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EDITED BY

Airton Kunz,
EMBRAPA Swine and Poultry, Brazil

REVIEWED BY

Akash Phillip,
IIMT University, India
Iyyadurai Mariappan,
Institute of Microbial Technology (CSIR), India

*CORRESPONDENCE

Tonderayi S. Matambo
✉ matamts@unisa.ac.za

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A critical review of food waste and poultry manure anaerobic co-digestion: an eco-friendly valorization for sustainable waste management and biogas production

Ayandeji Sunday Ayantokun¹, Tonderayi S. Matambo^{1,2,3*}, Charles Rashama^{2,3,4}, Ismari Van der Merwe¹ and Johan Adam Van Niekerk¹

¹Department of Sustainable Food Systems and Development, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, South Africa, ²Centre of Competence in Environmental Biotechnology, Department of Environmental Sciences, College of Agriculture and Environmental Sciences, University of South Africa, Johannesburg, South Africa, ³The Bioenergy Consortium, College of Agriculture and Environmental Sciences, University of South Africa, Johannesburg, South Africa, ⁴Department of Life and Consumer Sciences, College of Agriculture and Environmental Sciences, University of South Africa, Johannesburg, South Africa

Anaerobic co-digestion (AcoD) has emerged as an effective technology for treating poultry manure (PM) and food waste (FW), converting these organic materials into valuable biogas and bio-fertilizers. The management of PM and FW has become increasingly critical due to environmental challenges associated with their disposal, which often leads to pollution and greenhouse gas (GHG) emissions. By employing AcoD, both PM and FW can be processed simultaneously, optimizing resource utilization and enhancing waste management (WM) strategies. This strategy relies on the use of sustainable waste-to-energy technology (WET) that harnesses agricultural biomass as a clean, renewable, and carbon-neutral energy source. The advantages of AcoD over traditional anaerobic digestion (AD) include improved biogas yields, better nutrient balance, and enhanced microbial stability due to the diverse substrate mix. Co-digesting animal-based wastes, such as PM, with plant-based wastes like FW enables more efficient degradation of organic matter, leading to increased methane production. Various studies have demonstrated the successful co-digestion of PW with various types of FW, resulting in significant increases in methane yields, as a potent renewable energy source. This review critically highlights the characteristics and benefits of AcoD, focusing on the synergistic effects that various FW substrates have when paired with PM. Essential process parameters influencing microbial activity, such as pH, organic loading rate (OLR), temperature, carbon-to-nitrogen (C/N) ratio, and hydraulic retention time, are discussed for optimizing biogas production (BGP). The findings underscore the greenness of AcoD as an eco-friendly approach, reducing dependency on fossil fuels, and mitigating environmental pollution, thereby contributing to sustainable WM practices and BGP.

KEYWORDS

poultry manure, food waste, anaerobic co-digestion, biogas, waste management

1 Introduction

Co-digestion of animal waste, such as poultry manure (PM), and food waste (FW), particularly through anaerobiosis [anaerobic co-digestion (AcoD)], presents a significant opportunity for sustainable waste management (WM) and Biogas production (BGP), contributing to nutrient recycling and reducing greenhouse gas (GHG) emissions (Kadam et al., 2024; Adnane et al., 2024). This approach relies on sustainable waste-to-energy technology (WET) that harnesses agricultural biomass as a clean, renewable, and carbon-neutral energy source.

Food wastes (FWs) are fractions of edible and non-edible foods removed from the food supply chain (FSC). Approximately 1.3 billion tons of global food production are lost or wasted yearly along the FSC, which encompasses every stage from initial production to final consumption (Food and Nations, 2012). These wastes comprise crop products like fruits, vegetables, and cereals, as well as animal products, primarily meat and dairy, along with other agricultural food items. The global volume of FW is projected to rise steadily, particularly in sub-Saharan Africa, as the world's population is expected to hit 9.6 billion by 2050 (Bajželj, 2015). If proper WM strategies, such as nutrient recycling, are not implemented, this surge in FW will not only exacerbate food scarcity issues but also lead to serious environmental consequences, including increased GHG emissions and greater pressure on WM systems. For instance, (Ganesh et al., 2022) reported that fruits and vegetables are among the most widely consumed food products, and their wastes constitute 42% of the global FW. In another report from the World Wide Fund for Nature, the South Africa report (WWF-SA, 2017) reveals that South Africa produces 31 million tonnes of food annually, of which 10 million tonnes are wasted. The information went further to state that the wastage includes fruits and vegetables (44%), grains (26%), and meat (15%). The remaining 15% are combinations of oilseeds, roots, and tubers. In the same vein, a study conducted by Cronjé et al. (2018) amongst 100 households in Kimberly, South Africa, showed that bananas, apples, and avocados are the most wasted fruits, while tomatoes, potatoes, and cabbage are the most wasted vegetables. In another study, Esparza et al. (2020) noted that fruit and vegetable wastes (FVWs) occupy an ever-increasing space in waste treatment facilities and landfills.

Based on the reported findings, they affirmed that FVW valorisation resulted in extracting bioactive compounds, producing enzymes and exopolysaccharides, synthesizing bioplastics and biopolymers, and producing biofuels. However, through traditional activities, these FVWs are poorly disposed of in landfills or rivers. Global warming, depletion of the ozone layer, acid rain, and public health concerns are some of the adverse environmental effects of greenhouse gas (GHG) emissions from these wastes (Sahoo et al., 2021). According to Cantera et al. (2018), landfills generate GHGs such as methane (CH_4), sulfides, ammonia (NH_3), carbon dioxide (CO_2), among others, that contribute to global warming. The methane gas produced has an impact 25 times greater than that of CO_2 . Parvin and Tareq (2021) also note that toxic substances called leachates generated from these landfills pose a great risk to public health as they filter gradually through the soil to pollute the groundwater and subsequently migrate into the surface water. These raise an environmental concern about the need to find a sustainable solution to FVWs.

Poultry manure (PM), characterized by its nitrogen-rich content stemming from poultry litter, feather waste, and spilled feeds, is one of the driest and bulkiest manures generated in intensive agricultural practices (Lakshmi et al., 2020; Lynch et al., 2013). However, while PM, as a product of poultry farming, serves as a vital source of nutrients and plays a major role in crop production as an organic fertilizer, it also poses considerable environmental challenges, including soil and water pollution resulting from waste management issues (Muduli et al., 2019). This waste can lead to detrimental effects on both human and animal health when not properly managed. To mitigate these environmental risks, co-digesting PM anaerobically with FVWs presents a promising approach (Adnane et al., 2024). This proposition not only reduces pollution risks but also transforms agricultural wastes into useful resources.

The social and environmental implications of FVWs reflect a pressing sustainability issue, as outlined in the United Nations' 2030 Agenda (De Moraes et al., 2020). By integrating the digestion of PM and FVWs, it becomes possible to produce beneficial materials while simultaneously contributing to several sustainable development goals (SDGs), including poverty alleviation (SDG 1), zero hunger (SDG 2), promoting health and well-being (SDG 3), ensuring clean water and sanitation (SDG 6), and generating affordable and clean energy (SDG 7) (Biermann et al., 2017).

Anaerobic digestion (AD) is an economically feasible, eco-friendly, and socially acceptable biological process that transforms complex substrates into biogas and digestates in the absence of oxygen (Vats et al., 2020). The biogas generated is a combination of CO_2 , CH_4 , and minute quantities of other gases. Researchers (Náthia-Neves et al., 2018) found that AD, whether applied singularly or in a co-digestion framework, can serve as a source of clean energy since the biogas produced typically contains 50–75% CH_4 gas, depending on the substrate used. The CH_4 gas produced can be used as a substitute for natural gas, while the digested biomass can be used as fertilizers rich in nitrogen, phosphorus, and potassium. This capacity to produce renewable energy and nutrient-rich fertilizers further highlights the ecological advantages of AD, especially AcoD, over traditional WM. For instance, Arif et al. (2018) affirmed that AD could be used to reduce GHG emissions in organic waste treatment. It will still provide sustainable alternative by-products such as biogas for clean energy production and beneficial materials for composting and fertilizing.

The utilization of AcoD, which involves the combined processing of animal manure, such as PM, and FW, for WM and biogas generation, has seen substantial growth over the past decade. Initial studies established the groundwork for the development of AcoD, highlighting its environmental benefits, cost efficiency, and sustainability. Innovative advancements in AD, including anaerobic mono-digestion (AMD) and AcoD methods, have spurred its widespread adoption throughout this decade. This trend is evidenced by a notable rise in published research on the subject, as illustrated in Figure 1.

