

Abattoir effluents are characterised by extremely high NH_3 levels that result from the rapid degradation of protein-rich animal tissues. In AD, ammonia is highly toxic to methanogens, disrupting their metabolic activities and leading to reduced CH_4 yields and overall process instability. Biochar is often employed as an additive to counteract NH_3 inhibition through adsorption and pH buffering; however, in the case of protein-rich substrates such as abattoir effluents, the excessive NH_3 concentrations may quickly saturate the adsorption sites on the biochar, thereby limiting its effectiveness in mitigating toxicity and stabilising the microbial community (Tripathi et al., 2025).

Abattoir effluents contain significant amounts of lipids that are hydrolysed into LCFAs during digestion. These LCFAs tend to accumulate and form scum layers that block gas transfer and impede microbial accessibility, thereby worsening the inhibition of methanogenesis. Although biochar's porous structure and abundant functional groups are designed to adsorb inhibitory compounds and support microbial colonisation, the overwhelming presence of LCFAs in abattoir effluents can compromise biochar's ability to facilitate DIET and effective substrate degradation (Ma et al., 2023).

6.2. Mitigation strategies

Several studies have demonstrated that biochar can mitigate ammonia inhibition in AD systems, thereby enhancing biogas production from substrates other than abattoir effluents. For instance, Chen et al. (2022) showed that adding biochar produced from agricultural residues to dairy manure digesters significantly reduced free ammonia concentrations and stabilised the reactor pH, resulting in improved CH_4 yields. Similarly, Lu et al. (2020) found that incorporating biochar in the AD of poultry manure promoted robust microbial colonisation, which helped alleviate ammonia toxicity and enhance overall biogas production. These studies highlight the dual benefits of biochar. Its high porosity facilitates the adsorption of

inhibitory NH_3 , while its inherent alkalinity buffers pH fluctuations, creating a more favourable environment for methanogens.

In addition to addressing NH_3 inhibition, research has also focused on biochar's role in mitigating the inhibitory effects of LCFAs, which are common in lipid-rich waste streams like abattoir effluents. Feng et al. (2025) observed that the addition of biochar to food wastewater digesters helped adsorb LCFAs, preventing the formation of scum layers that can obstruct gas transfer and hinder microbial activity. Complementing this, Zhao et al. (2020) reported that conductive materials like biochar enhanced direct DIET between the bacteria contributing to the degradation of organics and the methane-producing archaea

6.3. Synergistic effects

Recent studies have shown that combining biochar with trace element supplementation can create synergistic effects that enhance AD performance. For example, Chen et al. (2022) demonstrated that the co-addition of biochar with essential trace elements such as iron, cobalt, and nickel resulted in a significant improvement in microbial activity and CH_4 production. These trace elements are critical cofactors for methanogenic enzymes, and their controlled release from the biochar matrix helps stabilise the microbial community under high-ammonia conditions. Similarly, Hassan et al. (2020) reported that integrating biochar with trace element additives not only facilitated the availability of these nutrients but also promoted the formation of robust biofilms, thereby accelerating the methanogenic process.

Parallel studies have investigated the synergistic potential of biochar in co-digestion strategies, especially when combining abattoir effluents with other organic wastes. Zhang et al. (2020) found that biochar addition in co-digestion systems improved process stability and increased CH_4 yields by adsorbing inhibitory compounds such as ammonia and long-chain fatty acids. The presence of co-substrates in these systems helps balance the carbon nitrogen (C/N) ratio, which further reduces the risk of inhibition, while the biochar's porous structure enhances microbial attachment and facilitates direct interspecies electron transfer. This combined effect leads to a more resilient AD process and improved biogas production, highlighting the value of integrating co-digestion strategies with biochar supplementation.

Beyond these approaches, recent research has also investigated the synergistic integration of biochar with advanced pre-treatment methods and electrochemical treatments to further mitigate inhibitory effects. Some studies have combined biochar with hydrothermal or electrochemical pre-treatments to break down complex organic compounds in abattoir effluents before digestion, while the biochar simultaneously adsorbs the resulting inhibitors. Such integrated treatment methods have been shown to not only enhance the degradation of recalcitrant compounds but also to support a more efficient microbial metabolism, thereby leading to improved biogas yields and overall process stability (Wang et al., 2024).

7. Economic feasibility and environmental benefits of biochar in anaerobic digestion

AD is a mature technology for managing organic waste and producing renewable energy in the form of biogas (Moreroa,2025). Research demonstrates that incorporating biochar improves AD performance by increasing biogas yields, stabilising the process, and reducing toxic byproducts. Evaluating the economic and environmental feasibility of using biochar in AD processes requires consideration of production costs, operational benefits, long-term implications, and environmental impacts.

Biochar is produced via pyrolysis, a thermal decomposition process that occurs in the absence of oxygen, making it a versatile product derived from a wide variety of feedstocks such as agricultural residues, municipal waste, and forestry by-products. The cost of production is highly dependent on the type and availability of the feedstock; for instance, using waste-derived biomass can substantially reduce expenses while aligning with modern waste management and sustainability policies (Huang et al., 2023). However, overall production costs are also influenced by energy demands of the pyrolysis process, capital investments for reactor design, and costs associated with transportation and storage. The efficiency of the pyrolysis process, determined by operating temperature, heating rate, and reactor design, plays a critical role in controlling energy consumption and, subsequently, production costs (Díaz et al., 2024). Integrating waste-to-energy strategies and optimising process parameters through technological innovations have been identified as effective means to lower costs and improve economic feasibility (Sharma & Suthar, 2021).

Despite the initial expenses, biochar production offers ancillary benefits that can offset costs and create additional revenue streams (Moreroa & Motshekga, 2024). Beyond enhancing AD performance by stabilising process conditions and increasing biogas yields, biochar is widely recognised as an effective soil amendment. Its application improves soil fertility, water retention, and crop productivity, while also providing a long-term method of carbon sequestration. This multifaceted utility supports environmental sustainability and opens opportunities for generating carbon credits and other economic incentives in agricultural markets (Adhikari et al., 2024). Evaluating the economic viability of biochar requires considering these extended benefits, as they can significantly enhance the overall value proposition of biochar production. Figure 3 illustrates how AD technology can contribute to the circular economy for the treatment of abattoir effluents.

