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Review Article

Advancements in high solid anaerobic co-digestion: a comprehensive review

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The increasing amount of organic solid waste produced worldwide highlights the need for effective and durable treatment methods. Unlike traditional liquid anaerobic digestion, High Solid Anaerobic Digestion (HS-AD), which typically operates at total solids (TS) contents above 15%, has become a promising technology because it requires less reactor volume, less heating energy, and generates less leachate. However, HS-AD often faces challenges such as mass transfer limitations, ammonia inhibition, and process instability. Co-digestion-the simultaneous digestion of two or more substrates-has proven successful in overcoming these issues by balancing nutrients, neutralising inhibitory chemicals, and regulating the carbon-to-nitrogen (C/N) ratio. This paper thoroughly examines recent advances in High Solid Anaerobic Co-Digestion (HS-AcoD). It critically analyses the fundamental mechanisms, the synergistic effects of different substrate combinations, and the influence of operational parameters on process performance. Particular attention is given to reactor configurations, microbial community dynamics, and methods to mitigate inhibition. The study also discusses technological and financial challenges that hinder the large-scale implementation of emerging techniques, such as bioaugmentation and the addition of conductive materials. The review concludes with perspectives on future research directions aimed at enhancing the efficiency and resilience of HS-AcoD systems for waste valorisation and bioenergy production.

Keywords: *High solid anaerobic digestion, co-digestion, synergistic effects, bioenergy, microbial community, process stability*

Introduction

Significant environmental challenges, such as issues with land use, pollution, and the acceleration of climate change, are driven by the global increase in waste production, especially organic waste from agricultural activities. Methane is produced during the decomposition of organic waste in landfills. Therefore, managing this waste sustainably is crucial. Additionally, traditional energy sources particularly fossil fuels substantially contribute to greenhouse gas emissions worldwide, leading to climate change and environmental degradation. Switching to renewable alternatives like biogas can help mitigate these impacts. Moreover, societies can improve their self-sufficiency and reduce their vulnerability to global energy price fluctuations by adopting advanced technologies such as anaerobic digestion. This transition not only ensures a stable electricity supply but also stimulates regional economies through job creation in emerging sectors. Furthermore, poor waste management can pose serious health risks, including respiratory problems from garbage burning, contaminated water, and other public health issues. Consequently, efficient waste-to-energy methods can decrease waste volume while addressing these health concerns. Anaerobic digestion is a process commonly used to manage biowastes. In the absence of oxygen, it breaks down organic components, producing biogas and digestate as residual materials. Digestate contains cell material, nutrients, humic and fulvic compounds, and residual solids that microorganisms cannot decompose in anaerobic conditions. The stabilised organics produced through this process have properties influenced by the reactor's performance and input materials. With promising potential for recovering nutrients and humic compounds, this liquid digestate can be considered agricultural wastewater (Ellacuriaga et al., 2021). Any type of water that has been affected by human activity and cannot be discharged into surface or ground waterways without specific treatment is considered wastewater. The excess water that runs off from fields into basins, furrows, boundary strips, and flooded regions during irrigation is essentially agricultural wastewater. "Irrigation tailwater" is another term for these types of agricultural effluent. The harvesting and processing are another source of agricultural wastewater (Mehta et al., 2021). The operational and environmental aspects of the HS-AD process may contribute to its challenges. Temperature, pH, and ammonia concentration changes can inhibit the HS-AD process, but this inhibition is similar to that observed in the LS-AD process. Therefore, the composition of feedstock, handling, pumping, and mixing of the high solid waste streams present the greatest challenges (Lissens et al., 2001).

Figure 1. High speed anaerobic challenges

Anaerobic (Figure 1) digestion (AD) is an environmentally beneficial method for biodegradable waste disposal and energy recovery, although it has not been used ideally (Daniel-Gromke et al., 2018). AD is a process where microbial activity breaks down biodegradable organic wastes without air, producing digestates and biogas for soil fertilization and energy, respectively. The retention time in bioreactors typically ranges from 20 to 40 days, making it a slow process (Wainaina et al., 2019). A key component of AD processes is total solids (TS), which can be divided into two main groups based on the TS content in solid wastes: high solid or dry anaerobic digestion (HS-AD) and low solid or wet anaerobic digestion (LS-AD). Biodegradable wastes with TS contents of ≤10% and ≥20%, respectively, are processed using LS-AD and HS-AD (Abbassi-Guendouz et al., 2012). Due to its straightforward technology, LS-AD is the most widely used anaerobic digestion method worldwide (Di Maria et al., 2017; Shinners et al., 2007). However, there are certain issues with LS-AD that affect its maximum productivity. One limitation is the large digester footprint needed because of the low TS content of the feedstock; a high-volume digester is necessary for optimal feedstock valorization. Another challenge is the need for significant water input to reduce the feedstock's solid content, which poses a problem in water-scarce areas (Matheri et al., 2018).