This critical review aims to investigate studies on BGP from the AcoD of poultry and food wastes (P&FWs), while also exploring the benefits and drawbacks of AMD or single-substrate digestion (SSD) in BGP, thereby providing insights into the role of AcoD as a sustainable solution for WM and biogas generation.

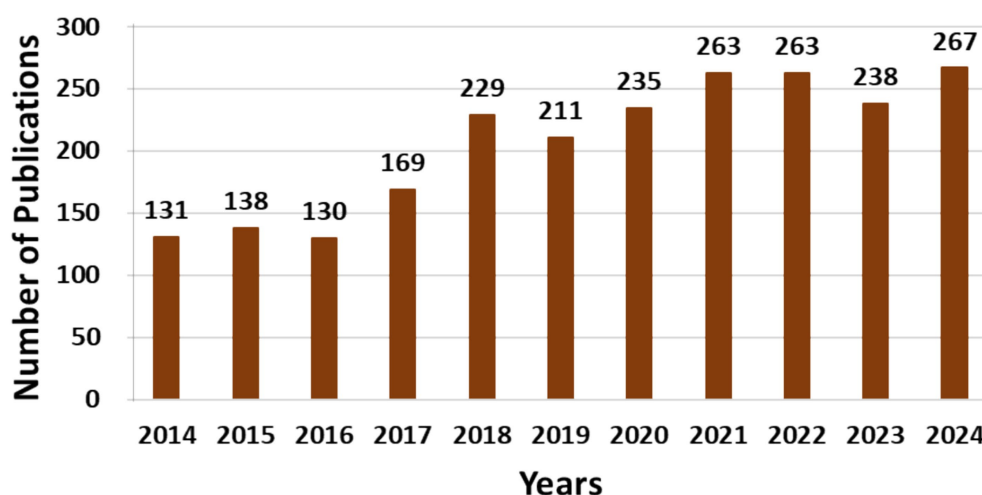


FIGURE 1

During a decade (2014–2024), several publications were generated on the use of anaerobic digestion (including AcoD) for BGP. Search keywords: “anaerobic co-digestion for biogas production.” Scopus (February 2025).

2 Poultry manure

The use of animal waste, such as poultry manure (PM), as a substrate for BGP over decades has gained more interest as it lowers GHG emissions, enhances nutrient re-circulation, and reduces dependence on fossil energy (Ahlberg-Eliasson et al., 2021; Holm-Nielsen et al., 2009; Hou et al., 2017). Choosing animal manure for biogas depends on the animal type and management practices. Furthermore, the suitability of such manure is dependent on the water content, herd size, and biogas potential (Liebetrau et al., 2021). PM ranks the highest among the common substrates for BGP. About 0.5 m³ of biogas (58% CH₄) has been reported to be produced by 1 kg of organic matter in PM (Tawfik et al., 2023). This has been attributed to their high potential for BGP arising from their high content of total solids, volatile matter, and high biodegradability rate, as shown in Figure 2 (Maj, 2022; Tawfik et al., 2023).

Studies on the proximate composition of PM revealed moisture content ranging from 8.84 to 9.62% moisture content, 21.60–39.01% ashes, 54.33–57.51% volatile matter, 90.3% dry matter, 2.61% fat content, and 16.09% crude fiber (Simbolon et al., 2019; Inna et al., 2022; Usman et al., 2019), as shown in Table 1.

Moisture: The high moisture content of poultry manure is of great importance to BGP as it enhances the breakdown of nutrients and substrate decomposition, contributing to an efficient rate of CH₄ production and final yield (Zobeashia et al., 2021; Czekala et al., 2023; Liotta, 2013).

Crude protein: The high crude protein content of PM also enhances its BGP, as protein-rich substrates have been reported to have a higher yield of methane (Kovács et al., 2015; Nwokolo et al., 2020).

Volatile solid: This is the organic fraction of the total solid of a substrate, and it is a major determinant of the amount of biogas that can be produced (Mrosso et al., 2023; Orhorhoro et al., 2017). It also contributes to the efficiency of the fermentation process (Mrosso et al., 2023; Orhorhoro et al., 2017).

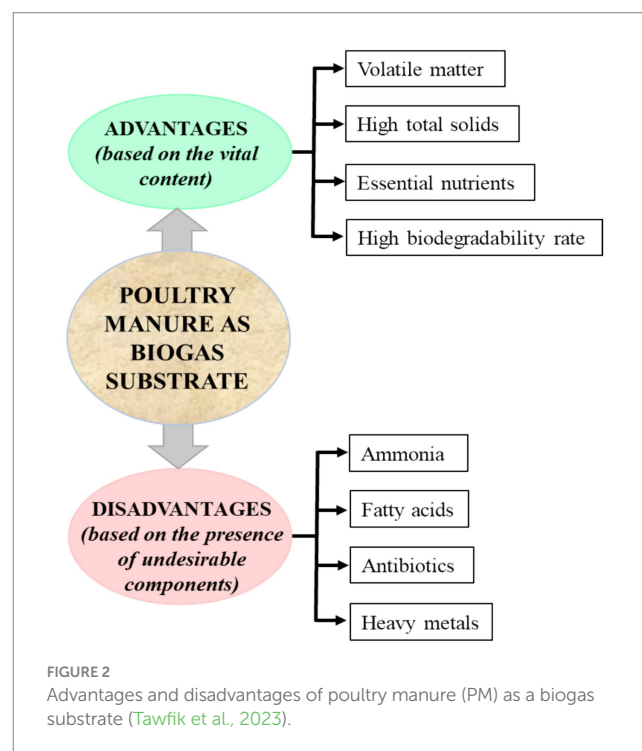


FIGURE 2

Advantages and disadvantages of poultry manure (PM) as a biogas substrate (Tawfik et al., 2023).

TABLE 1 Proximate composition of poultry manure (Simbolon et al., 2019; Inna et al., 2022; Usman et al., 2019).

Parameters	Values (%)
Moisture content	8.84–9.62
Ashes	21.60–39.01
Volatile matter	54.33–57.51
Dry matter	90.3
Total protein	21.34
Lipid content	2.61
Total fiber	16.09

Crude fiber: The fiber contents of substrates have been linked to enhanced BGP, as their fermentation has been linked to the production of soluble sugars, which increases the energy content required for the production of biogas (Chomini et al., 2019).

Dry matter: The high dry matter content of poultry substrate makes it easy to undergo isolation, which increases methane yield (Kreuger et al., 2011).

Fat content: The low-fat content of PM is advantageous to its use as a substrate for BGP. Fatty acids have been implicated in decreased BGP owing to their toxicity to the fermenting microbes, which causes a drop in pH (Nwokolo et al., 2020). This leads to the failure of the fermentation system (Pramanik et al., 2019; Nwokolo et al., 2020).

The high ash content of PM measures its total elemental composition. The composition elements include zinc, selenium, nitrogen, potassium, calcium, molybdenum, phosphorus, manganese, cobalt, iron, and copper (Drózd et al., 2020), and of these, calcium and potassium have been reported to be the major metals (Quiroga et al., 2010). These elements are important in the degradation of organics into bioenergy by metabolizing microorganisms (Tawfik et al., 2023). However, PM has been reported for its low concentrations of trace elements, such as copper and zinc, which may affect its microbial degradation in producing methane (Tawfik et al., 2023; Quiroga et al., 2010).

3 Food waste

Food waste (FW) has been acknowledged as an important contributor to environmental pollution and public health issues, as it is highly biodegradable and contributes to the high organic content of solid waste (Plazzotta et al., 2017; Shi et al., 2018). Their

biodegradability can be attributed to the high organic contents consisting of carbohydrates (starch and cellulose), proteins, and lipids, as well as high moisture content (Liu R. et al., 2022; Perin et al., 2020). FW includes leftovers from restaurants, canteens, and homes, as well as waste from food processing.

According to the Food and Agriculture Organization (FAO), FWs are produced annually from about 33% of the edible parts of human food (FAO, 2011). The European Union (EU) wastes nearly 89 million tons of food each year, a critical issue that requires urgent action (Stenmarck et al., 2016), while about 195, 22, and 90 million tons of FW are produced annually in China, Japan, and the United States (US), respectively (Thi et al., 2015). Agricultural production wastes are the major sources of FW in industrialized nations. They arise mostly from overproduction and post-harvest assessment of crops based on quality criteria demanded by retailers (FAO, 2011; Segrè and Falasconi, 2011). In developing countries, poor production and distribution of agricultural produce, leading to post-harvest loss and accumulation of perishable commodities, account for most of the FW (Plazzotta et al., 2017).