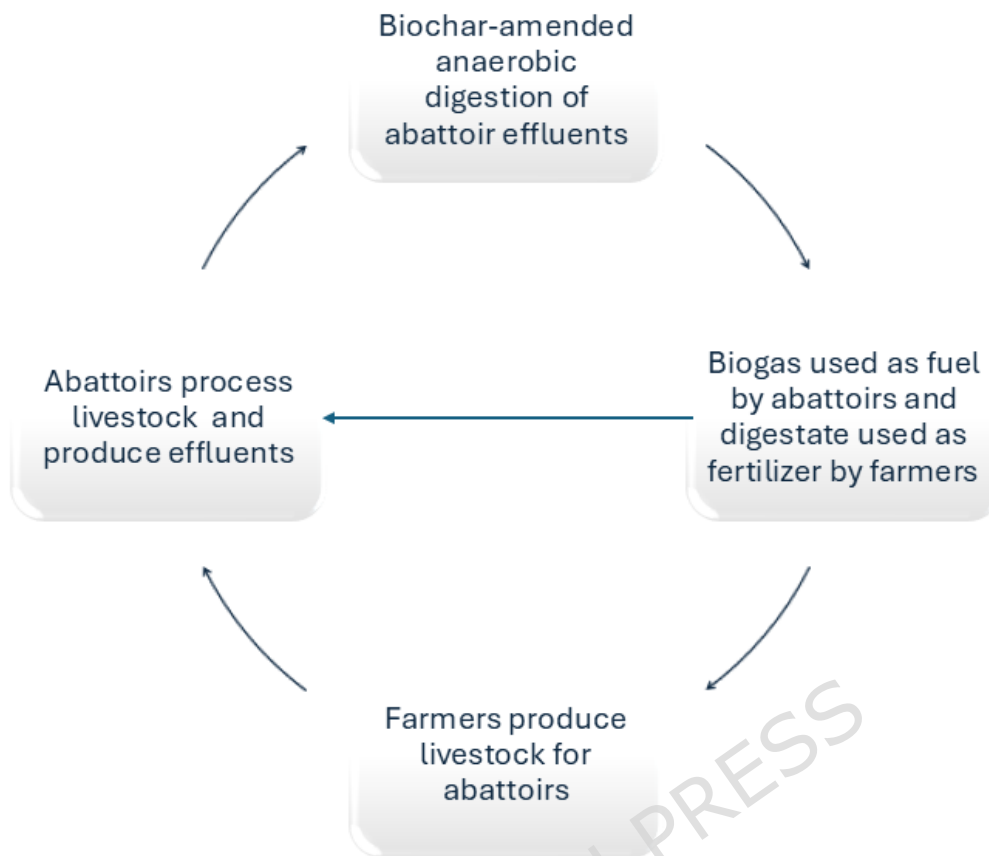


Figure 3: A demonstration on the implementation of circular economy through the utilisation of anaerobic digestion technology in abattoirs.

Future research is focusing on reducing the energy intensity and capital costs associated with biochar production through innovative technologies such as microwave-assisted pyrolysis, which has shown promise in reducing processing times and energy consumption (Zhu et al., 2023). Comprehensive life cycle assessments and techno-economic analyses are being employed to pinpoint key cost drivers and identify potential areas for cost reduction through process integration and improved logistics (Alavianghavanini et al., 2024). Policy interventions and targeted subsidies are being explored to support biochar production, particularly in regions where sustainable waste management and renewable energy initiatives are prioritised. These advances enhance the economic feasibility of biochar production and underscore its critical role in the circular economy, transforming waste materials into valuable resources with far-reaching environmental and economic benefits (Zhu et al., 2023).

The addition of biochar to AD enhances process efficiency by improving microbial activity and increasing CH_4 production. Biochar provides a surface for microbial attachment, facilitating biofilm formation and stabilising microbial communities involved in methanogenesis (He et al., 2023). Studies have demonstrated that biochar can increase biogas yields by up to 30%, depending on the type of feedstock and operational conditions (Zhang et al., 2025). It also improves the digestate's quality by adsorbing ammonia, heavy metals, and other contaminants,

reducing environmental risks, and enhancing its marketability as an organic fertiliser (Qi et al., 2021). Furthermore, biochar buffers pH fluctuations in digesters, reducing the risk of process failure and lowering maintenance expenses (Khoei et al., 2021).

Economic feasibility depends on context-specific factors, including feedstock availability, production scale, and local energy and waste management policies. Improved biogas yields translate to higher revenues, particularly when biogas is used for electricity generation or upgraded to biomethane. Improved process stability reduces downtime and operational expenses, while enhanced digestate quality provides additional revenue opportunities (Awode et al., 2022). In regions with access to carbon credit schemes, biochar's ability to sequester carbon adds further economic viability, as projects can generate offsets in compliance with voluntary or regulated carbon markets (Khalid et al., 2022).

Despite these advantages, challenges persist, including high upfront costs and a lack of standardised biochar production. Economic benefits are not uniform and depend on local energy prices, waste policies, and market demand for biochar-related products. Detailed cost-benefit analyses that account for these factors are crucial for assessing project feasibility (Ning et al., 2023).

From an environmental perspective, biochar provides a sustainable method for converting organic waste into valuable resources. Environmentally harmful methods like open burning or landfilling often underutilise or dispose of feedstocks such as agricultural residues, forestry byproducts, and municipal waste. Pyrolysis transforms these waste streams into biochar, reducing their volume and stabilising organic carbon (Huang et al., 2023; Ning et al., 2023). In AD, biochar enhances biogas production by providing a conductive medium that facilitates electron transfer between microbial communities, improving waste-to-energy conversion and reducing fossil fuel reliance (Khoei et al., 2021; Kumar et al., 2021).

Biochar's role in greenhouse gas mitigation is significant. It sequesters carbon in a stable form, preventing its release into the atmosphere, with studies estimating that biochar can lock away carbon for centuries (Khalid et al., 2022). In AD, biochar reduces CH₄ and nitrous oxide (N₂O) emissions by adsorbing ammonia and stabilising nitrogen compounds, thereby minimising N₂O formation during waste degradation (Qi et al., 2021). By buffering pH fluctuations, biochar also reduces the likelihood of incomplete digestion, a common source of fugitive CH₄ emissions (Khoei et al., 2021).

When applied to soil, biochar improves structure, increases water retention, and enhances nutrient availability, reducing dependency on synthetic fertilisers and combating soil degradation (Wu et al., 2022). Its high adsorption capacity captures and immobilises heavy metals, pesticides, and other pollutants, reducing groundwater contamination risks. When combined with the digestate from AD, biochar further improves environmental safety, enabling its use as an organic fertiliser without harmful runoff (Qi et al., 2021; Huang et al., 2023).

These environmental benefits align with circular economy principles and sustainable development goals. By converting waste streams into valuable

resources, biochar promotes resource efficiency and reduces dependency on non-renewable inputs, such as chemical fertilisers and fossil fuels. Additionally, biochar production and application can have socioeconomic benefits, particularly in rural areas, by creating jobs and providing affordable waste management and soil rehabilitation solutions (Khoei et al., 2021).