Fundamentals of high solid anaerobic co-digestion

Defining HS-AD and Co-Digestion

A TS content greater than 15% within the reactor is typically used to classify HS-AD, although definitions vary widely in the literature. The physical state of the digestate, which functions more like a solid matrix or a non-Newtonian, high-viscosity pseudo-plastic fluid, is what differentiates HS-AD and significantly impacts mass transfer and mixing needs (Li et al., 2011).

Benefits of Co-Digestion

The concept of synergy is vital to co-digestion (Figure 2). It involves diluting potential inhibitors (such as ammonia, lipids, and heavy metals), supplying essential trace elements that one substrate might have but another lacks, balancing the C/N ratio critical for microbial growth and enhancing rheological properties, which improve mixing. These factors all help create synergistic effects (Hartmann and Ahring, 2006). Co-digestion can also boost substrate bioavailability for HS-AD by improving moisture distribution within the solid matrix.

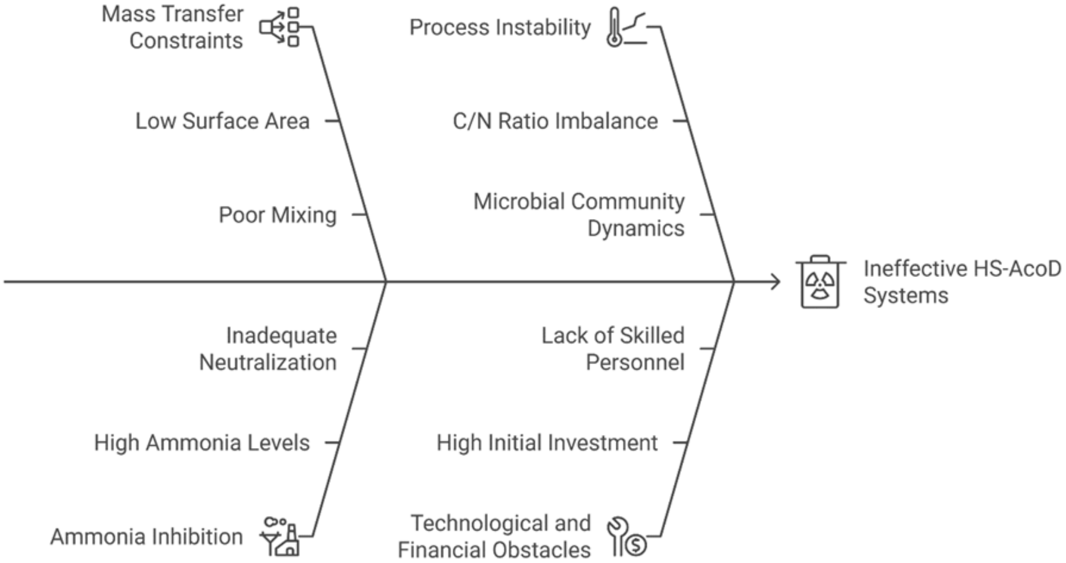

Figure 2. Challenges in high solid anaerobic co-digestion

Substrate combinations and synergistic effects

For HS-AcoD to succeed, selecting compatible substrates is crucial. Typically, substrates are classified based on their primary composition: either nitrogen-rich (such as sewage sludge, animal manure, and slaughterhouse waste) or carbon-rich (such as straw, paper, and garden waste).

C/N ratio optimization

One essential factor in AD is the carbon-to-nitrogen ratio. Methanogenesis is often inhibited by excessive ammonia production caused by a low C/N ratio (<15). A high C/N ratio (>35) indicates a nitrogen deficiency, which reduces reaction rates and limits microbial protein synthesis. Although recent research suggests that steady operation may be possible at lower ratios if the microbial community is acclimated, the optimal C/N ratio in HS-AcoD typically lies between 20 and 30 (Wang et al., 2012).