The use of FW as a substrate for BGP has been adopted in some countries to manage the environmental and public health threats it poses. Thus, providing a significant economic opportunity for sustainable development in addition to addressing the problem of sustainable waste management and lessening environmental pollution (Sarkar et al., 2021). In China, food waste has the ability to contribute up to 30.3% of the annual natural gas demand, which is equivalent to 70 billion m³ of methane production (Rajendran et al., 2014; Shi et al., 2018). The BGP potential of food wastes can be attributed to their organic composition, which includes volatile solids (70–90%, dry mass) (Perin et al., 2020). Figure 3 presents the proximate composition of different FWs.

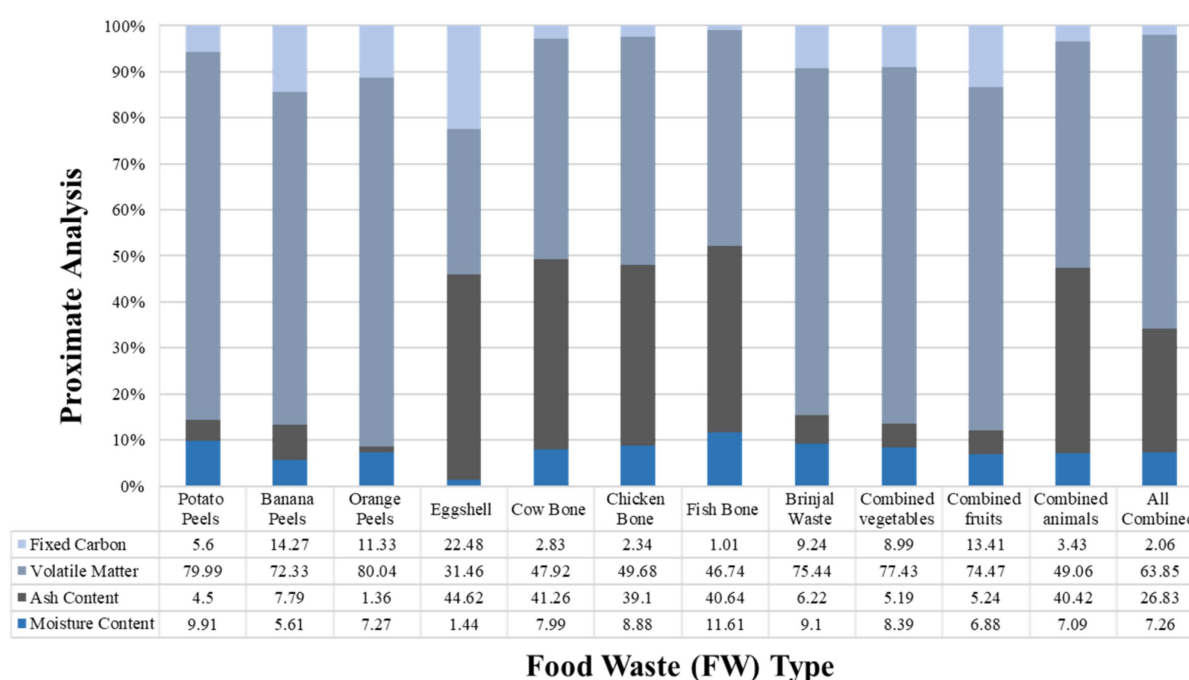


FIGURE 3
Proximate composition of various food wastes (Tawfik et al., 2023).

There are certain concerns regarding the use of FW as a single substrate for BGP. These have been attributed to the low pH values, low C/N ratio, and high nitrogen content (Perin et al., 2020). During digestion, the fraction of food waste that has low total solids and high levels of volatile fatty acids is hydrolyzed rapidly, leading to acidification and inhibition of the digestion process (Shen et al., 2013; Plazzotta et al., 2017). The low C/N ratio and high nitrogen cause rapid accumulation of ammonia. Ammonia has been implicated in the inhibition of the methanogenic activities of digestive microbes (Feng et al., 2021; Shi et al., 2018). The sodium, volatile, and long-chain fatty acids contents of food wastes also contribute to the inhibition of methanogenic activities (Feng et al., 2021; Pavi et al., 2017). The high simple sugar content also instigates rapid acidification and inhibition of methanogenic activity (Pavi et al., 2017). All these effects lead to a suppressed organic loading rate (OLR) and methane production.

The advantages and disadvantages of FW as a mono-substrate for BGP are presented in Figure 4.

4 Biogas, compositions, and production

As a renewable energy source, biogas is produced from biomass used for domestic cooking, machinery, electricity, and other energy applications (Persson and Jönsson, 2007). It is composed of CO₂ and CH₄, which are generated by the microbial decomposition of organic materials such as human and animal excretory products (manures) and plant materials under anaerobic conditions (Raven and Gregersen, 2007; Olugasa et al., 2014). Biogas also contains other gases such as NH₃, nitrogen (N₂), gaseous hydrocarbons, hydrogen sulfide (H₂S), oxygen (O₂), and Si–O–Si bond-containing organic compounds like siloxanes (Awe et al., 2017; Alhassan et al., 2019).

As described in Figures 5, 6, the production of biogas involves several processes, including the methanation of biomass and organic waste materials derived from anaerobically digested sewage sludge, landfills, commercial composting, biomass gasification, and the AcoD of animal farm manure combined with agro-food waste (AFW) (Awe et al., 2017; Alhassan et al., 2019). The resulting residual digestates can also serve as fertilizers for agriculture.

4.1 Compositions of biogas

As shown in Table 2, biogas produced from household waste is composed of CH₄ (50–60%), CO₂ (34–38%), N₂ (0–5%), H₂O (6%), and O₂ (0–1%), with traces of H₂ and H₂S (NE, 2009; Liu et al., 2006). Biogas from agro waste has been reported to consist of CH₄ (50–80%), CO₂ (30–50%), N₂ (0–1%), H₂ (0–2%), H₂S (0.70%), carbon monoxide (CO) (0–1%), O₂ (0–1%) and H₂O (6%), with a trace of NH₃ (NE, 2009; Chen et al., 2015).

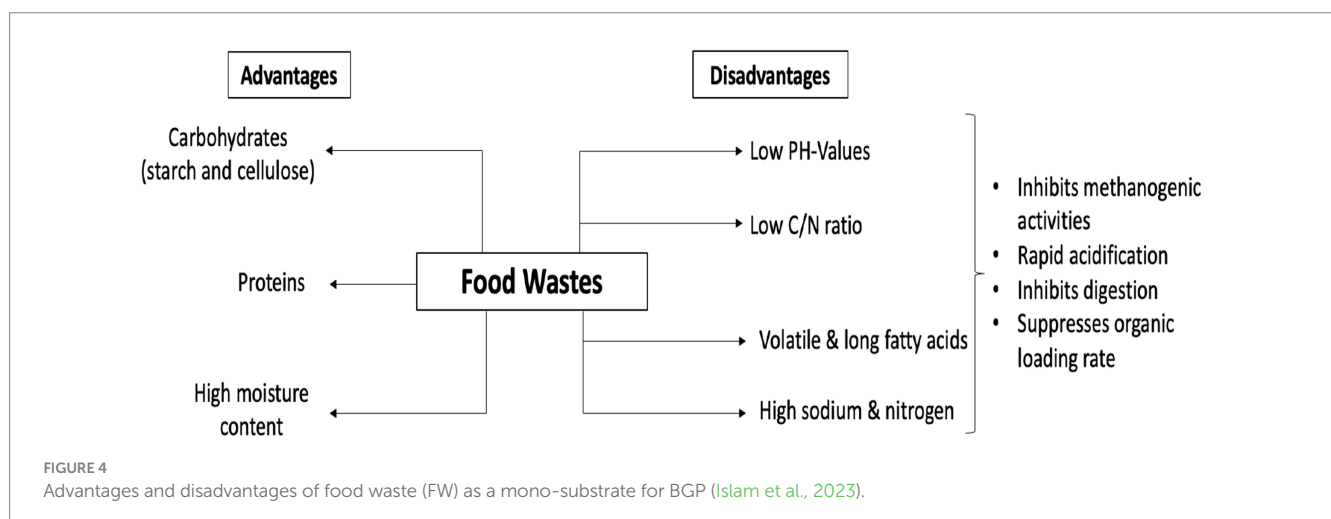
In addition, biogas from landfills is composed of CH₄ (50–80%), CO₂ (20–50%), N₂ (0–3%), H₂ (0–5%), H₂S (0.10%), CO (0–1%), and O₂ (0–1%), with a trace of NH₃ (Chen et al., 2015). Meanwhile, the biogas generated from industrial waste is composed of CH₄ (50–70%), CO₂ (30–50%), N₂ (0–1%), H₂ (0–2%), H₂S (0.80%), CO (0–1%), and O₂ (0–1%), with a trace of NH₃ (Chen et al., 2015).

