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REVIEW ARTICLE

Bioenergy production from chicken manure: a review

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Abstract

Adopting waste-to-wealth strategies and circular economy models can help reduce biowaste and add value. For instance, poultry farming is an essential source of protein, and chicken manure can be converted into renewable energy through anaerobic digestion. However, there are a number of restrictions that prevent the utilization of chicken manure in bioenergy production. Here, we review the conversion of chicken manure into biomethane by anaerobic digestion with focus on limiting factors, strategies to enhance digestion, and valorization. Limiting factors include antibiotics, ammonia, fatty acids, trace elements, and organic compounds. Digestion can be enhanced by co-digestion with sludge, lignocellulosic materials, food waste, and green waste; by addition of additives such as chars, hydrochars, and conductive nanoparticles; and by improving the bacterial community. Chicken manure can be valorized by composting, pyrolysis, and gasification. We found that the growth of anaerobic organisms is inhibited by low carbon-to-nitrogen ratios. The total biogas yield decreased from 450.4 to 211.0 mL/g volatile solids in the presence of *Staphylococcus* aureus and chlortetracycline in chicken manure. A chlortetracycline concentration of 60 mg/kg or less is optimal for biomethanization, whereas higher concentrations can inhibit biomethane production. The biomethane productivity is reduced by 56% at oxytetracycline concentrations of 10 mg/L in the manure. Tylosin concentration exceeding 167 mg/L in the manure highly deteriorated the biomethane productivity due to an accumulation of acetate and propionate in the fermentation medium. Anaerobic co-digestion of 10% of primary sludge to 90% of chicken manure increased the biogas yield up to 8570 mL/g volatile solids. Moreover, chemicals such as biochar, hydrochar, and conducting materials can boost anaerobic digestion by promoting direct interspecies electron transfer. For instance, the biomethane yield from the anaerobic digestion of chicken manure was improved by a value of 38% by supplementation of biochar.

Keywords Chicken manure · Anaerobic digestion · Mono-digestion · Co-digestion · Biochar

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Introduction

In recent decades, the production and consumption of energy in relation to urbanization, modernization, and industrialization have become increasingly significant in a variety of economic, scientific, and social sectors. In addition, the anticipated 10-billion-person global population by 2050 is a significant and pressing issue that necessitates increased food security and energy production (Allam et al. 2015; Manogaran et al. 2020; Osman et al. 2022). Therefore, investigating alternative solutions is crucial for resolving the impending global energy crisis and rising biofuel demands while also taking environmental issues and their mitigation into account (Ji et al. 2015; Elsayed et al. 2020). The vast majority of the world's energy needs are met by fossil fuels, but their greenhouse gas emissions pose a serious environmental threat (Tawfik et al. 2022a). In accordance with the Paris roadmap agreement from December 2015, greenhouse gas emissions must be reduced by 50% by 2050 if the average global temperature rise is to be limited to 2 ℃ (Eraky et al. 2022).

In addition, animals, particularly chickens, have played a crucial role in providing protein sources and promoting global food security. Farming manure is one of the most prevalent organic wastes produced globally, and improper disposal could lead to eutrophication and contamination of water bodies, which raises grave environmental concerns. Several operators have adopted anaerobic digestion, which converts carbon waste into biogas, an important source of renewable energy, in order to address this issue (Sobhi et al. 2019; Elsayed et al. 2022). Untreated chicken waste emits an offensive odor that attracts vermin and rodents, spreads infections, and poses a significant threat to human health. Therefore, it is necessary to investigate feasible and cost-effective options for the management and application of chicken manure (Duan et al. 2019). Waste-to-wealth is a waste management strategy that aims to recover and add value to waste streams while fostering new technologies, job creation, and environmental benefits (Elreedy et al. 2015). The waste-to-wealth strategy is closely related to the circular economy model, which aims to reduce waste through resource regeneration and recycling (Mostafa et al. 2017). Adopting this paradigm can lead to waste-free value chains and the use of renewable energy and natural resources. It is crucial to modernize systems for managing chicken manure because it can generate circular economy outputs such as energy (Nasrollahzadeh et al. 2019; Manogaran et al. 2022).

Due to the high content of total and volatile solids as well as highly biodegradable substances, chicken manure has a high potential for bioenergy production via the anaerobic digestion process (Elsamadony et al. 2015). However, several challenges limit the anaerobic digestion of chicken manure (Jurgutis et al. 2020). One such limitation is the presence of high concentrations of ammonia and volatile fatty acids in the chicken manure, along with antibiotics and heavy metals that are added to the animal feed, which can negatively affect the anaerobic microorganisms (Mahdy et al. 2020). To overcome these limitations, several practices have been reported to enhance the anaerobic digestion of chicken manure. One such approach is the anaerobic co-digestion technology, in which other feedstocks are added to the chicken manure. It has been found that the addition of other feedstocks can enhance biogas productivity and alleviate inhibitory factors by diluting the ammonia in the substrate and providing more nutrients required for the anaerobes (Magbanua et al. 2001; Wang et al. 2022). The addition of some substances, such as biochar, hydrochar, and conductive materials, can enhance the anaerobic digestion and enhance the direct interspecies electron transfer process. Great attention has been paid to the following reviews for treatment processes of chicken manure (Manogaran et al. 2022), anaerobic digestion of chicken litter, animal manure and green policy(Bhatnagar et al. 2022), ammonia inhibition (Fuchs et al. 2018). However, no comprehensive review focuses on the limiting factors affecting the anaerobic digestion process, i.e., antibiotics and aromatic substances (phenol and catechol) that is extensively addressed here. Furthermore, this review article thoroughly examines the appropriate methods for handling chicken manure and explores potential applications to maximize its benefits. Specifically, it highlights the use of chicken manure as a substrate in anaerobic digestion technology while addressing the limitations and possible solutions for improving the process.

Chicken manure characteristics

Chicken manure characteristics play a big role in choosing the proper management method to save energy and chemical consumption and optimize the bioenergy productivity from such waste (Meky et al. 2021). Chicken manure is rich in organics, ammonia–nitrogen, pathogens, and microorganisms degrading bacteria, as shown in Fig. 1 and reported by Ibrahim et al. (2022). The total solids are 59.16 ± 0.06%; the volatile solids are 48.19 ± 0.24%, and the volatile solids-to-total solids ratio is 80.15%. Chicken manure is a suitable substrate for bioenergy production strategies such as biogas production technologies due to the high total solids content and high biodegradability within chicken manure. Furthermore, the high nutrient contents of chicken manure increased the wide range of exploitation methods. For example, carbon, nitrogen, sulfur, and hydrogen contents of 38.91% ± 0.78, 9.39% ± 0.21, 0.47% ± 0.02, and

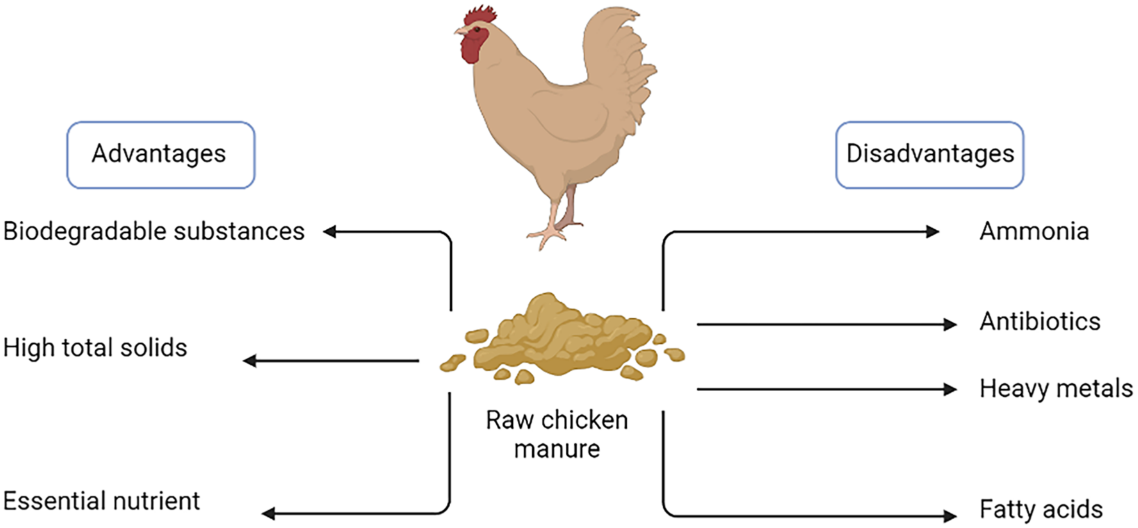

Fig. 1 Characteristics of chicken manure that can aid in selecting the most effective management strategies. Due to an abundance of biodegradable materials, high total solids, and essential nutrients, chicken manure presents a significant advantage for the anaerobic digestion process. The unfavorable components of chicken manure, such as ammonia, antibiotics, heavy metals, and fatty acids, may hinder anaerobic digestion

5.68% ± 0.16, respectively, encourage the land application of chicken manure as fertilizer (Wang et al. 2022).

Due to the high protein and fat content, chicken manure is utilized in the animal feed industry. However, these protein fractions result in high ammonia concentrations and a low carbon-to-nitrogen ratio, which pose significant technological obstacles to biogas production (Bhatnagar et al. 2022). Li et al. (2022) characterized the chicken manure harvested from a company with the following characteristics: total solids (% fresh matter) of 22.82% ± 0.03, volatile solids (%fresh matter) of 19.94% ± 0.1, carbon (%total solids) of 39.42% ± 0.9, hydrogen (% total solids) of 5.53% ± 0.01, nitrogen (% total solids) of 7.32% ± 0.6, and carbon/nitrogen ratio of 5.4 ± 0.5.

In conclusion, considering the composition of chicken manure can improve the effectiveness of an application strategy. It has high biodegradable solid components, which supports the use of chicken manure as a substrate for biogas production; however, high ammonia and lower carbon/nitrogen are significant obstacles to the application of the anaerobic digestion process (Table 1).