Process optimization and operational parameters

Total solids (TS) content

Mass transfer is directly affected by TS composition. Viscosity increases sharply with TS, hindering bacteria and metabolites from moving freely. Although higher TS allows for greater OLR, there is a limit (usually between 35 and 40% TS) beyond which metabolite accumulation and water-activity restrictions severely slow methanogenic activity.

Temperature regimes

HS-AcoD is often performed in thermophilic (55–60°C) or mesophilic (35–37°C) environments. Thermophilic digestion is highly effective for treating manures and sludge because it offers better pathogen elimination and faster reaction kinetics. However, ammonia inhibition and environmental disturbances have a greater impact on thermophilic systems. Recent developments in "temperature-phased" anaerobic digestion (TPAD) suggest that a hybrid strategy might offer stability advantages.

Reactor technologies and configurations

The physical properties of high solid feedstocks require specialised reactor designs that differ from the traditional Continuous Stirred Tank Reactors (CSTR) used in liquid AD.

Batch reactor

Batch systems, such as garage-type or tunnel digesters, are simple and sturdy. The process involves loading, sealing, digesting, and unloading the substrate. Leachate is often recycled to spread moisture and inoculate new material. Batch systems are straightforward to operate, but over time, they experience uneven gas output rates (Kothari et al., 2014).

Continuous plug-flow reactors

The most popular setup for continuous HS-AD is PFRs. As feedstock passes through the reactor like a "plug," longitudinal mixing is minimised. This ensures a retention period for pathogen destruction. To prevent stratification and gas bubble release without fully mixing the longitudinal axis, horizontal PFRs often use slow-spinning agitators (Demirel and Scherer,2008).

Inhibition factors and mitigation strategies

Ammonia inhibition

The main factor preventing nitrogen-rich substrates from co-digesting is free ammonia nitrogen, or FAN. FAN disrupts proton gradients because it is membrane-permeable. Since HS-AD systems lack dilution water, they are particularly vulnerable. Mitigation methods include using adsorbents like zeolite or charcoal, struvite precipitation, and pH regulation, as FAN concentration increases with pH (Chen et al., 2008).

VFA accumulation

Local accumulation of volatile fatty acids (VFAs) might result in "acid hotspots" that hinder methanogens because of mass transfer constraints in the solid matrix. In order to disperse VFAs and distribute alkalinity, enough mixing or leachate recirculation is necessary.

Overview of high-solid anaerobic digestion

Food waste, agricultural waste, cow manure, sewage sludge, energy crops, municipal solid waste, garden waste, and industrial waste streams are all included in the organic fraction of municipal solid waste for which HS-AD offers an effective solution (Gao et al., 2023). Different bacterial and archaeal populations facilitate HS-AD in oxygen-depleted environments, producing nutrient-rich digestate as well as by-products of around 60% methane (CH_4) and 40% carbon dioxide (CO_2) (Li et al., 2011). A number of interrelated biochemical and physical events that take place both sequentially and concurrently are involved in the AD process. The four steps of these reactions are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Ren et al., 2018). The first rate-limiting step in AD is hydrolysis. Complex chemical compounds are broken down by hydrolysis bacteria into simpler, soluble components, which are then further degraded by microorganisms during fermentation to produce volatile fatty acids (VFAs). Genera like Syntrophomonas and Syntrophobacter assist in the creation of acetic acid, another crucial stage. Meanwhile, methanogens are classified as either hydrogenotrophic or acetoclastic, depending on whether they use acetate or hydrogen and CO_2 as their main substrates. Specific microbial communities promote each step, and maintaining the balance of these communities and achieving optimal AD performance depends on the interaction and connectivity of microbial populations across these stages (Gerardi, 2003). AD systems may fail due to imbalances or disturbances in microbial ecology during these stages (Tchobanoglus et al., 2003).