Several factors, such as substrate composition and concentration, pH, and temperature, have been reported to affect the composition of biogas (Dobre et al., 2014).

4.2 Substrate for biogas production

Studies have shown that biogas production (BGP) is greatly dependent on the type of substrate. This can be attributed to the carbohydrate, fat, protein, and other organic contents of the substrates (Alhassan et al., 2019). Plant and animal products constitute the bulk of these substrates, which can readily undergo fermentation. Substrates for BGP are grouped into mono-substrates and co-substrates. Mono-substrates comprise various organic materials, including animal manure, slurry, and some other animal digestive contents, particularly those of ruminants. These substrates possess the fermentation capacity attributed to the presence of methane-producing bacteria (Ignatowicz et al., 2023). Co-substrates are substrates added to digesters to suppress inhibition, improve process efficiency, and attain proper hydration (Ignatowicz et al., 2023).

The common substrates for BGP are FVWs, slurry, food industrial wastes, beet pulps, dairy industrial wastes, animal manure, energy crops, and stillages (Alhassan et al., 2019; Ignatowicz et al., 2023). As shown in Figure 5, maize or corn silage (19%), as an energy crop, was



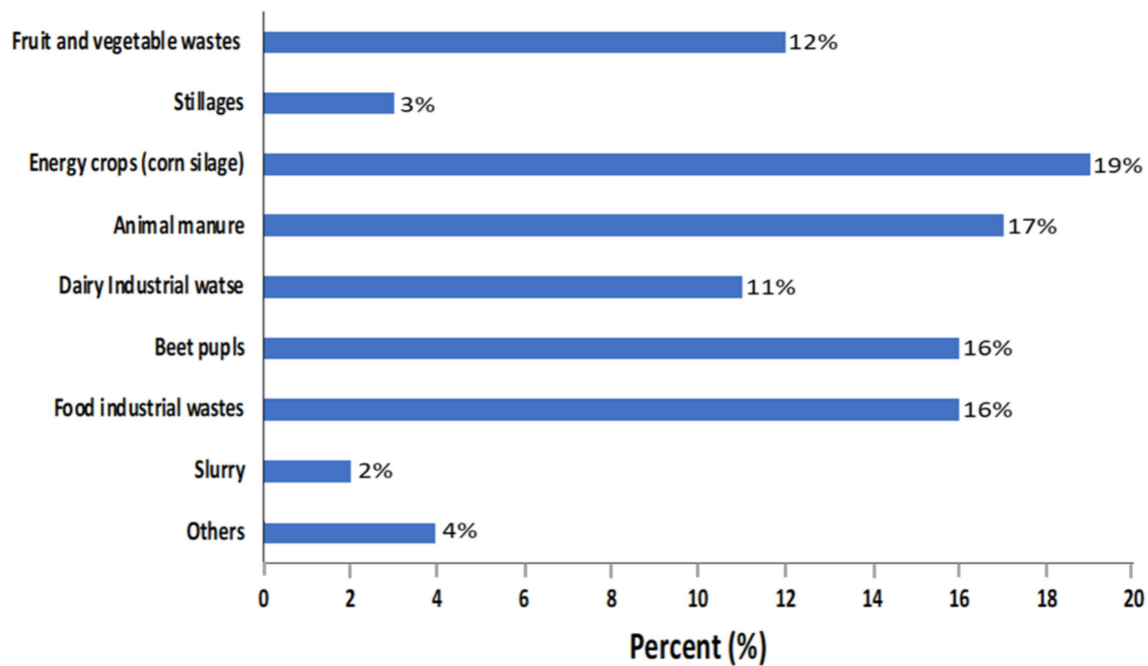


FIGURE 5
Substrate utilization in BGP in Poland 2021 (Ignatowicz et al., 2023).

the largest utilized substrate for BGP in Poland in 2021 (Ignatowicz et al., 2023). This was followed by animal manure (17%), food industrial waste (16%), and beet pulp (16%).

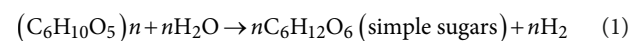
5 Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process involving the disintegration of organic matter by methanogenic organisms in the absence of oxygen (O_2) to generate a gaseous mixture referred to as biogas (Felton et al., 2014; Uddin and Wright, 2023). The produced biogas consists of methane (50–80%), carbon dioxide (20–50%), carbon monoxide, hydrogen, nitrogen, hydrogen sulfide, and water vapor (Felton et al., 2014). The microorganisms that play a role in AD form a large and diverse consortium that works together to catalyze the digestion process (Kunatsa and Xia, 2022).

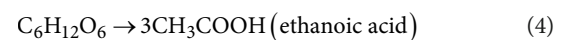
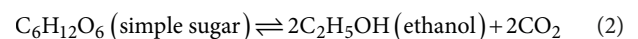
5.1 Stages of anaerobic digestion

The anaerobic digestion (AD) process consists of four biochemical stages, vis-à-vis, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as illustrated in Figure 6.

Hydrolysis: This step, in the presence of water, involves the breakdown of inputted feedstocks consisting of complex polymers such as carbohydrates (starch and cellulose), proteins, and lipids into sugars, amino acids, and fatty acids (Uddin and Wright, 2023; Menzel et al., 2020). This step is catalyzed by hydrolytic enzymes such as cellulase, lipase, amylase, and pectinase (Uddin and Wright, 2023). Equation 1 summarizes the hydrolytic reaction.



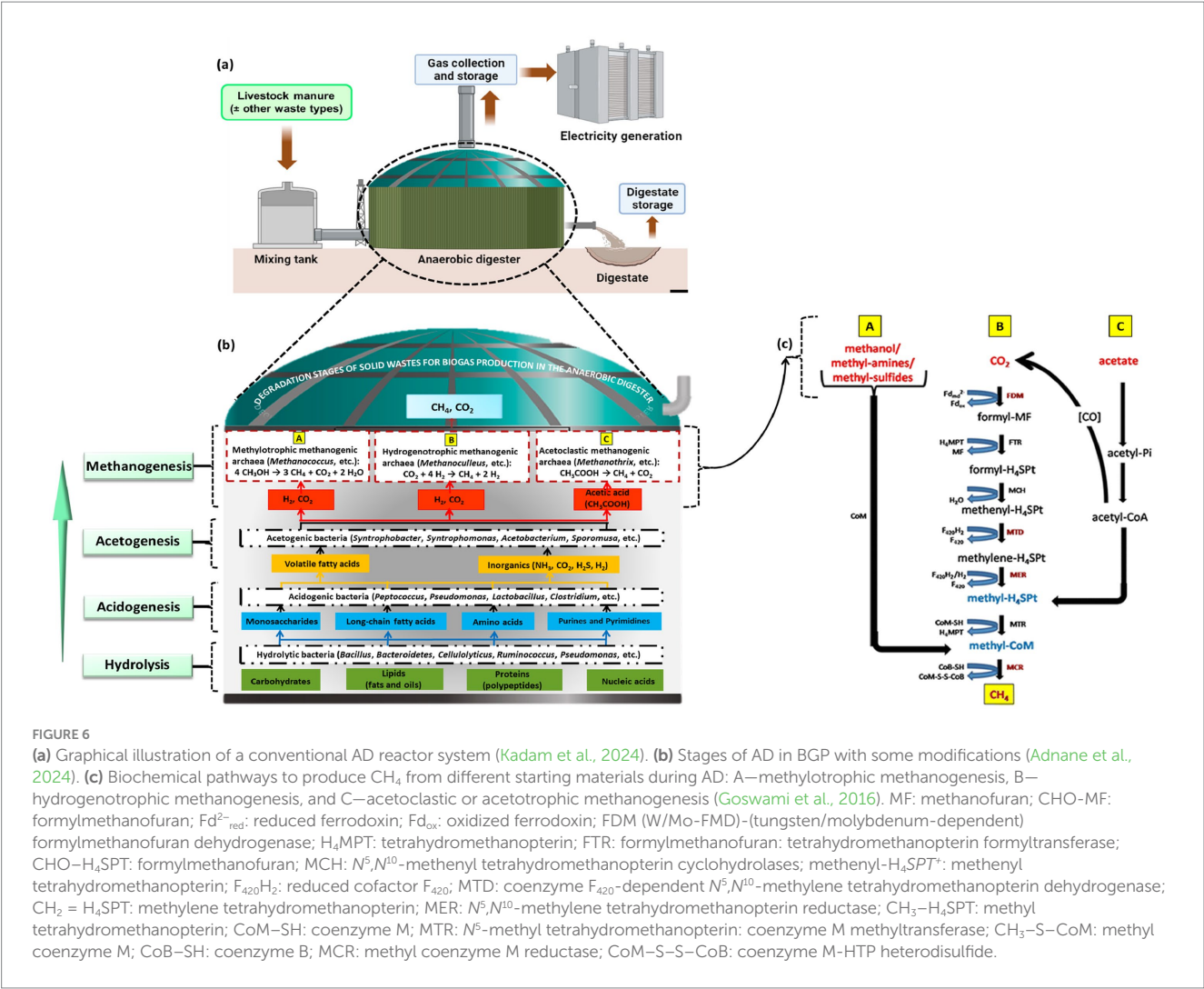
Acidogenesis: After hydrolysis, acidogenic bacteria break the hydrolytic products into ketones, alcohols (mainly methanol and ethanol), short-chain volatile acids, CO_2 , and H_2 (Rezapoor and Rahimpour, 2023; Uddin and Wright, 2023). This step is catalyzed by hydrogenases (Hendriks et al., 2018). The acidogenic reactions are summarized in Equations 2–4.