Anaerobic digestion as a bioenergy production strategy

Anaerobic digestion is a challenging technology with enormous potential for treating organic waste (Tawfik and Salem 2012). In addition to lowering greenhouse gas emissions, it has the capacity to produce biogas and organic fertilizer. Large-scale operations have demonstrated the technology's viability from an economic standpoint (Ran et al. 2022). Using anaerobic digestion, a type of biorefinery technology, multiple biowaste streams can be converted into digestate and biogas that are rich in nutrients and energy. Additionally, it may reduce the odor and greenhouse gas emissions that biowaste causes. However, the sustainability of anaerobic digestion is contingent on its capacity to control the substantial amount of digestate produced during the process, as inefficient treatment of it could result in significant environmental problems (Eraky et al. 2022). Chicken manure is a viable option for generating renewable energy due to its high biomethane potential, which is one of the highest among all livestock manures. Each kilogram of organic matter in chicken manure is estimated to produce around 0.5 m^3 of biogas containing about 58% methane. According to a commonly used biogas handbook, the methane yield for chicken manure falls within the range of 200–360 mL/g volatile solids (Fuchs et al. 2018).

Although there has been little research on using chicken manure as a sole substrate for anaerobic digestion, it has a substantial degree of biodegradability (Song et al. 2019**). This is due to the high ammonia content in chicken manure, which can raise pH levels and impair the anaerobic digestion process. Moreover, the antibiotics in chicken manure can inhibit the growth of anaerobic organisms, and the low carbon-to-nitrogen ratio makes it difficult for these organisms to survive. Additionally, volatile fatty acids in chicken manure can inhibit anaerobic digestion (Nie et al. 2015; Alhajeri et al. 2022). There are numerous ways to improve the anaerobic digestion of chicken manure through processing. For instance, diluting the substrate can reduce the

Table 1 Basic characteristics of chicken manure

Parameters	Units	Wang et al. (2019)	Hassan et al. (2016)	Wang et al. (2022)	Li et al. (2022); Linsong et al. (2022)	Zhao et al. (2022)
Total solids	wt%	33.2 ± 0.2	29.56	59.16 ± 0.06	22.82 ± 0.03	27.19
Volatile solid	wt%	25.6 ± 0.2	67.04	48.19 ± 0.24	19.94 ± 0.1	16.51
Volatile solids -to- total solids	wt%	77.1	–	80.15	87.3	60.7
Total nitrogen	wt%	–	4.23	9.39 ± 0.21	7.32 ± 0.6	3.12
Carbon	wt%	–	–	38.91 ± 0.78	39.42 ± 0.9	40.20
Hydrogen	wt%	–	–	5.68 ± 0.16	5.53 ± 0.01	5.49
Sulfur	wt%	–	–	0.47 ± 0.02	–	0.68
Total ammonia nitrogen	mg/Kg	2240 ± 11.4	1343.33	–	–	–
Total organic carbon	wt%	321,800 ± 9700	35.95	–	5.4 ± 0.5	–
Carbon-to-nitrogen ratio	-	–	8.51	–	–	–
Cellulose	wt%	–	–			
Hemicellulose	wt%	–	–	–	–	–
Lignin	wt%	–	10.13			
pH	–	7.71 ± 0.2	7.78	8.66	–	–
Alkalinity	mg/L	6270 ± 24.5	–	-	–	-

The volatile organics are significant in the chicken manure that increased the biodegradability. The carbon-to-nitrogen ratio is an important parameter affecting the biogas productivity. The anaerobic digestion process type, either dry or wet, highly depends on the biosolids composition. Trace elements are essential for the anaerobic digestion process that should be considered for the analysis of chicken manure

toxicity of ammonia, and adjusting the hydrolytic retention time can enhance anaerobe performance (Vanwonterghem et al. 2015; Karki et al. 2021). However, it has been demonstrated that the co-digestion of chicken manure with other organic waste can reduce the negative effects of mono-digestion and increase biogas production.

In conclusion, anaerobic digestion is a promising method for treating chicken manure and producing biogas and organic fertilizer. Although chicken manure has a high biomethane potential, its low carbon-to-nitrogen ratio and other factors can impede anaerobic digestion. Co-digestion of chicken manure and other organic waste can help overcome these obstacles and increase biogas production.

Anaerobic digestion limiting factors

Antibiotics

Chlortetracycline

The infected chicken flocks produce manure contaminated with pathogenic *Staphylococcus aureus* and antibiotic chlortetracycline. Antibiotics, primarily chlortetracycline, are prescribed at the flock level in poultry farms to prevent and control the common disease. Thus, significant quantities of manure containing antibiotics are excreted daily by infected birds into the effluent manure. The anaerobic digestion process could highly destroy *Staphylococcus aureus* populations in chicken manure (Kirby et al. 2019). However, the anaerobic digestion process is highly affected due to the presence of both chlortetracycline and *Staphylococcus aureus* in the manure feedstock resulting in a lower total biogas yield. Total biogas productivity was 450.4 mL/g volatile solids fed for chicken manure and reduced to 434.0 and 416.9 mL/g volatile solids fed for chicken manure containing *Staphylococcus aureus* and chicken manure containing *Staphylococcus aureus* and chlortetracycline, respectively. Likely, chicken manure containing *Staphylococcus aureus* and chlortetracycline produced the lowest methane yield of 211.0 mL/g volatile solids fed. The chicken manure and chicken manure-rich *Staphylococcus aureus* provided methane yields of 223.5 and 220.1 mL/g volatile solids fed, respectively.

Sorption of the chlortetracycline onto the sludge would occur, reducing the inhibition effect of antibiotics (Yin et al. 2016). However, the sorption of chlortetracycline onto the sludge could be reversible and depends on the operational conditions and antibiotic concentration (Spielmeyer 2018). Furthermore, chlortetracycline could be biodegraded by anaerobes existing in the sludge where some anaerobic bacteria have the capability to remove the hydroxyl (OH) and amino (NH_2) groups of the chlortetracycline compound (Yin et al. 2016). Some bacteria could use the antibiotic as a carbon and nitrogen source for their growth and metabolism (Liao et al. 2017). It was reported that 100 µg/L chlortetracycline was removed by 48.7–84.9% in the anaerobic culture bacteria. *Firmicutes*, *Bacteroidetes*, and *Proteobacteria* were the dominant phyla for the biodegradation of chlortetracycline. Chlortetracycline isomerization could have occurred under anaerobic conditions. Yin et al. (2016) found that biomethanization of chicken manure has occurred at chlortetracycline concentration of less than 60 mg/kg total solids. However, (Álvarez et al. 2010) observed that a significant drop in biogas yields of more than 62% is taking place at 60 mg/kg total solids. The stoichiometry of the biomethane fermentation of chlortetracycline is presented in Eq. (1), where 1.0 g of chlortetracycline could produce 0.43 L of biomethane. However, increasing the concentration of chlortetracycline from 60 to 500 mg/kg total solids reduced the biomethane harvesting due to an inhibition effect of the antibiotics on the methane-producing archaea.

$$C_{22}H_{23}ClN_2O_8 + 4H_2O \rightarrow 10CH_4 + 9CO_2 + 2NH_4^+ + HCO_3^- + Cl^- \quad (1)$$

Therefore, chicken manure from infected flocks contains *Staphylococcus aureus* and antibiotics (chlortetracycline), which can reduce the amount of biogas produced during anaerobic digestion. However, if chlortetracycline is biodegraded by anaerobic bacteria and absorbed by sludge, its inhibitory effect can be diminished. A chlortetracycline concentration of 60 mg/kg or less is optimal for biomethanization, whereas higher concentrations can inhibit methane production.

In conclusion, due to the high concentration of oxytetracycline present in animal husbandry, 60–90% of antibiotics are excreted in urine and feces, posing health concerns to humans and preventing the production of biogas from manure. In addition to preventing protein synthesis and peptide development in gram-negative bacteria, oxytetracycline inhibits manure biomethanization when used more than the recommended dose of 40 mg/kg total solids.

Oxytetracycline

Sixty to 90% of antibiotics are excreted daily in animals' urine and feces, posing risks to human health and negatively impacting agricultural activities. However, anaerobes can biodegrade this antibiotic into methane bioenergy (Eq. 2). Theoretically, 1.0 g of oxytetracycline could produce 0.49 L of biomethane. However, increasing oxytetracycline levels from 40 mg/kg total solids to 500 mg/kg total solids reduced the biomethane productivity due to an inhibition of the antibiotic (Yin et al. 2016). Oxytetracycline concentrations in manure varied from 0 to 121.8 mg/kg total solids (Agga et al. 2020). The application of anaerobic digestion for biogas harvesting from manure could be inhibited due to the presence of high concentrations of oxytetracycline (Ince et al. 2013).

Oxytetracycline levels in the manure slurry decreased from 20 to 0 mg/L and exhibited 50% inhibition in methane harvesting during the anaerobic digestion (Ince et al. 2013). Biogas harvesting from anaerobic digestion of manure containing oxytetracycline levels of 20, 50, and 80 mg/L was reduced by 43.83, 65.1, and 77.79%, respectively (Ke et al. 2014). Likely, the biomethane productivity was reduced by values of 56, 60, and 62% at oxytetracycline concentrations of 10, 50, and 100 mg/L in the manure, respectively (Álvarez et al. 2010).