Considering key parameters such as organic loading rate (OLR), pH, the presence of inhibitory and hazardous chemicals, temperature, and solids retention time (SRT) is vital for maximizing HS-AD efficiency (Sarker et al., 2019a). The LS-AD shows an OLR of about 5–6 kgVS/(m^3·d), whereas the HS-AD shows an OLR of approximately 10 kgVS/(m^3·d). Excessive OLR causes organic overload and toxicity problems, whereas insufficient OLR results in lower biogas production (Nkuna et al., 2022). Maintaining the proper pH range (6.5–7.5) is also crucial for the functioning of methanogenic archaea and acid-producing bacteria (Wang et al., 2023). Extreme pH values below 6.3 or above 7.8 can inhibit microbial species involved in AD and negatively impact methane generation (Sarker et al., 2019b). The accumulation of VFAs during acidogenesis lowers the pH of AD systems, which hampers methanogens from undertaking their methanogenic process. Toxic substances must be managed with proper procedures and ongoing monitoring, including heavy metals, sulfides, ammonia, and antibiotics that suppress microbial activity and cause process failure (Gao, Li, et al., 2023).

Furthermore, temperature plays a significant role in AD and can be divided into three main ranges: thermophilic (55-60 °C), mesophilic (35-40 °C), and psychrophilic (10-30 °C) (Li et al., 2023). Microorganisms' metabolic activity depends on temperature, with higher temperatures generally leading to faster digestion. Additionally, SRT is crucial for maintaining microbial balance and functional activity in AD (Akinbomi et al., 2022). A longer SRT is often recommended to reduce hazardous chemicals and irregular organic loading, but achieving optimal performance requires careful evaluation of the interactions among SRT, organic loading, and specific system characteristics. Despite the challenges in maintaining this stability, various strategies have been devised to address these issues. These include controlling bacterial populations involved in AD, optimizing mixing based on rheological properties, and pre-treating the substrate.

Classification of high-solid anaerobic digestion systems

Heat and mass transmission, biokinetics, and spatiotemporal hydrodynamics are all significantly influenced by digester design, size of implementation, and operating modes (Li et al., 2023).