However, environmental outcomes depend on feedstock type, production conditions, and application methods. High-temperature production can release harmful by-products such as PAHs, while over-application to soils can alter microbial activity and nutrient cycling, leading to unintended consequences (Huang et al., 2023; Wu et al., 2022). Regulatory frameworks and best practices are essential for maximising environmental benefits while minimising risks; further research is needed to optimise biochar systems and assess long-term ecosystem impacts.

8. Scalability

The use of biochar in AD processes holds significant potential for scalability due to its ability to enhance biogas production, improve waste management, and support sustainable energy solutions. However, scaling up this practice involves addressing technical, economic, and logistical challenges while leveraging opportunities for widespread adoption.

Biochar improves the efficiency of the AD process by acting as a biofilm carrier, enhancing microbial activity, buffering pH, and stabilising nitrogen compounds (Khoei et al., 2021). These enhancements increase the yield and quality of biogas, making the process more attractive for large-scale applications. For instance, in industrial and municipal waste treatment plants, the integration of biochar can optimise digestion processes and reduce the footprint of organic waste management. The availability of suitable feedstocks for both biochar production and AD significantly influences the scalability of biochar-enhanced AD. Biochar can be derived from a wide variety of biomass sources, such as agricultural residues, forestry by-products, and organic municipal waste (Huang et al., 2023). Similarly, AD feedstocks such as food waste, animal manure, and sewage sludge are abundant and underused in many regions. By aligning these resources, biochar and AD systems can be integrated into existing waste management infrastructures.

Economic factors play a critical role in scaling up biochar use in AD. Producing high-quality biochar at a large scale requires investment in pyrolysis facilities and energy inputs, which can be cost-intensive. However, advancements in pyrolysis technology and the potential to co-produce biochar and renewable fuels, such as syngas and bio-oil, can offset these costs (Kumar et al., 2020). The use of biochar in AD can reduce operational expenses by improving process stability, decreasing the need for chemical additives, and minimising maintenance requirements. The sale of by-products, such as nutrient-rich digestate for use as fertiliser, can further improve the economic feasibility of scaled-up systems (Batta et al., 2023).

The scalability of biochar in AD aligns with global environmental goals, such as reducing greenhouse gas emissions, advancing waste valorisation, and supporting renewable energy production. Policy incentives, including carbon credits, subsidies for renewable energy, and regulations on organic waste disposal, can drive the adoption of biochar-enhanced AD systems (Khalid et al., 2022). However, scaling up biochar-enhanced AD presents technological challenges, foremost among which is achieving uniformity in biochar properties. Biochar is produced from a wide range of feedstocks, such as agricultural residues, municipal waste, and forestry by-products, under varying pyrolysis conditions. This naturally leads to variability in its physicochemical characteristics, such as surface area, porosity, and functional group composition, all of which directly affect its performance in AD systems (Wu et al., 2022). This inherent variability necessitates the establishment of standardised production protocols to ensure consistent quality and predictable performance across large-scale applications. In addition, integrating biochar-enhanced AD into existing waste management and biogas production facilities often requires substantial infrastructure upgrades, as many current systems are not designed to handle the unique processing and handling requirements of biochar.

Another major challenge is optimising supply chain logistics and addressing knowledge gaps associated with biochar use in AD. The cost-effectiveness of biochar production is influenced not only by the selection of low-cost, waste-derived feedstocks (which can reduce raw material expenses) but also by the energy demands of the pyrolysis process itself (Huang et al., 2023). Moreover, the transportation and storage of biochar over large geographical areas add further logistical complexity and cost, potentially undermining its economic viability. Research efforts have also highlighted significant knowledge gaps regarding the long-term impacts of biochar on microbial communities, biogas composition, and digestate quality within AD systems. While several short-term studies have demonstrated improved CH₄ yields and process stability with biochar addition, comprehensive pilot-scale trials and life cycle assessments are needed to better understand these long-term effects and to develop robust, scalable implementation models (Khoei et al., 2021; Zhu et al., 2023). Addressing both the logistical hurdles and the unresolved scientific questions is a prerequisite for the successful scaling of biochar-enhanced AD technologies in commercial settings.

Scaling up biochar-enhanced AD presents significant opportunities for decentralised waste-to-energy systems, particularly in rural regions with limited infrastructure, where local biochar production can efficiently use available biomass and waste streams (Gotore et al., 2025; Kabeyi & Olanrewaju, 2022). Such decentralised systems generate renewable biogas while co-producing biochar and digestates, which function as high-quality organic fertilisers, thereby advancing sustainable local resource management and reducing reliance on chemical alternatives (Kulabako et al., 2025; Sharma & Suthar, 2021). These systems reduce transportation costs and energy consumption by leveraging local resources, making them economically viable for rural communities and small-scale agricultural operations (Gotore et al., 2025). The integration of biochar-enhanced AD into circular economy frameworks offers considerable promise due to biochar's

multifunctional role in waste valorisation (Nieet al., 2024). Beyond optimising AD performance through inhibitor adsorption and microbial community stabilisation (Kumar et al., 2021; Zhao et al., 2021), biochar serves additional purposes across the value chain, such as enhancing soil fertility, improving water retention, and sequestering carbon when used as a soil amendment (Afshar & Mofatteh, 2024; Kothari et al., 2024). Concurrently, digestates from AD can be refined into nutrient-rich fertilisers, creating a closed-loop system that transforms waste into energy and valuable by-products while ensuring long-term resource efficiency and environmental sustainability (Gotore et al., 2025; Havukainen & Dace, 2023).

Cross-sector collaborations among agricultural, industrial, and municipal stakeholders are pivotal for overcoming scaling barriers and optimising biochar-enhanced AD deployment (Kothari et al., 2024). Joint investments and integrated supply chains enable resource, technology, and expertise sharing, which reduce production costs and streamline logistics (Gutu et al., 2021). Such partnerships enhance large-scale feasibility by aligning waste management strategies with renewable energy objectives and sustainability policies, as demonstrated in regional implementation models (Huang et al., 2023; Kothari et al., 2024).

Conclusion

The biochar integration into AD systems shows strong potential to increase biogas output and improve process stability, especially for protein- and lipid-rich abattoir wastes. Its porous structure, large surface area, and adsorption capacity help reduce inhibition from NH_3 , heavy metals, LCFAs, and VFAs. By binding free ammonia and buffering pH swings, biochar supports methanogen activity, limits acidification, and can substantially improve CH_4 yields under high organic loading. It can also promote direct interspecies electron transfer, strengthening syntrophic cooperation between bacteria and methanogens, speeding VFA conversion, and shortening lag phases. Over longer operation, biochar can help sustain microbial diversity and enrich robust methanogenic groups, contributing to resilient performance under fluctuating conditions. Overall, biochar functions both as a stabiliser and a catalyst for digestion, supporting circular economy goals by upgrading waste into energy and usable by-products.