Yin et al. (2016) found that the biochemical methane potential of the anaerobic digestion of manure-rich oxytetracycline is feasible at a concentration not exceeding 40 mg/kg total solids where the antibiotic could be completely eliminated and converted into biomethane. However, oxytetracycline above the thresholds inhibited manure biomethanization, and the antibiotic removal rate exponentially decreased at levels of 40–100 mg/kg total solids. Oxytetracycline negatively affects gram-negative microorganisms (methanogen archaea) by combining with the A location of bacterial ribosomes preventing the coupling of tRNA and aminoacyl on the A location. This would inhibit protein synthesis and peptide growth leading to failure of the anaerobic digestion process and bacterial death (Stone et al. 2009; Huang et al. 2014).

$$C_{22}H_{24}N_2O_9 + 15H_2O \rightarrow 11CH_4 + 9CO_2 + 2NH_4^+ + 2HCO_3^- \quad (2)$$

Tylosin

To protect chickens from common diseases, antimicrobials such as tylosin are added to their food. Tylosin is a gram-positive bacteria-active antibiotic. The most effective antibiotic is Tylosin A, which is commonly used in farms. Animal manure excretes greater than 40% of the administered tylosin. Tylosin inhibits protein synthesis by interacting with 50S ribosomal subunits during the anaerobic digestion of manure (Mazzei et al. 1993). However, archaea, particularly acetate-utilizing *Methanosaeta* spp., are not suppressed and are sensitive to high tylosin concentrations due to the prevailing differences in 23S rRNA binding sites (Shimada et al. 2008). The effect of tylosin on the anaerobic degradation of manure was limited; nevertheless, the relative abundance of *Methanosarcinaceae* sp. was quite low.

An anaerobic sequencing batch reactor fed with wastewater containing tylosin concentrations (0, 1.67, and 167 mg/L) was investigated by Shimada et al. (2008). 1.67 mg/L tylosin addition did not affect the reactor performance. However, adding tylosin (167 mg/L) to the reactor highly reduced the biomethane productivity and accumulation of acetate and propionate. Biogas harvesting from butyrate-rich wastewater was fully inhibited in the presence of tylosin. This indicates tylosin inhibited butyrate and propionate oxidizing syntrophic bacteria and, subsequently, methanogenesis process.

In conclusion, chicken manure contains the antibiotic tylosin, which is added to chicken feed and inhibits protein synthesis during anaerobic digestion. Tylosin inhibits butyrate and propionate, thereby oxidizing syntrophic bacteria and decreasing biomethane production, both of which affect the methanogenesis process.

Ammonia

Nitrogen is abundant in chicken manure in urea and protein forms, accounting for 30 and 70% of total nitrogen contents, respectively. During anaerobic digestion, chicken manure's organic nitrogen and uric acid are converted into ammonium–nitrogen, which exists as ions and unionized ammonia. Temperature and pH increase the proportion of ammonia, which is toxic to bacteria by diffusing across their cell membranes (Shapovalov et al. 2020). Numerous stages of anaerobic digestion are shown to be inhibited by a high concentration of total ammonia nitrogen. Particularly sensitive to ammonia are acetoclastic methanogens. Aquatic environments contain both ionized ammonium nitrogen and unionized free ammonia nitrogen, which makes up total ammonia nitrogen. According to the literature, total and free ammonia nitrogen suppressed mesophilic anaerobic digestion of chicken manure at concentrations of 4.5 and 0.7 g/L, respectively. Methane yield declines under ammonia inhibition, and volatile fatty acid accumulation has been seen as a result (Fuchs et al. 2018; Bi et al. 2020).

The mechanism of ammonia toxicity is that high concentrations of extracellular ammonia cells can diffuse into methanogenic bacterial cells and produce ammonium ions, leading to an increase in protons and a pH imbalance. The procedure also requires the cell to expend additional energy in order to pump potassium ions out of the cell, resulting in potassium depletion. This can lead to cytotoxicity (Jiang et al. 2019). Even though ammonia inhibits anaerobic digestion, Wang et al. (2018a, b) reported the role of free ammonia nitrogen in boosting hydrogen production. The authors discovered that free ammonia inhibited all bioprocesses except for acetogenesis but that its inhibition of the hydrogen consumption processes such as homoacetogenesis, methanogenesis, and the sulfate-reducing process was much more severe than that of the hydrolysis and acidogenesis processes.

In conclusion, the high ammonia concentrations in chicken manure pose a significant challenge to anaerobic digestion due to its toxic effects on the anaerobes. However, the free ammonia could direct the anaerobic digestion process toward biohydrogen production.

Fatty acids

The lipid portion of the substrate is hydrolyzed by hydrolytic enzymes during the anaerobic digestion stages. In this stage of hydrolysis, long-chain fatty acids are produced. Due to their toxicity toward anaerobic bacteria, fatty acids have inhibiting effects (Alhajeri et al. 2022). In addition to lowering the pH, fatty acids can inhibit anaerobic digestion's acidogenesis and acetogenesis phases (Elsamadony et al. 2021). Furthermore, the long-chain fatty acids could need more time to by hydrolyzed by the hydrolytic anaerobes, hence increasing the anaerobic digestion time and decreasing the biogas production rates (Meng et al. 2022).

The substrate's carbohydrates and proteins also degraded anaerobically, leading to the formation of pyruvic acids and subsequent volatile fatty acids. The accumulation of these fatty acids inhibits the activity of anaerobes and causes a decline in pH levels. It was reported that the inhibitory threshold of volatile fatty acids is 6.0 g/L (Zhang et al. 2022; Ketsub et al. 2022). Propionate accumulation is a common inhibitory event. Because propionate has a slow degradation rate into biogas, the acidification of the anaerobic digestion system takes place, resulting in the failure of the system (Samarasiri et al. 2019).

In conclusion, the anaerobic digestion of substrates produces long-chain fatty acids. These fatty acids accelerate acidogenesis and acetogenesis, damage bacteria, and reduce biogas production. Carbohydrates and proteins produce pyruvic acids and volatile fatty acids, but their accumulation above 6.0 g/L is inhibitive; propionate accumulation is a common cause of system failure due to its slow breakdown rate into biogas and pH decline.

Trace elements

Chicken manure lacks trace elements such as cobalt, nickel, selenium, molybdenum, and tungsten that highly deteriorate the biomethanization process. Those elements play a necessary role in metabolizing microorganisms degrading organics into bioenergy. Cobalt (1 mg/L), nickel(1.0 mg/L), (0.2 mg/L), molybdenum (0.2 mg/L) and tungsten (0.2 mg/L) supplementation increased the biomethanization of chicken manure from 0.017 ± 0.01 to 0.27 ± 0.03 L/g volatile solids removed at ammonium concentration exceeding 6000 mg/L due to the promoting the growth of hydrogenotrophic methanogens, i.e., *Methanoculleus bourgensis* (Molaey et al. 2018a). The biomethane yield from chicken manure was increased by a value of 50% and reached 0.27 ± 0.01 L/g of volatile solids added with selenium addition (Molaey et al. 2018b). This was due to the selenium supplementation enhanced the digestion process stability and increased the number of *Methanoculleus bourgensis* genera. The addition of cobalt (1 mg/L), nickel (1.0 mg/L), molybdenum (0.2 mg/L), tungsten (0.2 mg/L), and selenium (0.2 mg/L) significantly increased the biomethane yield from 0.13 to 0.32 ± 0.01 L/g volatile solids added due to the growing *Methanobrevibacter*. Anaerobic co-digestion of chicken manure with corn straw and food waste alleviated the deficiency of trace metals and increased the biomethane productivity, yield by 125.3% and microbial composition of *Methanothermobacter* and *Methanoculleus* (Zhu et al. 2022). Corn stover was co-digested with chicken manure to eliminate the problem of trace metals deficiency by (Wei et al. 2021). Iron, cobalt, manganese, molybdenum, and nickel addition increased the biomethane yield by 34.5% from co-digestion of corn stover with chicken manure. Likely, the biomethane yield was increased by 20–39.5% from anaerobic digestion of chicken manure rich with 6000 mg/L with supplementation of 1.0 mg/L for nickel, 1.0 mg/L for cobalt, 0.2 mg/L for molybdenum, 0.2 mg/L for selenium, 0.2 mg/L for tungsten, and 5 mg/L for iron(Molaey et al. 2018a). Anaerobic digestion of chicken manure without trace element addition provided a methane yield of 0.12 m^3 /kg of volatile solids added due to an accumulation of acetic and propionic acid. This biomethane yield was increased up to 0.26 ± 0.03 m^3/ kg of volatile solids added with the addition of trace elements(Molaey et al. 2018c).

In conclusion, microelements such as trace metals are essential for anaerobic digestion. It enhances the metabolism of the organics-rich wastes by anaerobes. However, chicken manure suffers from a deficiency of trace elements that negatively affect the biomethanization process. The co-digestion with other substrates-rich trace elements still represents a promising option for valorizing chicken manure. The addition of trace metals enhanced the microbial community structure for anaerobic digestion of the chicken manure containing a high ammonia concentration of 6000 mg/L.

Organic compounds

Many organic substances could prevent the anaerobic process from occurring. Anaerobic digesters can serve as a collection point for hydrophobic or sludge-bound organic materials. Polar pollutants have the potential to harm bacterial membranes. By disrupting ion gradients, membrane swelling and permeability may ultimately result in cell lysis. Anaerobic processes are known to be sensitive to halogenated aliphatic alkanes, alcohols, halogenated alcohols, aldehydes, ethers, ketones, acrylates, carboxylic acids, amines, nitriles, amides, and pyridine and its derivatives. In addition, a few long-chain fatty acids, surfactants, and detergents have been found to be detrimental to anaerobic digestion (Hernandez and Edyvean 2008). Several types of bacteria involved in anaerobic digestion are shown to be inhibited to varying degrees by aromatic compounds. For instance, phenol and catechol were more detrimental to the digestive system as a whole than the specific process of methanogenesis from acetate. Aromatic chemicals disrupt the processes preceding methanogenesis, thereby reducing biogas production. Overall, aromatic chemicals inhibit hydrolysis and acetogenesis more effectively than methanogenesis (Ali et al. 2021; Ibrahim et al. 2022).

In conclusion, numerous organic compounds can inhibit anaerobic digestion, including hydrophobic substances and polar contaminants that can damage bacterial membranes. Aromatic substances, such as phenol and catechol, have been found to inhibit all stages of anaerobic digestion, with hydrolysis and acetogenesis being impacted more severely than methanogenesis.