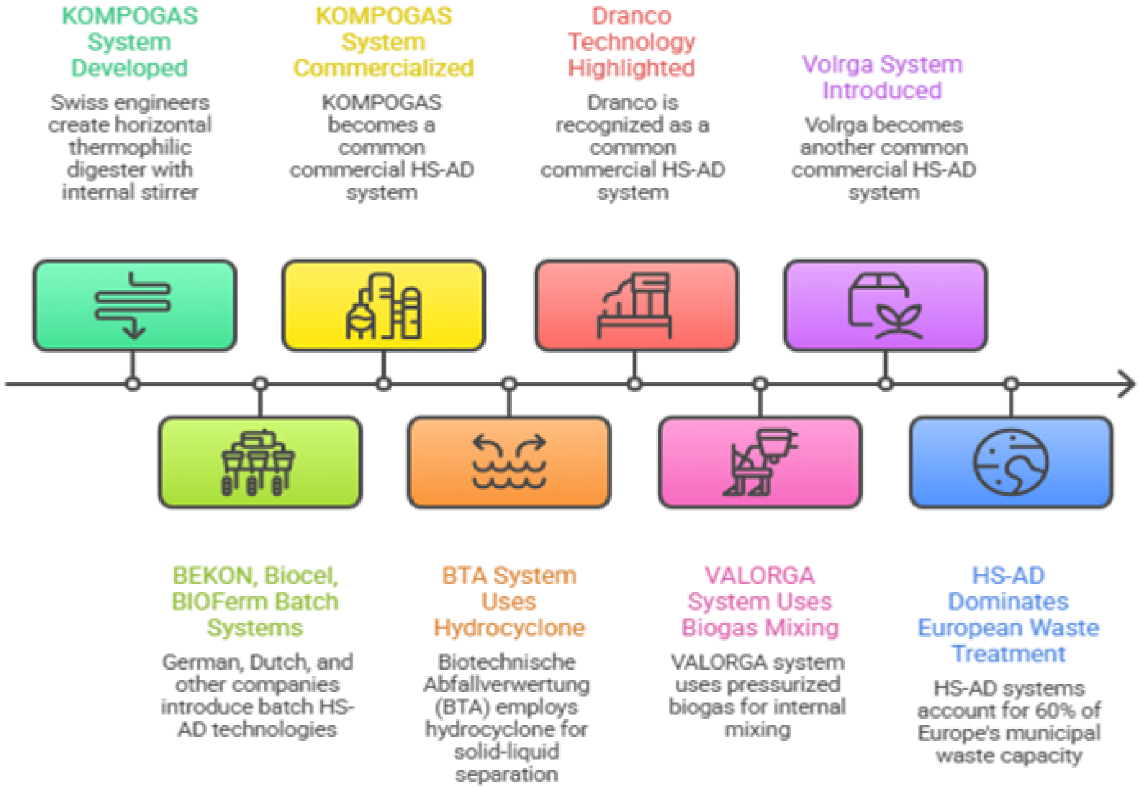

Figure 3. Key milestones in High-solid anaerobic digestion technology

Various reactor configurations have been developed in the field of HS-AD to satisfy different operational requirements. These configurations include the number of stages (single and multistage), feeding mode (batch and continuous), operating temperature (psychrophilic, mesophilic, and thermophilic), and flow direction (horizontal and vertical) (Figure 3). Dranco is one of the common commercial systems used in the HS-AD area (De Baere, 2010), Volrga (Álvarez et al., 2018), KOMPOGAS (Wellinger et al., 1993a), BEKON, Biocel, and BIOFerm (Akinbomi et al., 2022). Between 30% and 40% of the raw ingredients include TS. HS-AD systems account for about 60% of Europe's total capacity for treating municipal garbage (De Baere et al., 2010). The operational approaches used by these systems in digesters' design are then assessed to address the main obstacle slow mass transfer in HS-AD (Figure 4). Typical continuous and single-stage HS-AD systems, such as Dranco, VALORGA, and KOMPOGAS, can operate continuously with solid contents ranging from 20% to 60% (André et al., 2018; Fagbohungbe et al., 2015).