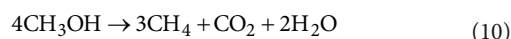
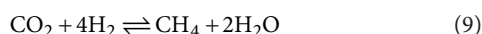
Acetogenesis: In this stage, acetogenic bacteria catalyze the transformation of acidogenic products and long-chain fatty acids from the hydrolysis stage into acetate (CH_3COO^-), CO_2 , and H_2 (Laçın et al., 2023). Acetogens catalyze this reaction (Gould, 2015). The acetogenic reactions are summarized in Equations 5–7.



Methanogenesis: This last stage of anaerobic digestion is carried out by acetotrophic or acetoclastic, hydrogenotrophic or



Methanosalsus, produce CH_4 through the utilization of methylated compounds like methanol, methylamine, and methyl sulfides (Equation 10).



5.2 Optimum process conditions for microorganisms in anaerobic digestion

Based on reported investigations, AD is mediated by microorganisms (Caruso et al., 2019). These microorganisms need to be maintained in optimum conditions to ensure effective AD. These conditions include pH, organic loading rate (OLR), temperature, carbon/nitrogen (C/N) ratio, and hydraulic retention time (HRT), as shown in Figure 7.

5.2.1 Influence of pH

pH is a measure of the acidity or alkalinity of a solution, which significantly influences anaerobic digestion (AD). Optimal activity of hydrolytic and acidogenic bacteria occurs within a pH range of 5.5–6.5, while methanogens perform best around a neutral pH of 7. Conversely, acidogenic bacteria favor higher pH levels (Latif et al., 2017; Uddin and Wright, 2023).

During AD, fluctuations in pH can affect process stability and microbial activity, particularly that of methanogens (Vargas-Estrada et al., 2022). The efficiency of CH_4 production is closely linked to pH, as CH_4 formation naturally neutralizes the pH (Carotenuto et al., 2020). Since the AD process involves four stages (Section 5.1), each stage requires specific pH conditions for the optimal activities of the associated microbes. Maintaining an optimal pH, generally between 5.5 and 7.5, is critical for maximizing CH_4 yield (Vargas-Estrada et al., 2022). Deviations from this range can alter microbial populations, impacting overall biogas production. For instance, low pH can lead to

volatile fatty acid (VFA) accumulation and process inhibition, while high pH may favor NH_3 formation, which can be toxic to microbes (Vargas-Estrada et al., 2022). Regarding the effect of pH, controlling initial pH through substrate selection or co-digestion is a practical approach to optimize AD, with adjustments often aiming for a pH around 7 to ensure stable and efficient operation.

5.2.2 Influence of OLR

The organic loading rate (OLR) indicates the amount of organic material introduced per unit volume of the digester (Ahmad et al., 2021). OLR (measured in $\text{kg VS m}^{-3} \text{d}^{-1}$) is a critical parameter in designing the digestion system, influencing factors such as digester size and type, as it reflects the daily input of volatile solids (VS) or organic dry matter (ODM) per cubic meter of reactor volume. It can be calculated using the formula stated in Equation 11 (Adnane et al., 2024).

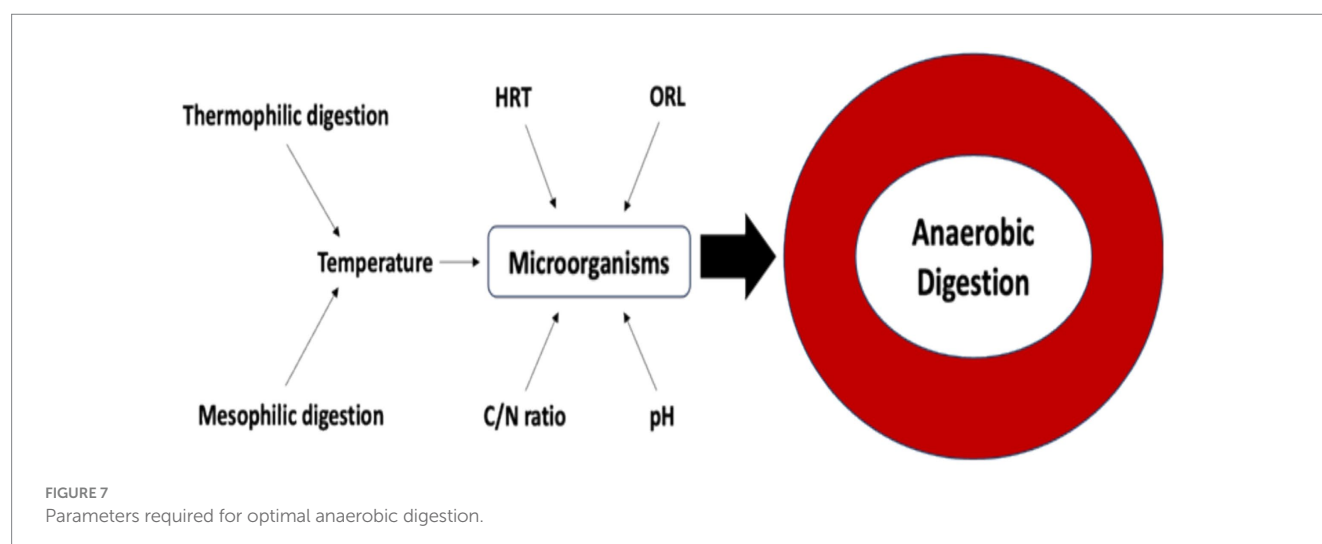
$$\text{OLR} = (Q \times \text{VS}) / V, \quad (11)$$

where Q is the daily feedstock flow rate, VS is the influent volatile solids concentration, and V is the reactor volume. Higher OLR values can enhance biogas production, reduce heating energy needs, and lower the required reactor size, but overloading may cause VFA accumulation and acidification, risking reactor failure. Excessive OLR can also impair heat transfer, cause uneven mixing, and damage circulating pumps beyond their capacity (Uddin and Wright, 2023).

Notably, co-digesting pig manure with sugar beet byproduct at an OLR of 11.2 gVS/L/day under mesophilic conditions achieved the highest methane productivity within 6 days (Adnane et al., 2024).

5.2.3 Influence of temperature

Temperature is a fundamental factor influencing microbial activity in anaerobic digestion. Two primary operating temperature ranges, namely mesophilic (35–40 °C) and thermophilic (55–60 °C), are recognized for optimal microbial performance (Gaby et al., 2017; Uddin and Wright, 2023). Thermophilic digestion accelerates feed degradation, reduces hydraulic retention time (HRT), and enhances biogas production, but it tends to be less stable and demands additional energy input. In contrast, mesophilic systems operate at



moderate temperatures, offering greater stability and lower operational costs, making them the most commonly used in commercial applications (Uddin and Wright, 2023).

AD can also occur under psychrophilic conditions (<20 °C), which are suitable for cold environments and are energy-efficient due to the absence of heating requirements (Adnane et al., 2024). Higher temperatures generally lead to faster reaction kinetics, pathogen deactivation, and increased solubility of organic matter, resulting in higher biogas yields, up to 41% more than cryophilic conditions. However, thermophilic processes are more susceptible to environmental disturbances and NH₃ or volatile fatty acid (VFA) accumulation, potentially inhibiting microbial activity (Adnane et al., 2024). Integrating optimal temperatures with an appropriate C/N ratio and pH mitigates NH₃ toxicity, especially in co-digestion systems.

Overall, mesophilic digestion is favored for its balance of stability, efficiency, and lower sensitivity to inhibitors, while psychrophilic systems are advantageous in cold climates with minimal heating costs (Adnane et al., 2024).