Enhancement of chicken manure anaerobic digestion

Co-digestion

Several studies indicate that co-digesting animal manure with different feedstocks increases methane production and is more economically advantageous than anaerobic digestion of animal manure alone, as shown in Fig. 2. During co-digestion, the increased methane yields are attributable to the improved feed-substrate degradability and higher volatile solids concentration, both of which result in a higher methane potential (Rabii et al. 2019). Additional advantages of co-digestion with manure include its use as a carrier for drying feedstocks, the maintenance of the digester's pH, the provision of essential nutrients for microbes, and the provision of the essential anaerobic microorganisms required to initiate the process (Montoro et al. 2019). Hence, co-digestion of complementary feedstocks can greatly improve the stability of microbial communities and subsequent microbial augmentation (Ma et al. 2020).

Co-digestion of untreated primary sludge with raw chicken manure under mesophilic environmental conditions

The yearly chicken manure production in Egypt is 2.3 million tons (Mahmoud et al. 2022). Furthermore, huge amounts of excess sludge from wastewater treatments are produced daily in Egypt. The authors investigated the biogas harvesting from mesophilic anaerobic cofermentation of untreated primary sludge and chicken manure at different ratios. The highest biogas yield of 8570 mL was obtained from cofermentation of 10:90 primary sludge: chicken manure, while the yield was reduced to 5600 mL at a ratio of 90:10 (primary sludge:chicken manure). Excess sludge from wastewater treatment plants poses a serious problem for developing nations. However, the sludge contains volatile fatty acids, less ammonia and is rich in microorganism-degrading

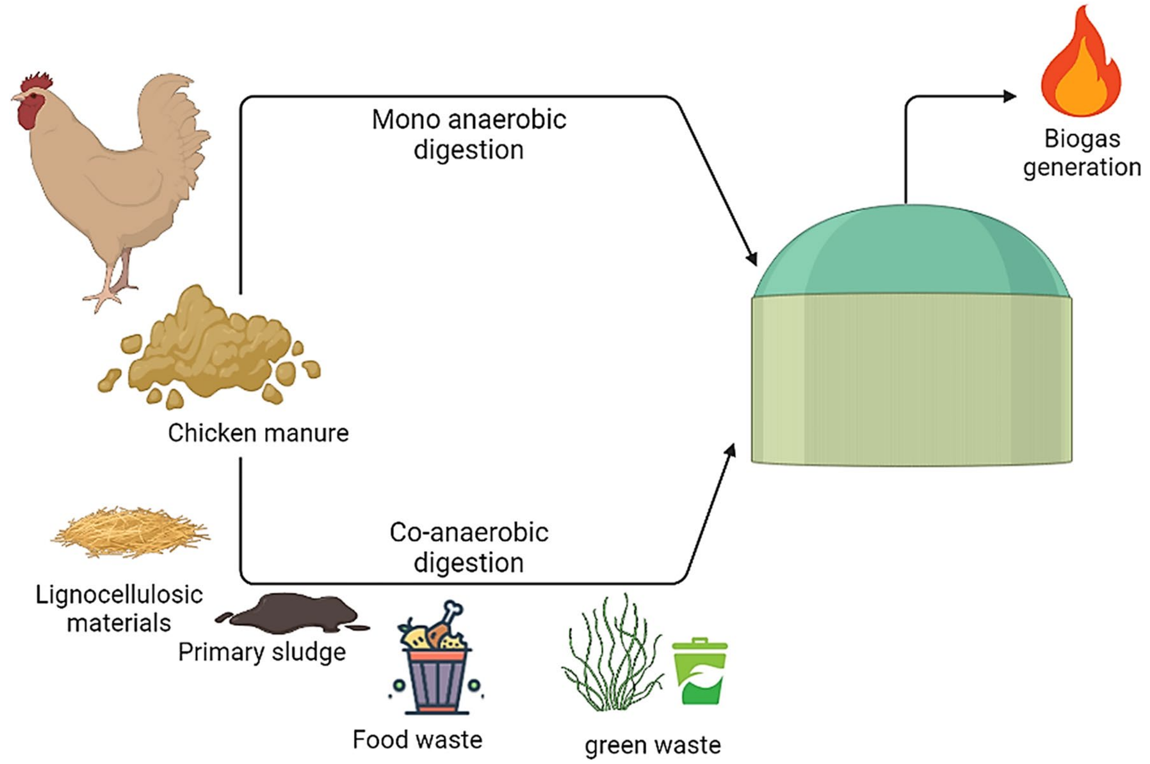

Fig. 2 Anaerobic co-digestion of chicken manure with different feedstocks. Adding lignocellulosic materials, primary sludge, food waste, or green waste could improve the properties of the chicken manure. The supply of essential nutrients for microbes is essential for the anaerobic digestion process. Co-digestion process maintains the pH at a neutral level. Co-substrate fermentation greatly improves the stability of microbial communities and subsequent microbial augmentation

organics (El-Kamah et al. 2010). However, solely anaerobic digestion of sewage sludge yielded low energy productivity due to the limitation of the biodegradable substrate and high carbon/nitrogen ratio, which caused a drop in the microbial producing energy (El-Bery et al. 2013).

Adding chicken manure would enhance bioenergy productivity due to a balanced carbon-to-nitrogen ratio, buffering capacity and supply of sufficient hydrogen and methane-producing microorganisms. Solely anaerobic digestion of sewage sludge provided a biomethane yield of 82.4 mL/g volatile solids added under mesophilic conditions and 33.9 mL/g volatile solids added under thermophilic conditions (Wang et al. 2022). Those values were highly increased with the addition of chicken manure at ratios (1 sewage sludge: 1.5–2 chicken manure) up to 123.1 mL/g volatile solids added under mesophilic and 171.3 mL /g volatile solids added under thermophilic conditions, respectively.

The bacterial communities dominating at thermophilic temperatures were *Firmicutes* (26.4– 37.6%), *Proteobacteria* (5.2–15.7%), *Actinobacteria* (13.5–29.1%), *Thermotogae* (0.6–6.7%), *Chloroflexi* (3.5–15.0%), and *Synergistetes* (0.5–4.4%). The *Firmicutes* are mainly responsible for organics metabolism, particularly hydrolysis and acidogenesis (Elreedy et al. 2019). *Actinobacteria* play a big role in the acidogenesis of organics and produce volatile fatty acids in the fermentation medium(Ali et al. 2021). *Thermotogae* bacteria highly metabolize carbohydrates into fatty acids, and a proper mixing ratio of chicken manure and sewage sludge promotes the microbial metabolism of *Synergistetes* and *Thermotogae* (Tawfik et al. 2014). The archaeal communities at thermophilic conditions were *Methanosaeta* (57.1–84.2%), *Methanospirillum* (3.7–9.0%), *Methanobacterium* (5.0–12.9%), *Methanobrevibacter* (0.5–2.1%), and *Methanolinea* (0.4–5.9%). *Methanosaeta* is known to be a strict aceticlastic organism, and it cannot utilize molecular hydrogen for methane productivity (Farghaly et al. 2019). Methanolinea and Methanospirillum are methanogens necessary for hydrogen scavenging into biomethane and play a role in volatile fatty acid conversion (Qyyum et al. 2022). *Methanobacterium* is mainly a hydrogenotrophic methanogen that has the capability to convert carbon dioxide and hydrogen into methane (Tawfik et al. 2022a). *Methanosarcina* is an efficient archaea methanogen at high total ammonium nitrogen compounds which could highly make a synergism effect between aceticlastic and hydrogenotrophic organisms. The combination of hydrogenotrophic methanogenesis and syntrophic acetate oxidation is the main microbial pathway of biomethane generation from organics degradation.

Hydrogenotrophic reaction by *Methanoculleus*, *Methanobrevibacter*, and *Methanobacterium* (Eq. 3)

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O\Delta G^\circ \left(-135\ \mathrm{KJ/mol\ CH_4}\right) \quad (3)$$

Methanogenesis process by *Methanoculleus* and *Methanobrevibacter* (Eq. 4) and by *Methanoculleus* and *Methanobacterium* (Eq. 5).

$$4HCOOH \rightarrow CH_4 + 3CO_2 + 2H_2O\left(-130\ \mathrm{KJ/mol\ CH_4}\right) \quad (4)$$

$$CO_2 + 4\left(CH_3\right)2CHOH \rightarrow CH_4 + 4CH_3COCH_3 + 2H_2O\left(-37\ \mathrm{KJ/mol\ CH_4}\right) \quad (5)$$

The methylotrophic reaction by *Methanomassiliicoccus* and *Methanobacterium* (Eq. 6)

$$CH_3OH\ +\ H_2 \rightarrow CH_4 + H_2O\ \left(-113\ \mathrm{KJ/mol\ CH_4}\right) \quad (6)$$

Aceticlasitic reaction by *Methanothrix* (Eq. 7)

$$CH_3COOH \rightarrow\ CH_4 + CO_2\left(-33\ \mathrm{KJ/mol\ CH_4}\right) \quad (7)$$

In conclusion, according to research conducted in Egypt on the potential for biogas production by cofermentation of chicken manure and untreated primary sludge at various ratios, the maximum biogas yield was found to be generated from a 10:90 ratio of primary sludge to chicken manure. Due to a balanced carbon-to-nitrogen ratio and the presence of microorganisms, the addition of chicken manure to the anaerobic digestion of sewage sludge enhanced bioenergy production. During the fermentation process, communities of bacteria and archaea were discovered, with diverse species participating in various aspects of organics metabolism and biomethane production.

Lignocellulose materials

Lignocellulosic materials have a high carbon content and cannot be used for anaerobic digestion alone due to their slow decomposition and low methane production. Although pretreatments can increase the potential for biogas production, they may not be economically viable because cellulose hydrolysis is the rate-limiting step in the process. (Peng et al. 2019; Ran et al. 2022). Co-digestion of lignocellulosic materials and chicken manure can balance the carbon-to-nitrogen ratio for anaerobic digestion, produce biogas while retaining a nutrient-rich residue, and produce bioenergy. Co-digestion also has advantages such as improving bacterial variety, optimizing nutrient utilization, decreasing the risk of ammonia inhibition, and enhancing buffering capacity (Karki et al. 2021).