However, several barriers still prevent standardised adoption. Biochar performance varies widely because its properties depend on feedstock and pyrolysis conditions, making outcomes harder to predict across substrates. High-temperature biochars can become too inert and reduce CH_4 gains, while low-temperature materials may adsorb inhibitors well but offer limited conductivity. Dosage remains highly context-specific, and excessive dosing can reduce effective reactor volume or introduce inhibitory compounds. Long-term effects also require clearer evidence, including biochar accumulation in digestate, downstream impacts after land application, and full lifecycle trade-offs. Cost and supply constraints further limit deployment, illustrating the importance of scalable production pathways and better integration with existing waste-management infrastructure.

Future work should focus on designing application-specific biochars tailored to the inhibitory profile of abattoir effluents and producing them through scalable, cost-efficient processes. Pyrolysis in the mid-temperature range is a promising compromise to preserve functional groups for NH₃ control while avoiding overly inert carbon formation, and catalytic or microwave-assisted approaches may improve consistency and economics. In parallel, microbial strategy development, such as targeted bioaugmentation and community management, should aim to strengthen syntrophic partnerships and maintain stability under ammonia stress. Finally, field-scale validation must combine techno-economic assessment with policy-ready frameworks that reward carbon storage, renewable energy generation, and high-value digestate use, while long-term monitoring clarifies soil safety, persistent microbial shifts, and net greenhouse-gas reductions beyond carbon sequestration alone.

Declarations

Ethical Approval

Not Applicable

Consent to participate

Not Applicable

Consent to publish

Not Applicable

Funding Declaration

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Clinical trial number

Not Applicable

Competing Interests declaration

There are no competing interests.

Author Contributions

Kudzai Mutisi performed the literature search, data curation, formal synthesis, and visualisation and wrote the original draft. *Mabatho Moreroa* led supervision, project administration, and methodology development and contributed to conceptualisation, validation, resource development, and revision of the manuscript. *Baraka Celestin Sempuga* led the validation and contributed to the methodology, resources, conceptualisation, and critical revision. All authors reviewed and approved the final manuscript.

References

- Afshar, M., & Mofatteh, S. (2024). Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results in Engineering*, *23*, 102433. <https://doi.org/10.1016/j.rineng.2024.102433>
- Agabo-García, C., Solera, R., & Perez, M. (2022). Anaerobic sequential batch reactor for CO-DIGESTION of slaughterhouse residues: Wastewater and activated sludge. *Energy*, *255*, 124575. <https://doi.org/10.1016/j.energy.2022.124575>
- Ahmad, M. M. (2024). Abattoir waste valorization: potential utilization of by-products into value-added chains. In *Food Waste Valorization* (pp. 267–280). Elsevier. <https://doi.org/10.1016/B978-0-443-15958-9.00016-2>
- Alavianghavanini, A., Moheimani, N. R., & Bahri, P. A. (2024). Producing protein-based products from microalgae cultivated on anaerobically digested abattoir effluent: Process integration and techno-economic analysis. *Bioresource Technology Reports*, *25*. <https://doi.org/10.1016/j.biteb.2023.101734>
- Antonangelo, J. A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. In *Journal of Environmental Management* (Vol. 277). Academic Press. <https://doi.org/10.1016/j.jenvman.2020.111443>
- Anyango, B. N., Wandera, S. M., & Raude, J. M. (2022). Abattoir Wastewater Treatment in Anaerobic Co-Digestion with Sugar Press Mud in Batch Reactor for Improved Biogas Yield. *Water*, *14*(16), 2571. <https://doi.org/10.3390/w14162571>
- Arwenyo, B., Varco, J. J., Dygert, A., Brown, S., Pittman, C. U., & MIsna, T. (2023). Contribution of modified P-enriched biochar on pH buffering capacity of acidic soil. *Journal of Environmental Management*, *339*, 117863. <https://doi.org/10.1016/j.jenvman.2023.117863>
- Atchala, M. S. R., Rao, P. V., Pilli, S., Pawar, A., Ganiga, R., & Tyagi, R. D. (2025). Pre-treatment and post-treatment strategies for enhancing anaerobic digestion in poultry slaughterhouse wastewater management. *Sustainable Chemistry for the Environment*, *9*, 100199. <https://doi.org/10.1016/j.scenv.2024.100199>
- Awode, A. E., Babatola, J. O., & Adelodun, A. A. (2022). Effect of Biochar on Biogas Yield of Poultry Wastes. *Environmental Protection Research*, 62–74. <https://doi.org/10.37256/epr.2220221349>
- Aziz, A., Rameez, H., Sengar, A., Sharma, D., Farooqi, I. H., & Basheer, F. (2022). Biogas production and nutrients removal from slaughterhouse wastewater using integrated anaerobic and aerobic granular intermittent SBRs – Bioreactors stability and microbial dynamics. *Science of the Total Environment*, *848*. <https://doi.org/10.1016/j.scitotenv.2022.157575>
- Bao, Z., Dai, W., Su, X., Liu, Z., An, Z., Sun, Q., Jing, H., Lin, L., Chen, Y., & Meng, J. (2024). Long-term biochar application promoted soil aggregate-associated potassium availability and maize potassium uptake. *GCB Bioenergy*, *16*(4). <https://doi.org/10.1111/gcbb.13134>