5.2.4 Influence of C/N ratio

The carbon-to-nitrogen (C/N) ratio reflects the balance between organic (energy source) and nitrogen (growth/metabolism) in the substrate, serving as an important indicator of nutrient availability for AD. A low C/N ratio indicates higher nitrogen content, which can lead to increased NH₃ production, raising the pH and inhibiting microbial activity (Induchoodan et al., 2022). Conversely, a high C/N ratio suggests nitrogen deficiency, resulting in suppressed microbial metabolism and reduced biogas production (BGP) (Induchoodan et al., 2022; Uddin and Wright, 2023).

Optimal C/N ratios for efficient AD are generally reported between 20 and 30 (Rajlakshmi et al., 2023), with 25 often cited as ideal (Klassen et al., 2016). Higher ratios above 35 can cause low CH₄ yields and NH₃ buildup, impairing methanogenic bacteria due to nitrogen deficiency. Conversely, very low ratios can be lethal to microbes, disrupting the digestion process. Combining carbon-rich and nitrogen-rich substrates in AD is a common strategy to achieve a balanced C/N ratio, enhance biogas yield, and improve overall process efficiency (Ajeej et al., 2015).

5.2.5 Influence of HRT

Hydraulic retention time (HRT) refers to the average duration that feedstock (both solids and liquids) remains within a digester, ensuring sufficient contact with microbial communities for effective digestion (Uddin and Wright, 2023). To achieve optimal biogas production (BGP), substrates must stay in the reactor long enough to allow complete breakdown processes (Shi et al., 2017; Uddin and Wright, 2023).

In continuous flow systems like continuously stirred tank reactors (CSTRs), where there is no recycling, the HRT equals the sludge retention time (SRT). When influent streams contain high solids content, longer HRTs are necessary to maximize biogas yields and process efficiency (Khanal, 2008). Essentially, HRT indicates the treatment duration, with longer times enabling better contaminant removal due to increased microbial contact. This leads to higher degradation efficiency and improved energy recovery from the waste (Sawyer et al., 2019).

5.2.6 Influence of substrates/nutrients

The biochemical and nutrient composition of substrates is a critical factor influencing the performance, biogas output, and stability of AcoD and any other anaerobic digestion processes. Selecting suitable (co-)substrates depends largely on their nutrient profiles, with protein-rich wastes from animal manure, meat processing, and slaughterhouses offering high CH₄ potential due to their elevated nitrogen content (Adnane et al., 2024). However, microbial breakdown of these substrates can lead to NH₃ accumulation, which, at levels above 4 g/L, can inhibit methanogenic activity and destabilize the process (Adnane et al., 2024).

Incorporating carbohydrate-rich substrates like lignocellulosic residues and food waste is an effective strategy to mitigate NH₃-related issues. Lipid-rich materials, such as slaughterhouse waste and effluents from oil industries, have higher theoretical methane yields but pose challenges due to the production of long-chain fatty acids (LCFAs) (Abomohra et al., 2022). Excessive LCFAs can hinder methanogenesis, cause operational problems like clogging, and reduce overall process efficiency, making co-digestion a valuable approach to balance nutrient content and minimize inhibitory effects (Adnane et al., 2024).

5.2.7 Influence of stirring or mixing

Stirring or mixing plays a key physical parameter in anaerobic digestion, significantly influencing biogas production efficiency. It promotes consistent and intimate contact between microorganisms, nutrients, and the organic substrate, enhancing microbial activity (Adnane et al., 2024). Additionally, stirring helps release trapped gas bubbles, improving gas flow and collection. It also prevents the formation of scum, sediments, crusts, and foam, maintaining optimal reactor conditions. Furthermore, stirring dilutes toxic compounds within the digester, reducing inhibitory effects (Adnane et al., 2024). Overall, it ensures a uniform environment, supporting the optimal growth and function of anaerobic bacteria.

6 Anaerobic co-digestion

Anaerobic co-digestion (AcoD) of animal manure and other substrates has been shown to increase BGP. This has been attributed to increased volatile solids concentration, substrate degradability, optimal pH, provision of microbial nutrients and anaerobic microorganisms, and inhibition of chemical toxicity, such as NH₃ production (Tawfik et al., 2023; Kunatsa and Xia, 2022; Kunatsa et al., 2022). Co-digestion with poultry manure has been shown to enhance the C/N ratio and provision of methanogenic microorganisms, thereby leading to increased methane production (Tawfik et al., 2023; Minale and Worku, 2014). This is advantageous to FWs as they are low in nitrogen (Odejebi et al., 2023). When co-digested with FWs, poultry manure increases the amount of *hydrogenotrophic* methanogens, such as *Methanoculleus* and *Methanothermobacter*, which enhance AD and contribute to increased BGP (Tawfik et al., 2023).

Table 3 provides a summary of research findings regarding the composition, volume, and quantity of biogas produced through PM and FW co-digestion.

TABLE 3 Summary of studies on biogas composition and volumes generated from PM and FW co-digestion.

Substrates	Co-digestion substrate	Type of digestion	Biogas composition	Biogas volume	References
Fluted pumpkin fruit rind	PM	Two samples (O and P) were subjected to mechanical and thermo-alkaline pre-treatments, while another sample (Q) had no thermo-alkaline treatment and served as the control.	Sample O: 66.5% methane, 25% carbon dioxide Sample P: 58.5% methane, 26% carbon dioxide Sample Q: 54.5% methane, 28% carbon dioxide		Dahunsi et al. (2018)
Banana waste	PM	Poultry droppings and banana peels were co-incubated at 35 °C at a ratio of 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 for 83 days.	The mean % CH ₄ for co-digestion ratios of 100:0, 90:10, 70:30, 50:50, 30:70, 10:90, and 0:100 was 56.65, 55.55, 57.05, 56.29, 57.10, 53.77, and 36.64%, respectively For the co-digestion ratios of 0:100, 10:90, 30:70, 50:50, 70:30, 90:10, and 100:0, the mean % CO ₂ were 57.23, 40.10, 36.77, 37.59, 36.82, 38.32, and 37.23%, respectively.	Co-digestion at 50:50 yielded the maximum biogas volume of 347.0 ± 53.6 mL/gVS	Khatun et al. (2023)
Wheat straw	PM	The digester, which has a working volume of 70 L, is a complete-mix pilot-scale model. The OLRs range from 1.0 to 4.0 kg VS/m ³ d within a 15-day HRT and at digestion temperatures of 25, 30, and 35 °C. (Co-digestion at 35 °C yielded the highest volume.)	53–70.2% methane	0.12 m ³ /kg VS	Babae et al. (2013)
Food waste	PM	For the experiments, anaerobic bottles with a total capacity of 300 mL and an operational volume of 150 mL were utilized. In every assay test, the substrate concentration was maintained at 10 g-VS L ⁻¹ , and the substrate was combined with FWs in different proportions.	Hydrogen and methane	The co-digestion process involving food waste in proportions ranging from 50 to 85% produced hydrogen yields between 15.5 and 57.5 mL·g ⁻¹ -VS.	Liu X. et al. (2022)
Peanut hull	PM	One sample of the mixture was subjected to mechanical and thermo-alkaline pretreatments, while another received mechanical treatment but not thermo-alkaline techniques. ANNs and RSM were used for optimization.	The methane and carbon dioxide contents of the generated biogas were 65.5 ± 1.5% and 26 ± 1% for RSM and 53 ± 1% and 26 ± 2% for ANNs.	The anticipated biogas yields for RSM and ANNs were 3,903.15 × 10 ⁻³ m ³ /kg TS fed and 3,338.3 × 10 ⁻³ m ³ /kg TS fed in the thermos-alkaline pretreated sample, respectively.	Dahunsi et al. (2017)
Pawpaw peels	PM	Optimization was carried out using ANNs and RSM. The peels were subjected to mechanical and thermo-alkaline pretreatments before mixing with poultry droppings. Further dilution to a ratio of 1:1 by volume was done by adding water.	The biogas compositions were 66–68% methane and 18–23% carbon dioxide.	The biogas yield for RSM and ANNs was 3,991.77 (10 ⁻⁴ m ³ /VS) and 3,875.10 (10 ⁻⁴ m ³ /VS), respectively.	Dahunsi et al. (2016)

(Continued)

TABLE 3 (Continued)