Furthermore, the co-digestion boosts buffering ability, dilutes potentially harmful substances, makes use of nutrients and a variety of microorganisms, and reduces the chance of ammonia inhibition. The high water content of animal manures can dilute the concentrated organic chemicals in lignocellulosic waste, thereby reducing the inhibitory effect on the process. Numerous anaerobic digestion processes that combine animal manure with lignocellulosic by-products or other carbon-rich materials as co-substrates are examined in this context.

Wheat straw is a common agricultural waste that has the potential to be used in the generation of biogas. Due to its high lignocellulose content, the material produces little methane since wheat straw degrades slowly and performs poorly during anaerobic digestion. The wheat straw's ineffectiveness is further constrained by its high carbon-to-nitrogen ratio, which is too high for anaerobic digestion, and its low trace element levels (Chen et al. 2020).

In conclusion, lignocellulosic materials produce little methane and degrade slowly; however, co-digestion with chicken manure can increase biogas production and preserve nutrient-rich residue. Wheat straw, a common agricultural waste, has the potential to produce biogas due to its slow decomposition and high carbon-to-nitrogen ratio, but its use alone is ineffective.

Food waste

Several studies have examined the benefits and difficulties of managing food waste through anaerobic digestion compared with landfills and incineration. Hegde and Trabold (2019) contend that anaerobic digestion is a more environmentally benign method of managing food waste. Although it is common to combine the digestion of animal manure with food waste, there is growing interest in just the digestion of food waste. Researchers have investigated the use of mixed restaurant food waste and other substrates in anaerobic digestion and discovered that stability and methane yield could be affected by factors such as the loading rate of organic material and the addition of trace elements (Zhang et al. 2019; de Jonge et al. 2020).

Anaerobic digesters may benefit from the co-digestion of food waste, and pretreating animal manure with activated carbon and microwave energy before digestion may increase methane production and decrease the genes associated with antibiotic resistance (Paranjpe et al. 2023).

Zhu et al. (2022) found that co-digestion of food waste, corn straw, and chicken manure in two-stage anaerobic digestion significantly increased hydrogen and methane production compared to mono-substrate digestion. The dominant hydrogen production pathways were butyrate and ethanol fermentation, with FW as the main substrate. The highest methane co-digestion efficiency was observed at a foods waste:(corn straw:chicken manure) ratio of 8:2 with a fixed corn straw:chicken manure ratio of 3:1. The easily bioavailable part of trace elements positively correlated with co-digestion efficiency. The increased relative abundance of obligate *hydrogenotrophic* methanogens, specifically *Methanoculleus* and *Methanothermobacter*, suggested positive co-digestion efficiency in the two-stage anaerobic digestion.

In conclusion, the anaerobic digestion of food waste has advantages as well as disadvantages, which have been the focus of numerous studies. Food waste can produce more methane and hydrogen when co-digested with other substrates, whereas stability and methane yield can be affected by factors such as loading rate and trace element addition. Additionally, pretreatment of animal manure with activated carbon and microwave energy may increase methane production and decrease antibiotic resistance genes before digestion.

Anaerobic co-digestion of chicken manure with Enteromorpha and green waste

Enteromorpha prolifera is one of the harmful algal blooms that resulted from pollution and formed during sea tides (Tawfik et al. 2006). Huge quantities of green waste, such as grass clippings, are annually produced and mainly incinerated, releasing harmful oxides. Furthermore, anaerobic digestion of solely green waste and *Enteromorpha prolifera* produced low quantities of biogas due to the difficulty of hydrolysis and the low nitrogen content (Tawfik and Salem 2014). Anaerobic co-digestion with chicken manure that is rich with easily biodegradable organics and nitrogenous compounds would promote microbial activities and subsequently increase the biogas yield. Co-substance of chicken manure was anaerobically digested with *Enteromorpha prolifera* and green waste to improve biomethanization (Zhao et al. 2022). Anaerobic mono-digestion of chicken manure, *Enteromorpha prolifera* and green waste produced biomethane yield of 1.162, 0.948, and 0.963 mL/g volatile solids per hour. Co-digestion of chicken manure: *Enteromorpha prolifera* at a ratio of 2:1 improved biomethane productivity by 32.7%. Further biomethanization improvement of 49.9% was achieved for co-digestion of three substrates of chicken manure, *Enteromorpha prolifera,* and green waste. This was mainly due to the enhancement of cellulase enzyme activities and increased the relative abundance of methanobacterium from 12.0 to 43.7%.

In conclusion, the co-digestion of chicken manure with green waste and *Enteromorpha prolifera* was investigated to enhance biomethanization. Little biogas yields were obtained from anaerobic mono-digestion of these substrates, but biomethane productivity was increased by the co-digestion of chicken manure and *Enteromorpha prolifera* at a 2:1 ratio. Due to primarily the enhanced cellulase enzyme activity and a larger relative abundance of methanobacterium, co-digestion of all three substrates, thereby increased biomethanization by 49.9%.

Additives

The addition of chars mitigates the ammonium inhibition and biogas productivity

Chars were reported to highly reduce the inhibition effect of ammonia, and metal ions, with improving methane yields (Yang et al. 2017; Masebinu et al. 2019). The biochar and hydrochar addition improves methane yields from manures by values ranging from 17 to 500% (Hurst et al. 2022). Biochar derived from rice husk and wood was efficiently used for ammonium elimination from anaerobic digestate (Kizito et al. 2015). The maximum adsorption capacity of wood and rice-husk-derived biochar was 44.64 and 39.8 mg/g, respectively. The adsorption was increased due to an increase in biochar adsorption sites. The adsorption efficiency of both biochars was highly increased with an increase in ammonium (NH_4) concentration, temperature, contact time, and pH. However, increasing the biochar particle size led to a substantial reduction in adsorption capacity (Linville et al. 2017).

Increasing the biochar dosage from 0.1 to 1.0 g enhanced ammonium adsorption from the digestate. At dosages greater than 1.0 g, however, the ammonium adsorption rate degraded dramatically. Lü et al. (2016) investigated the effect of biochar particle size on biogas productivity and ammonium adsorption capacity. The lag phase of ammonium adsorption on biochar was highly reduced by 23.9, 23.8, and 5.9% with biochar particle sizes of 2.5–5, 0.5–1, and 75–150 µm, respectively. Furthermore, the biomethane productivity was increased by 47.1, 23.5, and 44.1% for biochar particle sizes of 2.5–5, 0.5–1, and 75–150 µm, respectively, due to the increased *Methanosarcina* community. This indicates that biochar particle size is the major parameter affecting adsorption and promoting microbial growth. Taghizadeh-Toosi et al. (2012) found that the ammonium was adsorbed by biochar due to the large adsorbent surface area.

The biochar has the ability to adsorb free ammonia during the anaerobic digestion process of citrus waste, as reported earlier (Chen et al. 2008; Solé-Bundó et al. 2019). Torri and Fabbri (2014) found that methane content in the biogas composition increased from 34 to 60% with the addition of biochar derived from corn stalks. The biochar addition reduced the lag phase from 10 days to 5.5–5.9 days in the anaerobic digester (Sunyoto et al. 2016). This further resulted in an increase in biomethane productivity by 41.6%. However, the reactors ceased to produce methane at biochar dosage exceeding 16.6 g/L. The biochar encourages volatile fatty acids productivity during the hydrolysis process and promotes the methanogenesis process. Sunyoto et al. (2016) indicated that biochar adding enhanced the acidogenesis process at a pH of 5 and improved hydrogen productivity and yield by 32.5 and 31%. Similarly, methanogenesis at a pH of 7 and the supplement of biochar increased methane production and yield by 41.6 and 10%, respectively.

Furthermore, the biochar highly reduced the lag phase period by a value of 36% during acidogenesis and 41% during the methanogenesis process. This can be attributed to increased archaea with adding biochar (Luo et al. 2015). Shanmugam et al. (2018) compared biochar with activated carbon for the biomethanization of glucose-rich wastewater in batch anaerobic digestion. The authors found that both biochar and activated carbon promoted a direct interspecies electron transfer process. However, biochar increased the yield of methane by 72%; and activated carbon improved the yield of methane by 40%. This indicates that the biochar has high redox-active species compared with activated carbon, thereby facilitating the transfer of electrons between fermentative bacteria utilizing substrate and methanogens, converting volatile fatty acids, hydrogen, and carbon dioxide.

Likely, biochar supply enhanced the direct interspecies electron transfer process and, subsequently, the biomethanization of wastewater in an upflow anaerobic sludge blanket reactor (Zhao et al. 2016). The biochar-amended upflow anaerobic sludge blanket reactor showed an increase in methane by 16–25% compared with the control digester due to the growing of *Geobacter* and *Methanosaeta.* Due to the promotion of the direct interspecies electron transfer phenomenon, the addition of biochar during the anaerobic digestion process significantly reduces the rate of carbon dioxide production. The removal of carbon dioxide during anaerobic digestion of food waste by adding walnut shell-derived biochar was investigated by Linville et al. (2017). The biochar-amended anaerobic digester improved methane content harvesting by 77.5–98.1% and the carbon dioxide reduction by 40 and 96%. Biochar has a high capacity for the adsorption of carbon dioxide.

The pine and corn-stover-derived biochar-amended anaerobic digesters fed sewage sludge provided an increase in methane content by 9.1 and 25.3%, respectively (Shen et al. 2017). Likely, both biochars at a dosage of 1.75 g/g volatile solids increased the biomethane yield by 16.6% for pine-derived biochar and 36.9% for corn-stover-derived biochar. This indicates that biochar improves the anaerobic digestion stability and enables carbon dioxide adsorption. Wheat straw-derived biochar improved biomethane productivity and yield by 46 and 31% (Mumme et al. 2014). Vegetable waste-derived biochar cleaned biogas from carbon dioxide by a value of 84.2% within 25 min in an adsorption tower (Sahota et al. 2018). Likely, the removal of hydrogen sulfide from biogas exceeded 98% by the addition of biochar during the anaerobic digestion process (Kanjanarong et al. 2017).