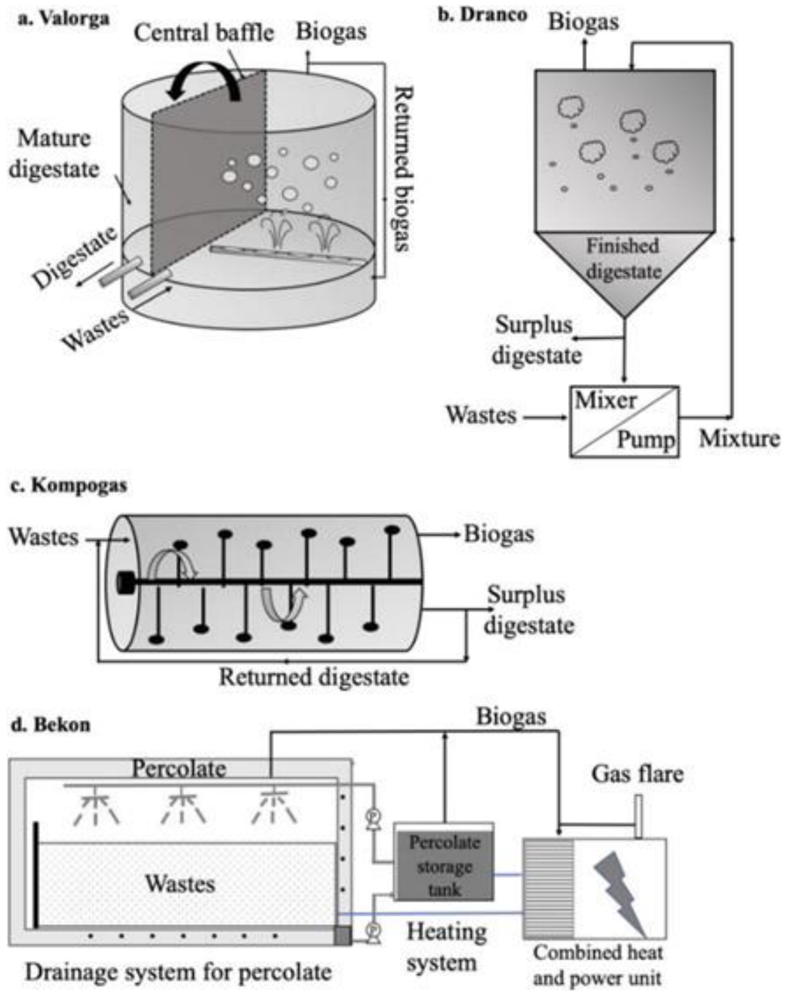

Figure 4. The operational approaches in HS-AD

Because some of these dry systems lack internal mixing, substrate and digestate must be combined before feeding the digester (Wellinger et al., 1993b). Besides the downward plug flow of waste during feeding, there is no mixing in the Dranco system (thermophilic or mesophilic). To produce 468 m^3/t of biogas, a Dranco digester in Brecht, Belgium, processed biomass feedstock with TS = 35% (15% food waste, 75% garden waste, and 10% paper) over an HRT of 14 days. In the VALORGA system (thermophilic or mesophilic, vertical), pressurized biogas is used for mixing, but this method consumes a lot of energy and has a high risk of organic debris blocking the nozzles (Li et al., 2011). The KOMPOGAS system (thermophilic, horizontal), developed in Switzerland in the 1980s, employs an internal stirring paddle for mixing and a horizontal push flow to complete digestion in about 14–20 days. It operates with total solids between 23% and 28%, similar to the Dranco process (Li et al., 2011). The batch HS-AD systems, developed later than the continuous HS-AD systems, reduce machinery maintenance and system complexity (Lutz, 2010). Wastes with feed TS of 25% to 35% and an HRT of 28 days have been treated successfully by the BEKON system in Germany, the Biocel system in the Netherlands, and the BIOFerm system (single stage, mesophilic); however, process stability issues such as incomplete mixing and VFA accumulation persisted (Ten Brummeler et al., 1992). Common multistage HS-AD enhances overall efficiency with separate stages for hydrolysis and acidogenesis, and for acetogenesis and methanogenesis. The two-step process includes a hydrolysis chamber with axial mixing and a methanogenic chamber, forming the innovative Biopercolat biogas technique (Ten Brummeler et al., 1992).

The Biotechnische Abfallverwertung (BTA) system uses a hydrocyclone to separate solids and liquids; the solid fraction is combined with pre-treated leachate and pumped into a hydrolysis tank (Chavez-Vazquez and Bagley, 2002).

Compared to single-stage reactors, dual-stage digesters offer quicker stability; nonetheless, disadvantages include hydrogen buildup that hinders acidogenic bacteria, reduced biomass stability, increased technical complexity, storage limitations, and higher operating costs (Srisowmeya et al., 2020). The choice of technology impacts capital and operating costs. For example, in Saffenburg, Austria, and Brecht, Belgium, large-capacity Dranco systems require significant investments in digester capacity, maintenance, and heat energy to maintain thermophilic conditions (Akinbomi et al., 2022). Although BEKON technology has limited digestion efficiency and a high reactor capacity, it is more economical regarding machinery and operational costs because it does not need pumps, agitators, or bulk waste processing (Lutz, 2010). Cost assessments for these technologies should involve detailed economic analysis; simulation models can assist in estimating costs. Advances that increase methane yields in biogas could also reduce overall costs and enhance the economic viability of HS-AD processes. Reactors with a single stage are common. However, there are certain disadvantages to using a two-stage method, such as the accumulation of hydrogen that may prevent the development of bacteria that produce acid, decreased biomass stability, technical complexity, and storage constraints (Rodríguez et al., 2012). It is determined that 20 days is the ideal solid retention period for dry mesophilic anaerobic OFMSW digestion. Promising options for effectively handling high solid waste are provided by the data of HS-AD technology. Although single-stage and continuous digesters are more common, the successful application of HS-AD processes in industrial settings depends on variables such as substrate characteristics, site selection, size, and effective automation for process parameter control.

Review literature on the high solid anaerobic co-digestion system

Although anaerobic digestion of organic wastes for biogas production has been used effectively, better procedures and more affordable reactor designs are still needed. Thus, due to their low construction and operating costs and technological simplicity, dry anaerobic digestion technologies are increasingly popular in both industry and research (Kothari et al., 2014). Dry anaerobic digestion treats food waste, manure bedded with straw, garden trash, and other high-solid waste fractions by processing more organic wastes per reactor volume with a total solid content greater than 20%. Because the reactor volume is reduced and the digestate residue is easier to handle, this technique offers greater economic feasibility compared to wet anaerobic digestion. It also allows for larger organic loading rates and requires less pre-treatment. In this study, untreated manure bedded with straw at a total solid content of 22% was used to test the effectiveness of a plug flow reactor designed for continuous dry digesting processes. With increasing organic loading rates of 2.8, 4.3, and 6 gVS/L/d and retention periods of 60, 40, and 28 days, respectively, this recently developed reactor operated effectively for 230 days. It achieved a methane yield of up to 0.163LCH_4/g/VSadded/d, or 56% of the theoretical yield, with organic loading rates up to 4.2 gVS/L/d improving process stability. Further increases to 6 gVS/L/d caused process instability, reduced volatile solid removal efficiency, and decreased cellulose degradation (Patinvoh et al., 2017).