Substrates	Co-digestion substrate	Type of digestion	Biogas composition	Biogas volume	References
<i>Cymbopogon citratus</i> (Lemon grass)	PM	<i>C. citratus</i> was mixed with poultry droppings in a ratio of 1:1 by mass. The experiment was monitored for 30 days at an environmental temperature of 27 °C to 37 °C.	66.20% methane	1.3 L/kg/day	Owamah et al. (2014)
Food and vegetable wastes (F&VWs)	PM	PM was co-digested with F&VW in a 1:1 weight ratio using two 19-L stirred tank reactors operating in a semi-continuous bench scale manner. The conditions for operation included a temperature of 34.5 °C, an organic load rate of 2 g VS/L. d, a hydraulic retention time of 28 days, and agitation at 100 revolutions per minute (1 h, three times a day).	62.6% ± 2.4 methane	0.33 ± 0.01 NL/g VS _{added} .	Bres et al. (2018)
Corn straw Wheat straw Rice straw	PM	This co-digestion type was conducted in 1-L conical flasks and assessed using batch digesters. A total of five different mixing combinations were tested over a 60-day HRT to determine the optimal mixing ratio. The digesters were maintained at mesophilic temperatures (35 ± 1 °C) and were stirred manually once daily.	The mixture with a 50:50 ratio yielded the greatest amounts of methane (CH ₄). Wheat straw: 345 mL/g of VS _{removed} Corn straw: 383 mL/g of VS _{removed} Rice straw: 378 mL/g of VS _{removed}	Corn straw had the highest biogas yield. Its yields were evaluated as 635, 717, 817, 768, and 601 mL/g of VS for the ratio mixture of 83.3:16.7, 75:25, 50:50, 25:75, and 16.7:83.3, respectively.	Zhang et al. (2014)
Corn stover	PM	The substrate and poultry manure were co-digested under four independent factors: hydraulic retention time, pH, temperature, and the ratio of PM to alkali-treated corn stover. Optimization was carried out with RSM and ANN.		The biogas yield estimated was 745 mL/g TS under optimum levels of pH 7, temperature of 37 °C, 13 days hydraulic retention time, and mixing ratio of 80%.	Aklilu and Waday (2023)
Wheat straw Meadow grass	PM	To improve substrate composition and C: N ratio for increased BGP, each substrate was co-digested with poultry manure at 5 different ratios. All the digesters were operated simultaneously at the same VS concentration and mesophilic temperature of 35 ± 1 °C.	After digestion for 90 days, the mixing ratios of 70:30 (wheat straw) and 50:50 (meadow grass) produced the highest concentration of methane, 330.1 and 340.1 normalized liters per kg volatile solids (NL kg ⁻¹ VS), respectively.	The highest biogas volume was obtained at a ratio of 50:50 for both substrates, i.e., 585.90 NL kg ⁻¹ VS and 610.70 NL kg ⁻¹ for wheat straw and meadow grass, respectively.	Rahman et al. (2017)
Fruit and vegetable wastes	Solid poultry slaughterhouse wastes (SPSWs)	The biogas reactor was microbially enriched with sludge from a commercial poultry wastewater treatment digestion facility for startup and seeding. The C/N ratio of the examined SPSW, measured at 5.75, was combined with FVSWs to generate C/N ratios of 20, 30, and 40%. The reactor was run for a duration of 40 days.	All three loadings' ratios had 48.6, 50, and 50.2% methane, respectively	The BGP volumes were 215.1, 241, and 182.7 L for all three loading ratios, respectively	Samadi et al. (2022)

(Continued)

TABLE 3 (Continued)

Substrates	Co-digestion substrate	Type of digestion	Biogas composition	Biogas volume	References
Rice husks	PM	100 g of the substrate was mixed with 25 g of poultry droppings or urea to obtain a feed to poultry droppings/urea ratio of 4:1 (w/w). Incubation was carried out at 30 °C with a hydraulic retention time of 28 days.		The highest biogas yield was 382 and 357 mL/day for a feedstock to water dilution ratio of 1:6 (w/v) and initial pH 7, respectively. After two days, the control and poultry droppings had maximal BGP rates of 30 and 69 mL/day, respectively.	Okeke et al. (2014)
Plant wastes (carrot, cabbage, leek, lettuce, parsley, onion, potatoes, and cucumber)	PM	The plant wastes were mixed with poultry manure at a dry matter content of 12%, a fermentation temperature of 35 °C, and a retention time of 30 days.	40.3% Methane	BGP was 1,055.7 L per day	Yaldiz et al. (2011)
Sugarcane press mud	PM	The substrate was equally mixed with poultry manure at a mesophilic temperature (35 °C) for 6 months	The specific methane yield was 260 NL kg ⁻¹ VS	The average highest ultimate methane yield was 325 NL kg ⁻¹ VS.	Rahman et al. (2022)
Avocado peel	PM	The substrate was co-digested with poultry manure in the ratios of 100:0, 0:100, 50:50, and 75:25 in an anaerobic digester.		The maximum biogas produced was 453.5 mL and was observed from the feedstock of a 50% ratio.	Kenasa and Kena (2019)
Cassava peel (CP)	PM	The substrate was co-digested with poultry droppings (PD) in five identical 10 L reactors, each with a working volume of 5 L, in the following batches: Digester A (100% PD, 0% CP), B (75% PD, 25% CP), C (50% PD, 50% CP), D (25% PD, 75% CP), and E (0% PD, 100% CP) at a mesophilic temperature of 37 ± 10 °C. The reaction was stopped after 44 days.		Digester B produced the highest biogas (24.6 L/g VS)	Achebe et al. (2018)
Rotten potato	PM	The substrate was co-digested with poultry manure at a ratio of 50:50 and 75:25 at 37 °C.	65.30% methane was observed in a ratio of 75:25.	The highest biogas volume of 341.22 mL/g VS was achieved at the ratio of 75:25.	Ali et al. (2017)

OLRs, organic loading rates; VS, volatile solids; ANNs, artificial neural networks; RSM, response surface methodology.

6.1 Pros and cons of anaerobic digestion

The widespread use of AD methods offers a wide range of advantages, which can be summarized as follows ([Reith et al., 2003](#)):

- **Energy production:** AD processes generate an energy source through CH₄ production.
- **Low energy consumption:** AD technology typically requires minimal energy. At room temperature, the energy needs range from 0.05 to 0.1 kWh per cubic meter (equivalent to 0.18–0.36 MJ/m³), largely dependent on pumping and effluent recycling requirements.
- **Reduced solid waste:** The process significantly decreases the volume of solids that must be managed. The excess sludge

produced during AD is considerably lower than that from aerobic methods when based on biodegradable chemical oxygen demand (COD).

- **Simplified dewatering:** Sludge dewatering is facilitated through anaerobic processes.
- **Stabilization of raw waste:** This treatment stabilizes raw waste effectively.
- **Minimal odor:** The end products of AD are relatively free of odors.
- **Nutrient retention:** There is nearly complete retention of crucial nutrients, such as phosphorus, nitrogen, and potassium.
- **High loading capacity:** Advanced AD systems are capable of handling substantial organic loads, with capacities 30 g COD/L/day at 30 °C and 50 g COD/L/day at 40 °C, particularly for medium-strength, primarily soluble wastewater.

- *Long-term sludge preservation*: Anaerobic sludge can be stored for extended periods without the need for feeding.
- *Lower construction costs*: The costs associated with building anaerobic treatment facilities are comparatively low.
- *Compact footprint*: Anaerobic systems require less space than traditional treatment systems.

However, there are also certain drawbacks associated with AD processes, as stated below.

- *Sensitivity to chemicals*: Methanogenic bacteria, which are crucial to the process, are highly sensitive to various chemical substances. While some anaerobic organisms can adapt to these chemicals, this sensitivity poses challenges.
- *Time-consuming start-up*: Initiating an anaerobic treatment system without adequate seed sludge can be slow due to the slow growth rates of anaerobic bacteria.
- *Odor issues with sulfur compounds*: When treating wastewater containing sulfurous compounds, the process can produce odors due to sulfide formation. A widely adopted approach to address this problem is the incorporation of a microaerophilic post-treatment phase, which facilitates the conversion of sulfide into elemental sulfur.

6.2 Pros and cons of anaerobic co-digestion

The major advantages of AcoD over the single-substrate AD are stated below (Kunatsa and Xia, 2022).

- *Enhanced biogas production*: AcoD often results in increased CH₄ yields due to synergistic effects among different substrates (co-substrates). This thus enhances energy recovery efficiency.
- *Improved process stability*: AcoD promotes consistent operation by balancing the C/N ratio (nutrient profile) and supplementing essential trace elements, ensuring a stable microbial environment.
- *Reduction of inhibitory substances*: AcoD dilutes toxic compounds, such as NH₃, lignin derivatives, long-chain fatty acids, and heavy metals, to levels below inhibitory thresholds, thereby safeguarding microbial activity.
- *Broader substrate flexibility*: AcoD enables the utilization of various organic wastes, such as food waste and manure, promoting waste valorization and reducing disposal challenges.
- *Nutrient balance optimization*: AcoD addresses nutrient deficiencies or imbalances typical in mono-digestion, leading to more efficient and stable digestion processes.
- *Increased organic loading*: Combining multiple substrates allows for higher concentrations of biodegradable organic matter, which boosts overall biogas production potential.
- *Production of nutrient-rich digestate*: The resulting co-digestate from the AcoD process is rich in nutrients, making it suitable for agricultural applications and contributing to sustainable nutrient recycling or waste management.
- *Improved process resilience*: As mentioned earlier, the diverse nutrient profile mitigates inhibitory effects and supports robust microbial activity, ensuring consistent digestion performance.