In conclusion, adding biochar during anaerobic digestion increases methane production by mitigating the inhibitory effects of ammonia and metal ions. Wood and rice husk biochar effectively remove ammonium from anaerobic digestate; however, the adsorption capacity decreases as biochar particle size increases. In addition, biochar accelerates the acidogenesis and methanogenesis processes, shortens the lag phase, and promotes the growth of archaea and methanogens. Moreover, biochar facilitates the direct interspecies electron transfer process during biomethanization and has a high carbon dioxide adsorption capacity.

Addition of hydrochar

Agriculture wastes subjected to acid hydrolysis yielded a solid residue primarily composed of lignin and recalcitrant lignocellulose. Particularly, these residues are humins. As a byproduct of biorefinery processes, macromolecular humins are produced from carbon-based materials, specifically saccharide-based ones. Humins are comparable to hydrochars. Hydrochars are residues-rich carbonaceous materials resulting from hydrothermal carbonization of biomass using a catalyst under free aqueous conditions. The utilized hydrochar can be used for the anaerobic digestion of chicken manure for enhancement of bio methane productivity. Supplying hydrochar and/or biochar to the fermentation medium could adsorb the fermentation inhibitors existing in the chicken manure and promotes the growth of degrading archaeal and bacterial organics (Nasr et al. 2021). Hydrochar from wood-derived improved biomethane yields by 10% at ammonium concentrations of 4 g/L in the chicken manure (Ganesh et al. 2014). Hurst et al. (2022) found that adding hydrochar (2–10 g/L) increased the methane yields by 14.1% from the anaerobic digestion of chicken manure. 6 g/L of hydrochar adsorbed 20% of ammonium concentrations and highly promoted the growth of microbial diversity, particularly *Firmicutes* and *Bacteroidetes* phyla. Nevertheless, archaea (*Euryarchaeota*) abundance was decreased with the addition of hydrochars. Likely, the biomethane yield from anaerobic digestion of chicken manure was improved by a value of 38% by supplementation of biochar. Hydrochar derived from sewage sludge highly enhanced the methane productivity from glucose by 37% (Ren et al. 2020). Hydrochar increases the biomethane productivity from acetate fermentation and promotes hydrogenotrophic methanogenesis by direct interspecies electron transfer where proton, electron, and carbon dioxide are converted into methane (Fig. 3). The hydrochar accepts electrons from anaerobic bacteria by organic oxidation and donates those electrons to methanogens for harvesting of methane from fermentation of wastes. The electrons are shuttled for direct interspecies electron transfer process to promote the methanogenesis process.

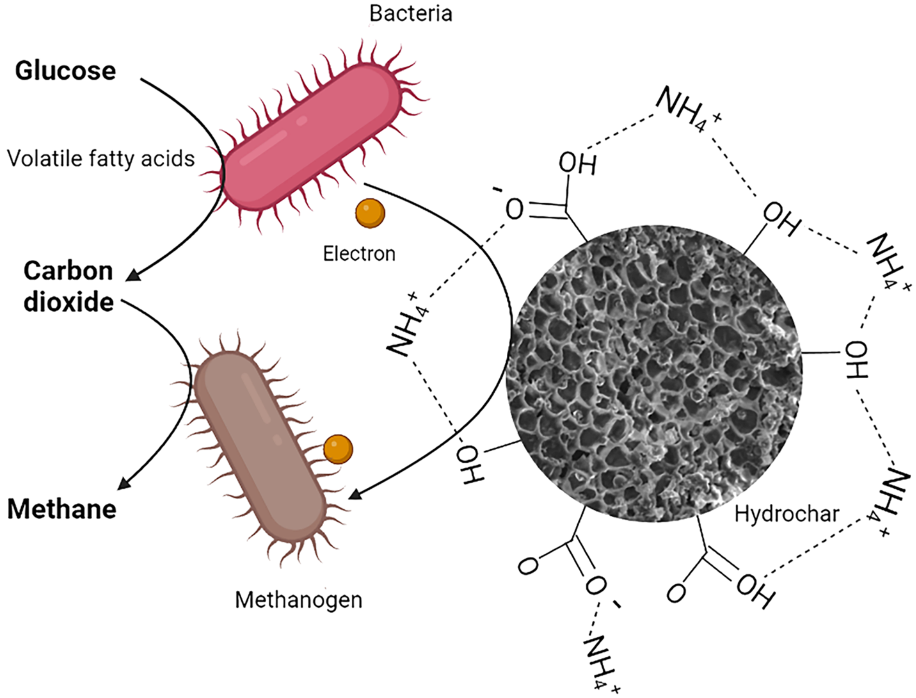

Fig. 3 Hydrochar's contribution to the enhancement of methane production. Hydrochar accepts electrons from anaerobic bacteria via organic oxidation and donates these electrons to methanogens in order to harvest methane from waste fermentation. To promote the methanogenesis process, electrons are transferred directly between anaerobic species. NH_4^+ and OH refer to ammonium and hydroxyl groups. The *Methanosaeta* (*Methanothrix*) was involved in the direct interspecies electron transfer process

Further, the redox activity of biochar served as an electron transfer shuttle and accelerated the process between bacteria and methanogens in the fermentation system. The *Trichococcus* and *Methanosaeta* were abundant with hydrochar added into the fermentation medium. Methanosaeta was highly involved in the direct interspecies electron transfer process, where protein upregulation was involved in the hydrogenotrophic methanogenesis process. The Methanosaeta (*Methanothrix*) was involved in the direct interspecies electron transfer process, where they utilized protons and electrons but not molecular hydrogen for enhancing hydrogenotrophic methanogenesis (Rotaru et al. 2014; Holmes et al. 2017). The authors (Ren et al. 2020) attempted to produce hydrochars from activated carbon, corn straw, poplar wood, and *Enteromorpha* algae and examined them in anaerobic digestion. Supplement of sewage sludge, *Enteromorpha* algae, and corn straw-derived hydrochar increased methane productivity by 39, 20, and 15%, respectively, compared with the control experiment. This was mainly due to hydrochar's redox property, electrical conductivity, and abundant surface functional groups (oxygen-containing).

Addition of conductive nanoparticles materials

As shown in Fig. 4, conductive carbon and non-carbon-based materials served as highly electrical conduits, thereby facilitating direct interspecies electron transfer between the bacterial degrading substrate and methanogen organism's activities. Granular activated carbon, graphite rod, biochar, and carbon cloth could highly accelerate the syntrophic transformation process of alcohols and volatile fatty acids into biomethane via direct interspecies electron transfer process using *methanosarcina barkeri* and *Geobacter metallireducens* (Rotaru et al. 2014; Tawfik et al. 2022c). Luo et al. (2015) found that the biochar established a direct interspecies electron transfer process between anaerobic bacteria and methanogens for the biomethanization of organics. Magnetite and granular activated carbon as conductive materials were used to accelerate and stabilize the organic waste conversion into a biomethane batch digester (Zhao et al. 2017). The results showed that magnetite enhanced the decomposition of the complex organic into simple structure components, and the conductive carbon-based materials highly promoted the syntrophic conversion of volatile fatty acids, hydrogen, and carbon dioxide into biomethane via direct interspecies electron transfer process.

The biomethane productivity was increased by 16% with magnetite addition due to stimulating the methanogenesis. Magnetite-granular activated carbon supplement increased biomethane productivity by up to 80%. This was due to a couple of mechanism actions of the direct interspecies electron transfer process and methanogens growing. Magnetite is a crystalline and insoluble form of ferric and ferrous oxides with a high electrical conductivity that serves as an electron conduit to enhance and improve the direct interspecies electron transfer between syntrophs activities and methanogens archaeal. Methanobacterium species or hydrogen-utilizing methanogens have the capability of maintaining the hydrogen balance and partial pressure in the anaerobic digester that was only 10% of the relative abundance communities in

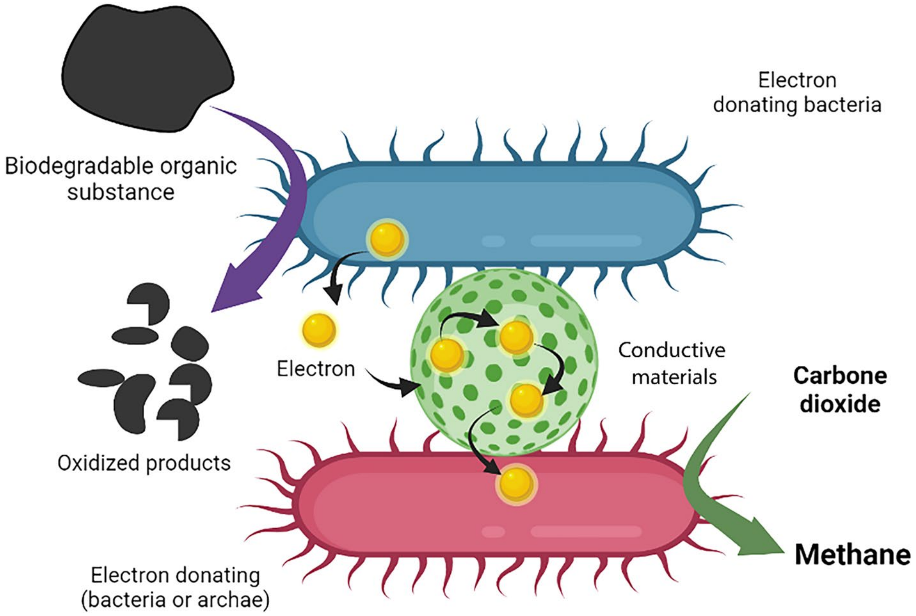

Fig. 4 Conductive nanoparticles material facilitates the direct interspecies electron transfer between electron-donating bacteria and electron-accepting methanogens. The biodegradable substances are oxidized and generate carbon dioxide, which is converted at the end to methane by the action of methanogens. The nanoparticles enhanced the bacterial decomposition of the complex organic into simple structure components. The conductive carbon-based materials highly promoted the syntrophic conversion of volatile fatty acids, hydrogen, and carbon dioxide into biomethane via a direct interspecies electron transfer process. The relative abundance of *Ruminococcaceae* and *Clostridiaceae* is increased by 30% with magnetite nanoparticles addition compared with the control digester

the control and increased to 80% with magnetite supplement. This increase in the abundance of methanobacterium species is described as a magnetite supplement that accelerates the bacterial complex organics decomposition into a simple one with hydrogen generation facilitating the growth of such species. The relative abundance of *Ruminococcaceae* and *Clostridiaceae* was increased by 30% with magnetite addition compared with the control digester.