- Basitere, M., Njoya, M., Ntwampe, S. K. O., & Sheldon, M. S. (2020). Up-flow vs downflow anaerobic digester reactor configurations for treatment of fats-oil-grease laden poultry slaughterhouse wastewater: A review. In *Water Practice and Technology* (Vol. 15, Issue 2, pp. 248–260). IWA Publishing. <https://doi.org/10.2166/wpt.2020.023>
- Batta, N., Sarchami, T., Moreira, C. M., Rehmann, L., & Berruti, F. (2023). Assessment of the effects of biochar on biogas production during anaerobic digestion of aqueous pyrolysis condensate: A circular economy approach. *Journal of Environmental Chemical Engineering*, *11*(3). <https://doi.org/10.1016/j.jece.2023.109982>
- Bingo, M. N., Njoya, M., Basitere, M., Ntwampe, S. K. O., & Kaskote, E. (2021). Performance evaluation of an integrated multi-stage poultry slaughterhouse wastewater treatment system. *Journal of Water Process Engineering*, *43*. <https://doi.org/10.1016/j.jwpe.2021.102309>
- Bist, S., Nepal, R., Regmi, T., & Sharma, R. K. (2024). Poultry slaughterhouse waste management through anaerobic digestion with varying proportions of chicken litter. *Environmental Challenges*, *17*, 101035. <https://doi.org/10.1016/j.envc.2024.101035>
- Boughattas, I., Mannai, H., Chebbi, L., Mkhinini, M., Abouda, S., Helaoui, S., Hattab, S., Alphonse, V., Livet, A., Giusti-Miller, S., Banni, M., & Bousserhine, N. (2025). Remediation of polymetallic soils using biochar and earthworms: assessing heavy metal speciation, soil microbiological activities and earthworms' responses. *Journal of Environmental Management*, *390*, 126158. <https://doi.org/10.1016/j.jenvman.2025.126158>
- Campion, L., Bekchanova, M., Malina, R., & Kuppens, T. (2023). The costs and benefits of biochar production and use: A systematic review. *Journal of Cleaner Production*, *408*, 137138. <https://doi.org/10.1016/j.jclepro.2023.137138>
- Cao, Q., Meng, X., Jia, F., Li, J., Liu, X., & Li, D. (2025). The metabolic redundancy relieving VFAs shocks in anaerobic digestion system exposed sequentially to increasing acetic acid loading. *Chemical Engineering Journal*, *505*, 159791. <https://doi.org/10.1016/j.cej.2025.159791>
- Chen, W.-S., Tsai, W.-T., Lin, Y.-Q., Tsai, C.-H., & Chang, Y.-T. (2022). Production of Highly Porous Biochar Materials from Spent Mushroom Composts. *Horticulturae*, *8*(1), 46. <https://doi.org/10.3390/horticulturae8010046>
- Chen, Y., Wang, Y., Xie, H., Cao, W., & Zhang, Y. (2023). Varied promotion effects and mechanisms of biochar on anaerobic digestion (AD) under distinct food-to-microorganism (F/M) ratios and biochar dosages. *Waste Management*, *155*, 118–128. <https://doi.org/10.1016/j.wasman.2022.10.030>
- Díaz, B., Sommer-Márquez, A., Ordoñez, P. E., Bastardo-González, E., Ricaurte, M., & Navas-Cárdenas, C. (2024). Synthesis Methods, Properties, and Modifications of Biochar-Based Materials for Wastewater Treatment: A Review. *Resources*, *13*(1), 8. <https://doi.org/10.3390/resources13010008>

- Dike, C. C., Shahsavari, E., Surapaneni, A., Shah, K., & Ball, A. S. (2021). Can biochar be an effective and reliable biostimulating agent for the remediation of hydrocarbon-contaminated soils? *Environment International*, *154*, 106553. <https://doi.org/10.1016/j.envint.2021.106553>
- Ding, J., Zhen, F., Kong, X., Hu, Y., Zhang, Y., & Gong, L. (2024). Effect of Biochar in Modulating Anaerobic Digestion Performance and Microbial Structure Community of Different Inoculum Sources. *Fermentation*, *10*(3), 151. <https://doi.org/10.3390/fermentation10030151>
- Dong, M., Jiang, M., He, L., Zhang, Z., Gustave, W., Vithanage, M., Niazi, N. K., Chen, B., Zhang, X., Wang, H., & He, F. (2025). Challenges in safe environmental applications of biochar: identifying risks and unintended consequence. *Biochar*, *7*(1), 12. <https://doi.org/10.1007/s42773-024-00412-4>
- Elsamadony, M., Mostafa, A., Fujii, M., Tawfik, A., & Pant, D. (2021). Advances towards understanding long chain fatty acids-induced inhibition and overcoming strategies for efficient anaerobic digestion process. In *Water Research* (Vol. 190). Elsevier Ltd. <https://doi.org/10.1016/j.watres.2020.116732>
- Feng, K., Ansari, A. J., Zhang, N., Peng, Y., & Song, X. (2025). Biochar addition to mitigate oil inhibition in anaerobic digestion of food wastewater: Microbial insights from biochemical methane potential tests. *Environmental Technology & Innovation*, *37*, 104000. <https://doi.org/10.1016/j.eti.2024.104000>
- Fu, S., Angelidaki, I., & Zhang, Y. (2021). In situ Biogas Upgrading by CO₂-to-CH₄ Bioconversion. *Trends in Biotechnology*, *39*(4), 336–347. <https://doi.org/10.1016/j.tibtech.2020.08.006>
- Ganesapillai, M., Mehta, R., Tiwari, A., Sinha, A., Bakshi, H. S., Chellappa, V., & Drewnowski, J. (2023). Waste to energy: A review of biochar production with emphasis on mathematical modelling and its applications. *Heliyon*, *9*(4), e14873. <https://doi.org/10.1016/j.heliyon.2023.e14873>
- Gautam, R. K., Vithanage, N., More, N., Muthukumar, S., & Navaratna, D. (2024). Biomethane recovery performance and microbial community dynamics of a high-biomass submerged AnMBR (HBSAnMBR) treating abattoir wastewater. *Biochemical Engineering Journal*, *205*. <https://doi.org/10.1016/j.bej.2024.109275>
- George, M. (2022). Unravelling the impact of potentially toxic elements and biochar on soil: A review. *Environmental Challenges*, *8*, 100540. <https://doi.org/10.1016/j.envc.2022.100540>
- Gotore, O., Nguyen, T. T., Masere, T. P., Shumba, A., Gumbo, A., Sittisom, P., Heritier, M. A., & Itayama, T. (2025). Biochar-synergy in anaerobic digestion of animal wastes for total pollution control and bioenergy production: A sustainable integrated perspective. *Cleaner Chemical Engineering*, *11*, 100177. <https://doi.org/10.1016/j.clce.2025.100177>