The start-up phase of anaerobic digestion of rice straw under wet, semi-dry, and dry conditions, focusing on the impact of volatile fatty acid (VFA) synthesis on process kinetics. It explores biodegradation kinetics and methane yields in reactors operating in dry and wet semi-dry environments. The data showed that the specific final methane production yield decreased by 57% and 63% in semi-dry (TS = 14.8%) and dry (TS = 23.4%) conditions, respectively, compared to wet (TS = 4.8%) conditions. Total VFA concentration and speciation are suggested as markers of process progress at various total solids contents, with maximum total VFA concentrations of 2110 mg/kg in dry conditions, 930 mg/kg in semi-dry, and 180 mg/kg in wet conditions (Liotta et al., 2016). Solid concentration significantly influences the anaerobic digestion process. This study examined four solid concentration levels (10%, 15%, 20%, and 25% of total solids) to evaluate their impact on biogas production from rapeseed oil cake, using four 2-liter laboratory batch reactors with a 30-day retention period. Measurements of daily and cumulative biogas output, along with degradation of total solids, volatile solids, and COD, allowed assessment of reactor performance. The highest biogas production occurred at 20% solid concentration, followed by 25%, 15%, and 10%. The study assessed process kinetics using Gompertz, modified Gompertz, and logistic models, with the modified Gompertz model demonstrating the best fit and less discrepancy between predicted and observed biogas yields (Deepanraj et al., 2021). Recycling waste and converting municipal solid waste (MSW) into energy sources is a crucial environmental strategy that reduces resource depletion and prevents pollution. The enhancement of biogas from MSW was examined in this study, investigating the effects of mixing ratios of sewage sludge (SS) and anaerobic digestion (AD) MSW under mesophilic conditions. Higher MSW ratios increased methane output but required longer hydraulic retention times (HRT).

The optimal ratio produced about 90% of total methane (376.84 mL/g VS) after 20 days. The impact of total solids (TS) levels (5–25%) on biogas yield was further studied; lower TS levels (5–10%) produced notably more methane 64% higher than at 25% TS, with methane production values of 230.3, 196.8, 159.5, 129.4, and 83.3 mL/g VS at 5%, 10%, 15%, 20%, and 25% TS, respectively (Ahmadi-Pirlou & Mesri Gundoshmian, 2021). Biomass from sources like cow dung is a significant renewable energy source, especially in regions like Brazil, China, India, and Africa, but the biogas yield per kilogram of biomass is low, and the biochemical process is slow and inefficient. This study investigates whether different dilution ratios (and total solids levels) can increase biogas production efficiency. Batch digesters tested various feed dilutions of cow dung to water, with total solids ranging from 1% to 12.5% and feed ratios from 2:1 to 1:20. Semi-batch tests, mimicking field-scale biodigesters, confirmed that as total solids decreased (dilution increased), specific biogas output rose steadily. Notably, maximum biogas production was not achieved at the common 1:1 feed ratio (~10% TS). Higher feed dilution ratios between 1:2 and 1:4 (TS 4–6.7%) are recommended for better biomass utilization, with empirical correlations established between total solids content and biogas yield (Jeppu et al., 2022). The study also assesses five parameters affecting biogas production from mango leaves: total solids (TS), substrate-to-inoculum ratio (S/I), pH, and NaOH pre-treatment (doses and durations). 26 batch experiments identified optimal conditions: pH 7.5, TS 8%, S/I 20%, NaOH for 10 hours, with a dose of 0.2 mol/L. The best biogas yields were recorded under these conditions, with the cone model providing the best fit for biogas kinetics. These results demonstrate the potential of mango leaves as a renewable methane source and the influence of process parameters on biogas production (Abudi et al., 2020). When handling high-solid organic wastes like food and livestock wastes, dry anaerobic digestion (AD) is preferable to wet AD, though its efficiency diminishes with increased total solids (TS). This study evaluated methane production from co-digesting food waste (FW) and pig manure (PM) at various TS levels (R1, 5%; R2, 10%; R3, 15%; R4, 20%). Data showed a decrease in methane at 20% TS (259.8 NmL/g VS added), while levels from 5% to 15% TS remained similar (278.8–291.7 NmL/g VS added). To explain the two-peak methane production at high TS, a new kinetics model was developed, revealing different methanogenic pathways in low- and high-solid systems, with the latter favouring mixotrophic and hydrogenotrophic pathways (Wang et al., 2020). Although high-solid anaerobic digestion is increasingly adopted for sustainable farm waste management, it has not been optimized for cow dung.