Furthermore, the *Methanosaeta* species was increased by 10–18% with granular activated carbon supplementation suggesting the potential occurrence of a direct interspecies electron transfer process. Enhancement of biomethanization of dog food waste was taken place by supplementation of granular activated carbon (Dang et al. 2017). The biomethane productivity was increased by 865% due to the addition of granular activated carbon, which improved the volatile solids degradation and chemical oxygen demand by 22 and 167%, respectively. The granular activated carbon (0–5 g) supplied onto the anaerobic digestion process treating sludge materials boosted biomethane productivity by 17.4% (Yang et al. 2017).

In conclusion, conductive carbon and non-carbon materials can promote biomethane production by facilitating direct electron transfer between bacteria and methanogens. Magnetite and granular activated carbon have been demonstrated to enhance the decomposition of complex organics into simpler components and to facilitate the conversion of volatile fatty acids, hydrogen, and carbon dioxide into biomethane. Magnetite or granular activated carbon can increase the number of methanogens in anaerobic digestion processes, such as *Methanobacterium* and *Methanosaeta* species, and significantly improve biomethane productivity.

Enhancement of the bacterial community

The anaerobic digestion of chicken manure is suffered from the inhibition effect of high ammonium accumulation in the fermentation medium due to the imposed high loading rate. The ammonia inhibition of methanogenesis in the fermentation medium is mainly due to the accumulation of volatile fatty acids caused by imposing a high organic loading rate (Tawfik et al. 2022b). Solving the problem of ammonia inhibition onto methanogens by dilution, co-digestion with low carbon-to-nitrogen ratio substrate, pretreatment (sir stripping) and trace elements addition was attempted by several investigators (Tyagi et al. 2021; Uzair Ayub et al. 2021). A culture of propionate degrading methanogenic improved biomethane productivity from chicken manure and overcame the ammonia inhibition by changing the imposed loading rate (Li et al. 2022). Methanogenic culture highly promoted the biomethane yield from chicken manure in an anaerobic digester by 17–26% at an imposed organic loading rate of 2–4 g/ L.d compared with the control digester. This was due to the dominance of *hydrogenotrophic* methanogens and increasing the growth of *aceticlastic Methanothrix* and *Syntrophobacter* (*syntrophic propionate oxidizing bacteria)*.

Nevertheless, the enhancement of biomethane productivity declined to 15–18% at increasing the organic loading rate from 4.0 to 5.0 g/ L.d, and ammonia level of 5.0–8.4 g NH_4^+-N/L. (Linsong et al. 2022) found that bioaugmentation of the anaerobic digestion of chicken manure increased the biomethane yield and shortened the fermentation time. The biomethane yield of digesters was increased by values of 1.2, 1.7, 2.2, 3.4, and 3.6-fold with methanogens supplementation ratios of 0.07, 0.14, 0.21, 0.27, and 0.34 g volatile solids (bioaugmentation seed)/g volatile solids (chicken manure), respectively. This was mainly due to the growing of *Methanothrix*, *Methanobacterium,* and *Methanomassiliicoccus*. Nevertheless, bioaugmentation of methanogenic ratio of 0.34 g volatile solids bioaugmentation seed/g volatile solids chicken manure did not highly improve the biomethanization process.

In conclusion, the accumulation of high levels of ammonium and volatile fatty acids due to high organic loading rates limits the anaerobic digestion of chicken manure. Dilution, co-digestion, and trace element addition have all been tried to overcome ammonia inhibition. The addition of methanogenic cultures can boost biomethane productivity, but the effect diminishes as organic loading rates and ammonia levels rise. Methanogen bioaugmentation can increase biomethane yield and reduce fermentation time, but high ratios do not result in significant improvements.

Valorization of chicken manure

Waste valorization efforts have recently increased in conjunction with the circular economy. The goal of the circular economy is to transition away from the linear economy in order to mitigate the negative environmental effects. The circular economy would reduce waste by regenerating and recycling resources, resulting in cleaner production. The circular economy will undoubtedly result in zero waste and, as a result, value adds chains that use natural resources and renewable energy in connected loops rather than linear flows that facilitate the disposal and depletion of valuable economic resources. One of the promising outcomes of chicken manure valorization could be a circular economy.

Composting

Composting is the aerobic breaks down of chicken manure or any organic under thermophilic conditions to generate stable and free pathogen digestate suitable for agricultural applications (Akdeniz 2019). Four biological steps could be used to compost waste. The first step involves microorganisms hydrolyzing organics (proteins, sugars, and lipids) at a mesophilic temperature of 20–45 °C. These microbial activities cause the compost to heat up to 65–68 °C, changing the reaction medium from mesophilic to thermophilic conditions and killing pathogens (Tuomela et al. 2000) in the second step. In the third step, the compost temperature is reduced, and fungi proliferate to degrade hemicellulose, cellulose, and lignin, producing stable humic substances (Sánchez et al. 2017).

Finally, compost-free pathogens are produced safely and contain sufficient nutrients for agricultural applications (Li 2020). The composting degree is highly dependent on the temperature. (Godlewska et al. 2017) reported that an initial temperature exceeding 40 °C and an oxygen of 900 mg/g volatile solids/h is required for composting. A temperature of 0–10 °C and oxygen demand of 1 mg/g volatile solids/hour are needed to terminate the composting process. In-vessel reactors, aerated and/or static bins are important for accomplishment of composting techniques (Sánchez et al. 2017). Temperature, carbon/nitrogen ratio, moisture, aeration rate, particle size, and pH are the main factors affecting compost quality, microbial structure community, and metabolism of bacterial degrading organics during composting process (Wang et al. 2018b).

Yu et al. (2015) found that the moisture content of the composting process of manure and agricultural waste needs to be maintained at a level of 50–60% wet basis. The carbon-to-nitrogen ratio (25–30), pH (5.5–9), temperature (55–63 °C), and oxygen content (higher than 5%) are the optimum conditions for producing good quality composting. Further, the pile has to be bulky to facilitate the air space flowing with high water-holding capacity in the pores. Chicken manure enjoys low porosity, alkaline pH, low carbon-to-nitrogen ratio, and high moisture. The addition of chicken manure to rice husk, wood chips, and sawdust for composting reduces the carbon/nitrogen ratio and water content and increases pile porosity and aeration channels (Zhang and Sun 2016). Composting of organic wastes is safe and low-cost technology compared to landfilling, which pollutes groundwater due to leachate contaminations (Ayilara et al. 2020).

Chicken manure compost is stable and easier to handle, storage, and transport for soil fertilization (Akdeniz 2019). Nevertheless, the composting process is highly consuming time and requires from 3 to 6 months for mature compost production. Moreover, the required footprint of the composting site is quite large compared with other technologies. Composting piles generate bad odors due to the deterioration of the carbon-to-nitrogen ratio, water content, and aeration. The piles generate ammonia at low imposed carbon-to-nitrogen ratios where the excess nitrogen is highly volatilized, causing a bad smell (Pardo et al. 2015). The piles could become anoxic and rich with pathogens due to insufficient oxygen content, resulting in fermentation by-products, i.e., alcohols and bad odor leachate (Ayilara et al. 2020).

To summarize, composting is a process that converts organic matter into stable, pathogen-free compost suitable for agricultural use. The process consists of four biological steps that are affected by temperature, oxygen, moisture, pH, and other factors. While composting is a less expensive and safer technology than landfilling, it requires time, space, and management to prevent odor and pathogen buildup.

Pyrolysis

Pyrolysis is the thermal decomposition of biomass or biosolids in the absence of oxygen, resulting in biochar, bio-oil, and gas products. As illustrated in Fig. 5, pyrolysis of wastes and/or biomass occurs in three types: flash, slow, and fast pyrolysis. Pyrolysis is classified into three types based on solid retention time, heating rate, biomass particle size, and temperature. The products of the pyrolysis process are determined by the type of biomass and the temperature (Hu and Gholizadeh 2019).

Fixed bed, ablative, and fluidized bed are the main designed reactors for the pyrolysis process (Ore and Adebiyi 2021). Based on the feedstock size and efficiency, the reactor is selected to avoid limitations and ensure functional efficient of heat transfer with operational performance troubles free. Therefore, feedstock such as chicken manure should be prepared and fractionized to be suitable for an efficient pyrolysis process. This could be carried out using mechanical machines for the grinding of wastes. The chicken manure has to be initially dried to get feedstock with moisture content below 10 weight %. This step overcomes the implications adverse of moisture on the viscosity, pH, stability, and corrosiveness of the end product. The products from the pyrolysis of chicken manure are biochar, gases, and vapors (Hu and Gholizadeh 2019). The main gases produced from the pyrolysis of chicken manure are syngas (hydrogen and carbon monoxide) with low water quantities, tar and ash that depends on the feedstock type and composition. Lee et al. (2017) found that chicken manure pyrolysis in the presence of carbon dioxide provided a high productivity of carbon mono-oxide compared with the nitrogen gas source. Furthermore, the addition of calcium carbonate increased the carbon mono-oxide productivity up to 6.9 mol.% at a temperature of 780 °C in the presence of both carbon dioxide and nitrogen gas. Pure nitrogen was utilized for chicken manure pyrolysis at 600–1000 °C (Burra et al. 2016). Catalytic pyrolysis of chicken manure was used to produce aromatic hydrocarbons (Shim et al. 2022).