- Gustafsson, M., Ammenberg, J., & Murphy Jerry D. (2022). *IEA Bioenergy Task 37- A perspective on the state of the biogas industry from selected member countries*.
- Gutu, L., Basitere, M., Harding, T., Ikumi, D., Njoya, M., & Gaszynski, C. (2021). Multi-integrated systems for treatment of abattoir wastewater: A review. In *Water (Switzerland)* (Vol. 13, Issue 18). MDPI. <https://doi.org/10.3390/w13182462>
- Habchi, S., Pecha, J., Šánek, L., Karouach, F., & El Bari, H. (2024). Sustainable valorization of slaughterhouse waste through anaerobic digestion: A circular economy perspective. *Journal of Environmental Management*, *366*, 121920. <https://doi.org/10.1016/j.jenvman.2024.121920>
- Hanum, F., Atsuta, Y., & Daimon, H. (2022). Methane Production Characteristics of an Anaerobic Co-Digestion of Pig Manure and Fermented Liquid Feed. *Molecules*, *27*(19), 6509. <https://doi.org/10.3390/molecules27196509>
- Havukainen, J., & Dace, E. (2023). Waste to energy and circular economy: the case of anaerobic digestion. In *Sustainable and Circular Management of Resources and Waste Towards a Green Deal* (pp. 105–115). Elsevier. <https://doi.org/10.1016/B978-0-323-95278-1.00017-6>
- He, J. T., Yao, N., Sun, Z. Y., Li, F., Cai, H. Q., Jin, L. F., & Tang, Y. Q. (2023). Improved biogas production from tobacco processing waste via biochar-assisted thermophilic anaerobic digestion. *Industrial Crops and Products*, *202*. <https://doi.org/10.1016/j.indcrop.2023.117038>
- Huang, X., Miao, X., Chu, X., Luo, L., Zhang, H., & Sun, Y. (2023). Enhancement effect of biochar addition on anaerobic co-digestion of pig manure and corn straw under biogas slurry circulation. *Bioresource Technology*, *372*. <https://doi.org/10.1016/j.biortech.2023.128654>
- Ibigbami, B. T., Adewuyi, S. O., Akinsorotan, A. M., Sobowale, A. A., Odoh, I. M., Aladetuyi, A., Mohammed, S. E., Nelana, S. M., & Ayanda, O. S. (2023). Advanced oxidation processes: a supplementary treatment option for recalcitrant organic pollutants in Abattoir wastewater. *Journal of Applied Research and Technology*, *21*(6), 1019–1041. <https://doi.org/10.22201/icat.24486736e.2023.21.6.2212>
- Ihoeghian, N. A., Amenaghawon, A. N., Ogoofure, A., Oshoma, C. E., Ajieh, M. U., Erhunmwunse, N. O., Obuekwe, I. S., Edosa, V. I. O., Tongo, I., Emokaro, C., Ezemonye, L. I. N., Semple, K. T., & Martin, A. D. (2023). Biochar-facilitated batch co-digestion of food waste and cattle rumen content: An assessment of process stability, kinetic studies, and pathogen fate. *Green Technologies and Sustainability*, *1*(3), 100035. <https://doi.org/10.1016/j.grets.2023.100035>
- Kabeyi, M. J. B., & Olanrewaju, O. A. (2020). *Optimization of Biogas Production for Optimal Abattoir Waste Treatment with Bio-Methanation as Solution to Nairobi Slaughterhouses Waste Disposal*.
- Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas Production and Applications in the Sustainable Energy Transition. *Journal of Energy*, *2022*, 1–43. <https://doi.org/10.1155/2022/8750221>

- Khoei, S., Stokes, A., Kieft, B., Kadota, P., Hallam, S. J., & Eskicioglu, C. (2021). Biochar amendment rapidly shifts microbial community structure with enhanced thermophilic digestion activity. *Bioresource Technology*, *341*. <https://doi.org/10.1016/j.biortech.2021.125864>
- Kothari, R., Azam, R., Bharti, A., Gorla, K., Allen, T., Ashokkumar, V., Pathania, D., Singh, R. P., & Tyagi, V. V. (2024). Biobased treatment and resource recovery from slaughterhouse wastewater via reutilization and recycling for sustainable waste approach. In *Journal of Water Process Engineering* (Vol. 58). Elsevier Ltd. <https://doi.org/10.1016/j.jwpe.2023.104712>
- Krysanova, K., Krylova, A., Kulikova, M., Kulikov, A., & Rusakova, O. (2022). Biochar characteristics produced via hydrothermal carbonization and torrefaction of peat and sawdust. *Fuel*, *328*, 125220. <https://doi.org/10.1016/j.fuel.2022.125220>
- Kulabako, R. N., Semiyaga, S., Tumwesige, R. S., Irumba, C., Opio, M. I., Manga, M., Tumwesige, V., Quintana-Najera, J., & Ross, A. B. (2025). Enhanced biogas production from water hyacinth and cow dung with wood and faecal sludge biochar. *Energy Nexus*, *17*, 100342. <https://doi.org/10.1016/j.nexus.2024.100342>
- Kumar, M., Dutta, S., You, S., Luo, G., Zhang, S., Show, P. L., Sawarkar, A. D., Singh, L., & Tsang, D. C. W. (2021). A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. *Journal of Cleaner Production*, *305*, 127143. <https://doi.org/10.1016/j.jclepro.2021.127143>
- Kundu, R., Kunnoth, B., Pilli, S., Polisetty, V. R., & Tyagi, R. D. (2023). Biochar symbiosis in anaerobic digestion to enhance biogas production: A comprehensive review. *Journal of Environmental Management*, *344*, 118743. <https://doi.org/10.1016/j.jenvman.2023.118743>
- Li, D., Sun, M., Xu, J., Gong, T., Ye, M., Xiao, Y., & Yang, T. (2022). Effect of biochar derived from biogas residue on methane production during dry anaerobic fermentation of kitchen waste. *Waste Management*, *149*, 70–78. <https://doi.org/10.1016/j.wasman.2022.06.006>
- Li, J., Sun, W., Lichtfouse, E., Maurer, C., & Liu, H. (2024). Life cycle assessment of biochar for sustainable agricultural application: A review. *Science of The Total Environment*, *951*, 175448. <https://doi.org/10.1016/j.scitotenv.2024.175448>
- Li, L., Niu, W., Cong, H., Meng, H., Niu, Z., Shen, X., Cao, L., & Kong, X. (2023). Effects of pyrolysis temperature on the release characteristics of polycyclic aromatic hydrocarbons during pyrolysis of corn stover pellet. *BioResources*, *18*(1), 2112–2136. <https://doi.org/10.15376/biores.18.1.2112-2136>
- Li, L., Xu, Y., Dai, X., & Dai, L. (2021). Principles and advancements in improving anaerobic digestion of organic waste via direct interspecies electron transfer. *Renewable and Sustainable Energy Reviews*, *148*, 111367. <https://doi.org/10.1016/j.rser.2021.111367>