Although AcoD offers numerous advantages, it also presents certain limitations, which are summarized below (Kunatsa and Xia, 2022; Sembera et al., 2019).

- *Complexity of process management*: Managing multiple substrates can complicate process control and monitoring of AcoD.
- *Potential for inhibitory interactions*: Certain substrate combinations may produce inhibitory compounds or imbalances if not properly managed.
- *Accumulation of solids within the digester*: Solids accumulation from indigestible materials like glass and metals that may be present in food waste (FW) reduces digester volume and shortens hydraulic retention time (HRT), leading to decreased CH₄ production, system clogging, equipment damage, and lower digestate quality.
- *Decline in HRT*: Reduced HRT due to solids buildup hampers treatment efficiency, affects digestate dewaterability, and compromises CH₄ recovery and sludge stabilization.
- *Nitrogen accumulation*: High protein co-substrates, such as FW and dairy byproducts, can cause nitrogen backload, increase ammonium levels, and risk free-ammonia inhibition.
- *Digestate sludge dewatering and drying*: Shortened HRT also results in higher volumes of solids that require drying and disposal, increasing operational costs.
- *Economic and logistical challenges*: Variability in substrate availability and the need for pre-treatment can increase operational complexity and costs.

6.3 Comparison of AcoD with other forms of AD

Anaerobic co-digestion (AcoD) stands out from other forms of AD, such as single-substrate AD (SSAD) or AMD, in several key aspects toward WM strategies and BGP. These aspects include continuous operational mode, which maximizes the efficiency of processing multiple substrates simultaneously, unlike traditional methods (like AMD), which operate in batch or semi-continuous modes that restrict throughput. Additionally, AcoD can adapt to both mesophilic and thermophilic temperature conditions, while thriving on wet feedstocks, and its flexible reactor configuration allows for either single-stage or multi-stage designs to enhance biogas yields. In contrast, some conventional systems, such as AMD, focus narrowly on SSD. Furthermore, AcoD's distinctive microbial community composition benefits from the diverse organic sources it processes, often resulting in a higher BGP rate compared to low-rate conventional AD (or AMD), and it can be implemented effectively at both small and large scales, making it a versatile choice for optimizing BGP across different applications.

Table 4 highlights the comparable features between AcoD and other forms of AD, especially SSAD or AMD, using animal manure, such as PM, and FWs for WM and BGP.

According to data from various studies (Kunatsa and Xia, 2022), as summarized in Table 5, co-digestion substrates tend to yield greater biogas production than mono-digestion processes. Combining lignocellulosic wastes with animal manure can mitigate the challenges associated with their recalcitrance by utilizing the native microbial populations in manure, thereby boosting biogas output. The selection

TABLE 4 Comparison between AcoD and AMD for WM strategies and BGP.

Criteria	AcoD	SSAD or AMD
Operational mode	Continuous	Batch, semi-continuous
Temperature conditions	Mesophilic/thermophilic	Mesophilic (often)/thermophilic (less common)
Moisture content	Generally wet	Wet or dry (depending on system design)
Reactor configuration	Multi-Stage or Single-Stage	Generally single stage
Feedstock type	Co-digestion of multiple substrates [e.g., animal manure (like PM) + FW]	Single substrate (e.g., only manure or only FW)
Process features	High-rate process, improved digestibility, and biogas yield	Generally, a lower rate of biogas yield may be limited
Microbial community composition	More diverse due to mixed feedstocks	More homogeneous and may be less adaptive
Scale of operation	Flexible (small-scale farms to large plants)	Generally, a large scale for cost-effectiveness
BGP efficiency	Higher potential due to synergistic effects from co-digestion	Generally lower, depending on substrate type
WM efficiency	Enhanced due to improved breakdown of diverse waste	Effective, but may not utilize resources as effectively

of different substrate combinations and mixing ratios influences both the volume of biogas produced and methane concentrations. Therefore, further research is essential to identify optimal feedstock combinations and blend ratios to maximize biogas yields.

7 Challenges and future directions

7.1 Challenges

Anaerobic digestion processes, especially AcoD of poultry manure and food wastes (PM & FWs), face challenges that can hinder BGP. Variability in the composition and quality of these wastes affects production efficiency. Moreover, optimizing conditions like pH, temperature, and carbon-to-nitrogen (C/N) ratio for diverse waste mixtures is complicated. The elevated nitrogen and ammonia levels in PM can also inhibit microbial activity, reducing biogas yields.

Additionally, the high initial setup and operational costs of AcoD systems pose economic challenges, limiting their broader adoption and commercial viability in the renewable energy sector.

7.2 Future directions

Future advancements in AcoD of PM&FWs for BGP require several strategic directions. Establishing standardized protocols for different waste mixtures will help tackle existing challenges in waste-to-energy initiatives. Further, research should prioritize biotechnology innovations, particularly the use of genetically engineered microbes

TABLE 5 Data from various studies on the AcoD effects on biogas yield (Kunatsa and Xia, 2022).

Feedstocks	Comparison of anaerobic mono-digestion and AcoD biogas yields
Poultry droppings (PD) and lignocellulosic co-substrates (LCSs) (wheat straw (WS) and meadow grass (MG))	In AcoD, the highest CH ₄ concentrations were found to be 330.1 and 340.1 NL kg ⁻¹ VS at a blending ratio of 70:30 (PD: WS) and 50:50 (PD: MG), respectively. This was an increase of 1.14 and 1.13 times higher than the LCSs individually on mono-digestion.
Wastewater sludge (WAS) and olive pomace	WAS and olive pomace mono-digestion yielded 0.18 and 0.16 L CH ₄ /g VS added for olive pomace and wastewater sludge, respectively. Co-digestion yielded 0.21 L CH ₄ /g VS added. Co-digestion increased methane production by 17–31%.
WAS and fish waste or garden grass (GG)	A gradual increase in fish concentration increased CH ₄ generation up to 1.9 when 75% was added. With grass CH ₄ production, it only improved after adding 25%; adding more than 50% grass increased the production rate and final product by 1.5 and 1.7 times, respectively.
Sugarcane press mud (P) and vinasse (V)	The combination V and P in a ratio of 75:25 had the best CH ₄ generation rate of 69.6 Nm L CH ₄ g ⁻¹ COD ⁻¹ fed per day. In AcoD, CH ₄ outputs of 365 L CH ₄ kg ⁻¹ VS and biogas production output of 1.6 L L ⁻¹ were achieved, which was 64% greater than mono-digestion.
Microalgae and primary sludge	AcoD of microalgae and primary sludge in a ratio of 25:75 on a volatile solids basis was compared to microalgae mono-digestion. AcoD improves CH ₄ generation by 65%.

COD, chemical oxygen demand; VS, volatile solids.

to boost digestion efficiency. Investments in affordable reactor designs could enhance the feasibility of small-scale operations, fostering broader participation. Life Cycle Assessments (LCAs) are necessary to assess the ecological benefits of the process.

Furthermore, an extensive review of the techno-economic analysis is crucial to evaluate the process's viability from both technical and economic standpoints. It is crucial to encourage policymakers to advocate for or support waste-to-energy initiatives. By implementing these strategies, the overall effectiveness and adoption of BGP from organic waste can be improved, contributing to greater environmental sustainability and optimal resource utilization.

8 Conclusion

BGP from agro-food biomass (AFB) residues or wastes via AcoD serves as a promising and innovative alternative bioenergy source compared to AMD, with this review emphasizing the significant advantages and efficiency of AcoD of PM and FWs. AcoD not only aids in generating clean energy, thereby diminishing dependence on fossil fuels and associated costs, but it also plays a crucial role in mitigating environmental pollution, leading to economic benefits and improved public health. This method responds effectively to the urgent need for healthy diets by converting waste into energy while simultaneously tackling critical challenges such as food insecurity and

environmental degradation. Ultimately, this narrative review underscores the significant potential of integrating PM&FWs into a sustainable approach that can foster energy-resilient communities and promote overall sustainability.

Author contributions

AA: Conceptualization, Methodology, Writing – original draft. TM: Funding acquisition, Supervision, Writing – review & editing. CR: Writing – review & editing. IM: Project administration, Writing – review & editing. JN: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

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