To summarize, pyrolysis is a thermal decomposition process that produces biochar, bio-oil, and gas from biomass or biosolids in the absence of oxygen. The type of pyrolysis process used, and the products produced are determined by variables such as solid retention time, heating rate, biomass particle size, and temperature. Depending on the feedstock size and composition, different types of reactors, such as fixed bed, ablative, and fluidized bed, can be used for efficient pyrolysis. The catalytic effects of calcium carbonate combined with carbon dioxide increased carbon mono-oxide productivity. Energy recovery, i.e., syngas (carbon monoxide and hydrogen) from chicken manure pyrolysis in the presence of carbon dioxide, is a promising approach from a circular economy point of view.

Gasification

The thermochemical conversion of carbon-rich feedstock into combustible product gas using gasifying agents such as carbon or nitrogen is known as gasification (Yang et al. 2021; Eraky et al. 2022). Gasification consists of four stages, as shown in Fig. 6, which are drying, devolatilization, also known as pyrolysis, combustion, and reduction. The drying

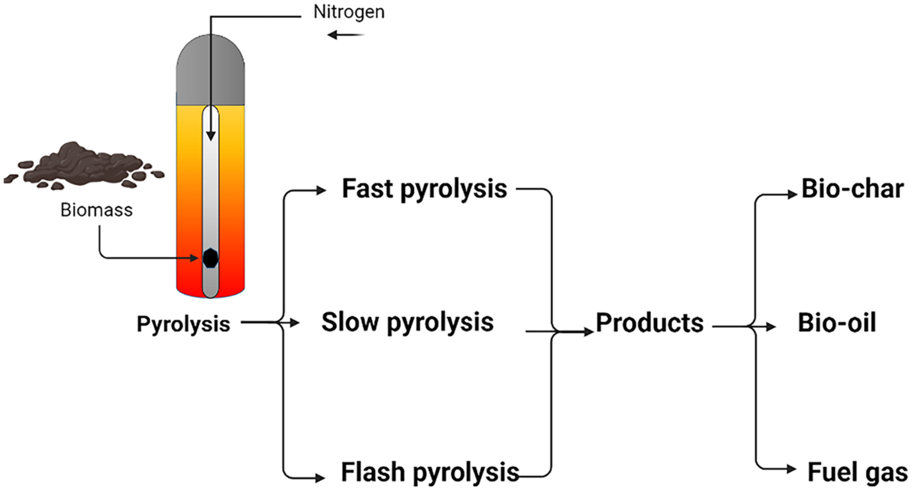

Fig. 5 Different types of pyrolysis processes. Three distinct processes are used to pyrolyze wastes and/or biomass: flash, slow, and fast pyrolysis. Three types of pyrolysis are distinguished based on temperature, biomass particle size, heating rate, solid retention time, and solid retention time. The type of feedstock and temperature have an impact on how pyrolysis produces its products. Syngas (carbon mono-oxide and hydrogen) recovery from chicken manure pyrolysis in the presence of carbon dioxide occurs at a temperature of 780 °C

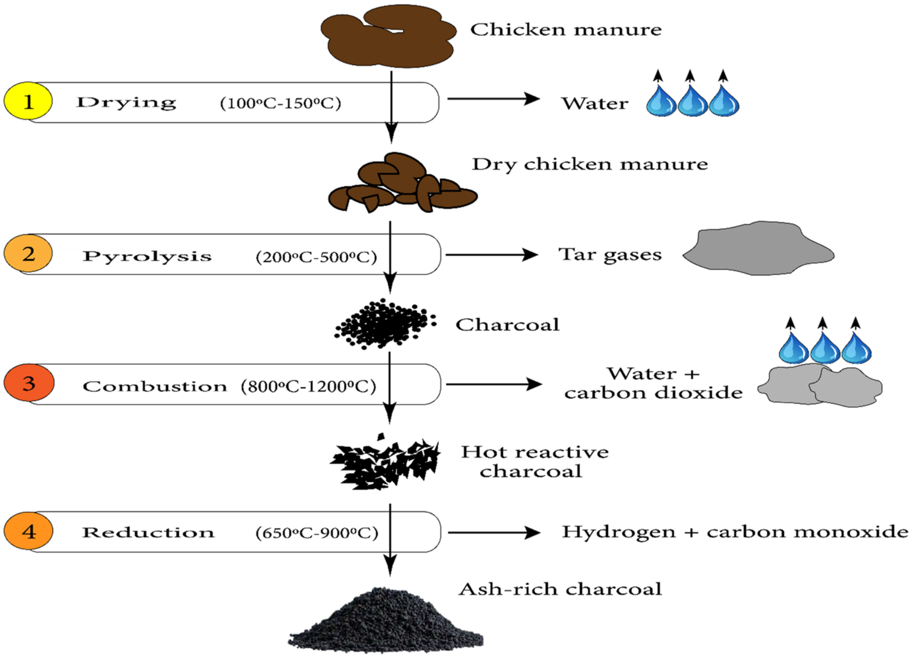

Fig. 6 Gasification of chicken manure stages. The gasification energy output of chicken manure is increased by increasing the temperature from 600 to 1000 °C, resulting in a high energy yield. Carbon dioxide is the suitable media for the gasification of chicken manure. Supercritical water chicken manure gasification produces hydrogen gas. Co-gasification of the chicken manure waste with other organic wastes is promising from a circular economy point of view

stage necessitates the evaporation of free and bound water in the feedstock by heat often supplied by exothermic reactions in the subsequent stages. The temperature is normally between 100 and 200 °C which satisfies the fundamental function of this stage in the overall process without thermally decomposing the feedstock. This is because the temperature condition does not meet the mark to execute such heavy duties (Yang et al. 2021).

The emission of certain air pollutants, such as volatile organic compounds, is a disadvantage of this stage. Nonetheless, the inclusion of this step is significant in the case of a feedstock with high moisture content. The drying stage prevents feeding or fluidization issues such as agglomerate formation and jamming, which are frequently associated with feedstock with high moisture content, such as chicken manure. The reduced heating value of the product gas reduces the overall energy efficiency of the gasification reaction in the absence of the drying step. Because of the decreasing reaction temperature, such conditions result in a significantly increased tar content in the product gas (You et al. 2018). Essentially, the drying rate is controlled by the heat and mass transfer between feedstock particles and their ambient atmosphere corresponding to the temperature difference, particle surface area, moisture, and convection velocity of surrounding flows as well as diffusivity of moisture within feedstock particles and moisture (Zeng et al. 2020). The purpose of this stage is to further degrade the feedstock particles into volatile matter and solid carbonaceous residue, also known as biochar, at high temperatures without oxygen (Eraky et al. 2022). The following stage is the combustion, which includes the complete or partial oxidation of carbonaceous output as well as certain gas species produced by pyrolysis. The combustion reaction frequently produces water, carbon dioxide, carbon monoxide, and hydrogen. This strongly exothermic reaction is responsible for supplying the gasifier heat required in the subsequent reduction reaction, as well as the drying and pyrolysis stages of the process, which are endothermic in nature. Gasification and pyrolysis of chicken manure were investigated by Hussein et al. (2017) using carbon dioxide, nitrogen, air, and steam and at 600–1000 °C temperatures. The energy recovery was increased by increasing the temperature from 600 to 1000 °C. The highest energy yield was obtained from the gasification of chicken manure by carbon dioxide, followed by steam. The lowest energy recovery from chicken manure was obtained by pyrolysis and air gasification. However, gasification reactions were the fastest, with air reducing the reaction time by a value of 75% compared with carbon dioxide gasification.

Furthermore, energy yield was decreased by 55% at a temperature of 1000 °C. Oxygen concentrations of 21 and 10% incorporation with nitrogen were utilized to gasify chicken manure (Burra et al. 2016). The energy yield was increased by increasing the oxygen content by 21%. The maximum hydrogen yield, hydrogen and carbon gasification efficiency of supercritical water chicken manure gasification reached up to 22.47 mol/kg, 174.53 and 81.34%, respectively, at a temperature of 620 °C and reaction time of only 12 min(Cao et al. 2022). The co-gasification of the chicken manure waste with petroleum coke highly increased the hydrogen gas content in the obtained syngas. The calcium and potassium of the manure ash are highly contributed as a catalyst in the gasification process(Liu et al. 2021).

To summarize, gasification is a thermochemical conversion process involving four stages: drying, devolatilization, combustion, and reduction. The drying stage removes free and bound water from the feedstock to prevent feeding or fluidization issues, whereas the devolatilization stage further degrades the feedstock particles into the volatile matter and carbonaceous residue. Combustion involves the complete or partial oxidation of carbonaceous output, resulting in the production of water, carbon dioxide, carbon monoxide, and hydrogen, which are used to heat the gasifier in subsequent stages. The decision wise of choosing the best gasifying agent is highly dependent on the resource availability and the desired output. The chicken manure was efficiently utilized as a catalyst for the gasification of petroleum coke.

Conclusion

For the valorization of chicken manure and the production of biogas and organic fertilizer nutrients, anaerobic digestion is a promising technology. Although chicken manure has a high biomethane potential, its low carbon-to-nitrogen ratio and other factors can hinder anaerobic digestion. Additionally, chicken manure from infected flocks contains antibiotics (chlortetracycline), which can reduce the amount of biogas produced during anaerobic digestion. A chlortetracycline concentration of 60 mg/kgtotal solids or less is optimal for biomethanization, whereas higher concentrations can inhibit methane production. Tylosin probably inhibits butyrate and propionate, oxidizes syntrophic bacteria, and reduces biomethane production, all of which influence the methanogenesis process. Aromatic substances, such as phenol and catechol, have been found to inhibit all stages of anaerobic digestion, with hydrolysis and acetogenesis being affected more severely than methanogenesis. Co-digestion of chicken manure and other organic wastes overcomes these obstacles and increases biogas production. Due to a balanced carbon-to-nitrogen ratio and the availability of microorganisms, the maximum biogas yield was achieved at a 10:90 ratio of primary sludge to chicken manure.

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