- Li, Y., Cheng, Z., Shang, H., Chen, Y., Li, S., Wei, X., Wang, T., Zhou, W., & Yu, Y. (2025). Design of functional groups on biochar for sulfamethoxazole adsorption from adsorption efficiency and adsorption mechanism. *Journal of Environmental Chemical Engineering*, *13*(3), 116874. <https://doi.org/10.1016/j.jece.2025.116874>
- Liu, G., Liu, Y., Frankó, B., Yang, H., Zheng, D., Deng, L., & Liu, J. (2022). Animal wastewater treatment with an improved combined Anaerobic-Aerobic System: Towards energy Self-Sufficiency. *Applied Energy*, *323*. <https://doi.org/10.1016/j.apenergy.2022.119551>
- Liu, Y., He, P., Duan, H., Shao, L., & Lü, F. (2021). Low calcium dosage favors methanation of long-chain fatty acids. *Applied Energy*, *285*. <https://doi.org/10.1016/j.apenergy.2020.116421>
- Lü, F., Wang, Z., Zhang, H., Shao, L., & He, P. (2021). Anaerobic digestion of organic waste: Recovery of value-added and inhibitory compounds from liquid fraction of digestate. *Bioresource Technology*, *333*, 125196. <https://doi.org/10.1016/j.biortech.2021.125196>
- Ma, J., Yao, Z., & Zhao, L. (2023). Comprehensive study of the combined effects of biochar and iron-based conductive materials on alleviating long chain fatty acids inhibition in anaerobic digestion. *Environmental Research*, *239*, 117446. <https://doi.org/10.1016/j.envres.2023.117446>
- Meier, S., de Souza Campos, P. M., Palma-Millanao, R., Rojas, N., González, M.-E., Muñoz, S., Ondrasek, G., Naser, K., Hirzel, J., & Seguel, A. (2025). Biochar-based controlled-release ammonium phosphate fertilizer: Synthesis and impact on soil nutrient dynamics, wheat growth, and yield under controlled conditions. *Environmental Technology & Innovation*, *39*, 104269. <https://doi.org/10.1016/j.eti.2025.104269>
- Moreroa, M., (2025). South African wastewater treatment plants as a resource for energy: a mini review. *Discover Water*, *5*(1),65. <https://doi.org/10.1007/s43832-025-00267-1>
- Moreroa, M., & Motshekga, S. C. (2024). The feasibility of using biogas generated from livestock manure as an alternative energy source: A South African perspective. *Journal of Energy in Southern Africa*, *35*(1), 1-16. <https://dx.doi.org/10.17159/2413-3051/2023/v35i1a17021>
- Mudzanani, K., Iyuke, S. E., & Daramola, M. O. (2022). Co-digestion of wastewater treatment sewage sludge with various biowastes: A comparative study for the enhancement of biogas production. *Materials Today: Proceedings*, *65*, 2172–2183. <https://doi.org/10.1016/j.matpr.2022.05.539>
- Nandomah, S., & Tetteh, I. K. (2023). Potential ecological risk assessment of heavy metals associated with abattoir liquid waste: A narrative and systematic review. *Heliyon*, *9*(8), e17359. <https://doi.org/10.1016/j.heliyon.2023.e17359>
- Nassar, A., Al-Najar, H., Abukmeil, R., & Al-Sa'ed, R. (2022). A feasible scheme for slaughterhouse wastewater treatment using an anaerobic digestion batch

- reactor followed by an aerobic treatment stage. *Desalination and Water Treatment*, 275, 260–267. <https://doi.org/10.5004/dwt.2022.28966>
- Nie, W., He, S., Lin, Y., Cheng, J. J., & Yang, C. (2024). Functional biochar in enhanced anaerobic digestion: Synthesis, performances, and mechanisms. *Science of The Total Environment*, 906, 167681. <https://doi.org/10.1016/j.scitotenv.2023.167681>
- Ning, X., Deng, C., Hickey, D. T., Hackula, A., O'Shea, R., Wall, D. M., Lin, R., & Murphy, J. D. (2023). Improving biomethane production from biochar-supplemented two-stage anaerobic digestion of on-farm feedstocks. *Journal of Cleaner Production*, 423, 138723. <https://doi.org/10.1016/j.jclepro.2023.138723>
- Olugbenga, O.S., Adeleye, P.G., Oladipupo, S.B., Adeleye, A.T. and John, K.I. (2024) 'Biomass-derived biochar in wastewater treatment: a circular economy approach', *Waste Management Bulletin*, 1(4), pp. 1–14. <https://doi.org/10.1016/j.wmb.2023.07.007>
- Pan, J., Sun, J., Ao, N., Xie, Y., Zhang, A., Chen, Z., & Cai, L. (2022). Factors Influencing Biochar-Strengthened Anaerobic Digestion of Cow Manure. *BioEnergy Research*, 17(2), 1145–1154. <https://doi.org/10.1007/s12155-022-10396-3>
- Pant, A., & Rai, J. P. N. (2021). Application of Biochar on methane production through organic solid waste and ammonia inhibition. *Environmental Challenges*, 5, 100262. <https://doi.org/10.1016/j.envc.2021.100262>
- Patel, M. R., & Panwar, N. L. (2023). Biochar from agricultural crop residues: Environmental, production, and life cycle assessment overview. *Resources, Conservation & Recycling Advances*, 19, 200173. <https://doi.org/10.1016/j.rcradv.2023.200173>
- Ragasri, S., & Sabumon, P. C. (2023). A critical review on slaughterhouse waste management and framing sustainable practices in managing slaughterhouse waste in India. *Journal of Environmental Management*, 327, 116823. <https://doi.org/10.1016/j.jenvman.2022.116823>
- Rajagopal, R. (2025). Enhancing low-temperature anaerobic digestion of nitrogen-rich feedstocks: Mitigating free ammonia and short-chain fatty acid inhibitions. *Bioresource Technology Reports*, 29, 102032. <https://doi.org/10.1016/j.biteb.2025.102032>
- Rasapoor, M., Young, B., Brar, R., Sarmah, A., Zhuang, W.-Q., & Baroutian, S. (2020). Recognizing the challenges of anaerobic digestion: Critical steps toward improving biogas generation. *Fuel*, 261, 116497. <https://doi.org/10.1016/j.fuel.2019.116497>
- Ravi, S., Li, J., Meng, Z., Zhang, J., & Mohanty, S. (2020). Generation, Resuspension, and Transport of Particulate Matter From Biochar-Amended Soils: A Potential Health Risk. *GeoHealth*, 4(11). <https://doi.org/10.1029/2020GH000311>
- Sharma, B., & Suthar, S. (2021). Enriched biogas and biofertilizer production from Eichhornia weed biomass in cow dung biochar-amended anaerobic digestion

- system. *Environmental Technology and Innovation*, 21. <https://doi.org/10.1016/j.eti.2020.101201>
- Shen, R., Jing, Y., Feng, J., Zhao, L., Yao, Z., Yu, J., Chen, J., & Chen, R. (2021). Simultaneous carbon dioxide reduction and enhancement of methane production in biogas via anaerobic digestion of cornstalk in continuous stirred-tank reactors: The influences of biochar, environmental parameters, and microorganisms. *Bioresource Technology*, 319. <https://doi.org/10.1016/j.biortech.2020.124146>
- Shi, Y., Liu, M., Li, J., Yao, Y., Tang, J., & Niu, Q. (2022). The dosage-effect of biochar on anaerobic digestion under the suppression of oily sludge: Performance variation, microbial community succession and potential detoxification mechanisms. *Journal of Hazardous Materials*, 421, 126819. <https://doi.org/10.1016/j.jhazmat.2021.126819>
- Sia, C. J., Kooh, M. R. R., & Lim, L. H. (2025). Polycyclic aromatic hydrocarbons in biochar: Influence of thermochemical parameters and analytical considerations. *Journal of Analytical and Applied Pyrolysis*, 192, 107296. <https://doi.org/10.1016/j.jaap.2025.107296>
- Soja, G., Sørensen, A., Droszg, B., Gabauer, W., Ortner, M., Schumergruber, A., Dunst, G., Meitner, D., Guillen-Burrieza, E., & Pfeifer, C. (2023). Abattoir residues as nutrient resources: Nitrogen recycling with bone chars and biogas digestates. *Heliyon*, 9(4). <https://doi.org/10.1016/j.heliyon.2023.e15169>
- Sugiarto, Y., Sunyoto, N. M. S., Zhu, M., Jones, I., & Zhang, D. (2021). Effect of biochar addition on microbial community and methane production during anaerobic digestion of food wastes: The role of minerals in biochar. *Bioresource Technology*, 323, 124585. <https://doi.org/10.1016/j.biortech.2020.124585>
- Thakur, N., Sharma, M., Alghamdi, H., Zheng, Y., Xue, W., Jeon, B.-H., Salama, E.-S., & Li, X. (2023). A recent trend in anaerobic digestion (AD): Enhancement of microbiome and digestibility of feedstocks via abiotic stress factors for biomethanation. *Chemical Engineering Journal*, 472, 145047. <https://doi.org/10.1016/j.cej.2023.145047>
- Tong, S., Zhao, Y., Li, J., Wei, J., & Li, J. (2023). Advanced removal of organics and nitrogen in upgraded anaerobic-aerobic slaughterhouse wastewater treatment process. *Desalination and Water Treatment*, 308, 80–89. <https://doi.org/10.5004/dwt.2023.29940>
- Tripathi, A., Ekanayake, A., Tyagi, V. K., Vithanage, M., Singh, R., & Rao, Y. R. S. (2025). Emerging contaminants in polluted waters: Harnessing Biochar's potential for effective treatment. *Journal of Environmental Management*, 373, 123778. <https://doi.org/10.1016/j.jenvman.2024.123778>
- United Nations. (2025). *Sustainable development Agenda item 6 High-level political forum on sustainable development, convened under the auspices of the Economic and Social Council Progress towards the Sustainable Development Goals*. https://docs.un.org/en/a/80/81&i=A/80/81_1748035261784

- Vongvichiankul, C., Deebao, J., & Khongnakorn, W. (2017). Relationship between pH, Oxidation Reduction Potential (ORP) and Biogas Production in Mesophilic Screw Anaerobic Digester. *Energy Procedia*, *138*, 877–882. <https://doi.org/10.1016/j.egypro.2017.10.113>
- Wang, C., Zhao, A., Qi, M., & Jiang, Y. (2026). Characteristics of tetracycline adsorption by different embedded biochar materials. *Journal of Contaminant Hydrology*, *277*, 104833. <https://doi.org/10.1016/j.jconhyd.2025.104833>
- Wang, H., Huang, F., Zhao, Z.-L., Wu, R.-R., Xu, W.-X., Wang, P., & Xiao, R.-B. (2021). High-efficiency removal capacities and quantitative adsorption mechanisms of Cd²⁺ by thermally modified biochars derived from different feedstocks. *Chemosphere*, *272*, 129594. <https://doi.org/10.1016/j.chemosphere.2021.129594>
- Wang, L., Wang, Z., Wang, Z., & Zheng, J. (2024). Integrated aerobic-anaerobic digestion of highly solids-loaded corn stover and swine manure under dynamic aeration: Temperature rise, physicochemical characteristics, and methane production. *Journal of Environmental Management*, *366*. <https://doi.org/10.1016/j.jenvman.2024.121864>
- Wang, S., Wang, Z., Usman, M., Zheng, Z., Zhao, X., Meng, X., Hu, K., Shen, X., Wang, X., & Cai, Y. (2023). Two microbial consortia obtained through purposive acclimatization as biological additives to relieve ammonia inhibition in anaerobic digestion. *Water Research*, *230*, 119583. <https://doi.org/10.1016/j.watres.2023.119583>
- Wenjing, T., Qin, J., Liu, J., Liu, F., & Gu, L. (2022). Effects of pine sawdust and shrimp shell biochar on anaerobic digestion under different acidification conditions. *Journal of Environmental Chemical Engineering*, *10*(1), 106581. <https://doi.org/10.1016/j.jece.2021.106581>
- Wu, X., Zhou, Y., Liang, M., Lu, X., Chen, G., & Zan, F. (2022). Insights into the role of biochar on the acidogenic process and microbial pathways in a granular sulfate-reducing up-flow sludge bed reactor. *Bioresour Technol*, *355*, 127254. <https://doi.org/10.1016/j.biortech.2022.127254>
- Xia, F., Zhang, Z., Zhang, Q., Huang, H., & Zhao, X. (2024). Life cycle assessment of greenhouse gas emissions for various feedstocks-based biochars as soil amendment. *Science of The Total Environment*, *911*, 168734. <https://doi.org/10.1016/j.scitotenv.2023.168734>
- Yin, C., Shen, Y., Yuan, R., Zhu, N., Yuan, H., & Lou, Z. (2019). Sludge-based biochar-assisted thermophilic anaerobic digestion of waste-activated sludge in microbial electrolysis cell for methane production. *Bioresour Technol*, *284*, 315–324. <https://doi.org/10.1016/j.biortech.2019.03.146>
- You, J., Farghali, M., Osman, A. I., Yoshida, G., & Ihara, I. (2024). Mechanisms of biochar-mediated reduction of antibiotic-resistant bacteria and biogas production enhancement in anaerobic digesters. *Biochemical Engineering Journal*, *211*. <https://doi.org/10.1016/j.bej.2024.109465>
- Zeynali, R., Asadi, M., Ankley, P., Esser, M., Brinkmann, M., Soltan, J., & McPhedran, K. (2024). Sustainable enhancement of biogas production from a

cold-region municipal wastewater anaerobic digestion process using optimized sludge-derived and commercial biochar additives. *Journal of Cleaner Production*, 478, 143948.

<https://doi.org/10.1016/j.jclepro.2024.143948>

Zhao, W., Yang, H., He, S., Zhao, Q., & Wei, L. (2021). A review of biochar in anaerobic digestion to improve biogas production: Performances, mechanisms and economic assessments. In *Bioresource Technology* (Vol. 341). Elsevier Ltd. <https://doi.org/10.1016/j.biortech.2021.125797>

Zhao, Z., Li, Y., Zhang, Y., & Lovley, D. R. (2020). Sparking Anaerobic Digestion: Promoting Direct Interspecies Electron Transfer to Enhance Methane Production. *iScience*, 23(12), 101794.

<https://doi.org/10.1016/j.isci.2020.101794>

Zhu, M., Liu, Y., Xu, J., & He, Y. (2023). Compound-specific stable isotope analysis for characterization of the transformation of γ -HCH induced by biochar. *Chemosphere*, 314, 137729.

<https://doi.org/10.1016/j.chemosphere.2022.137729>

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