This study examined microbial communities after batch digestion of cow dung at TS levels of 5%, 10%, 15%, and 20%, finding steady processes up to 15%. Biomethane production at 10% and 15% TS was 352.2 mL/g VS and 318.6 mL/g VS, respectively, reaching 83% and 75% of the 5% TS benchmark. Kinetics suggest that higher solids volume may still allow biodegradation, but at a slower rate, as indicated by microbial shifts toward methylotrophic and hydrogenotrophic methanogens. This work helps advance understanding of high-solid anaerobic digestion of cow dung (Abid et al., 2021). A promising method to produce energy from abundant waste, like poultry litter, is anaerobic digestion, which also reduces waste volume. Recent research shows adding biochar (pyrolyzed biomass) can enhance methane yields in ammonia-stressed, low-solids digesters and shorten lag times. The influence of biochar addition at different total solids levels has not been fully explored owing to varied feedstocks and reactor types. This study demonstrates that, as total solids increase, biochar addition shortens lag time by 17%, 27%, and 41% at TS levels of 5%, 10%, and 20%, respectively and boosts peak methane production. The highest increase (136%) occurred at 10% TS, with a 46% rise at 20%, while 5% TS showed no significant change. PCR analysis confirms Methanosaetaceae's preference for attaching to biochar and its ability to promote interspecies electron transfer, regardless of total solids. Additionally, biochar's attachment does not diminish with rising TS, and shorter retention times can improve volumetric efficiency when adding biochar (Indren et al., 2020). The growing amount of agricultural waste from cattle and pineapple processing has made large-scale waste disposal challenging. Anaerobic digestion offers a sustainable way to produce biogas and reduce waste. In this study, cow dung and pineapple waste were co-digested in batch experiments at 38±1°C with a 100 mL working volume in a 125 mL serum bottle. Different substrate ratios and total solids contents (12%, 20%, 28%) were tested, including ratios of 1:1, 1:2, and 1:3. The maximum biogas yield of 313 mL occurred with 28% total solids at a 1:1 ratio, while a yield of 246 mL was observed at 28% solids and a 1:3 ratio. The highest methane yield (17.19 CH_4/g VS) was achieved at 12% total solids with a 1:2 ratio. Overall, the results show that co-digestion of pineapple waste with cow dung is effective in reducing solid waste and generating methane, with lower total solids levels producing higher methane yields and overall reductions in solid content (Aili Hamzah et al., 2020). Biogas is a promising alternative fuel to reduce dependence on fossil fuels. Lignocellulosic biomass like corn stover, which has at least 15% total solids, can be converted into biogas through solid-state anaerobic digestion, often co-digested with food waste to enhance output. This study evaluated how the kinetic model, volatile solid (VS) reduction, and food waste proportion affect biogas production from corn stover. The results showed that food waste significantly influenced biogas yield ($p < 0.05$), with 20% food waste yielding 584.49 mL g^{-1} VS and 40% VS reduction, using a first-order kinetic model to describe the process (Shitophyta et al., 2020).

Conclusion

High Solid Anaerobic Digestion (HS-AD), operating at total solids (TS) content exceeding 15–20%, has emerged as a highly efficient and sustainable technology for the large-scale management and valorization of organic solid waste. Compared to conventional liquid anaerobic digestion, HS-AD offers significant operational advantages, including a smaller reactor footprint, lower water consumption, reduced heating energy requirements, and minimized leachate generation making it particularly suitable for municipal, agricultural, and industrial organic waste streams. However, the technology is not without challenges. Increased TS content tends to elevate viscosity, which imposes mass transfer limitations and can hinder microbial activity. Additionally, the accumulation of inhibitory compounds such as ammonia and volatile fatty acids (VFAs), especially under thermophilic conditions (55–60°C), can compromise process stability. Mesophilic conditions, while slower in kinetics, demonstrate greater resilience to these inhibitors. High Solid Anaerobic Co-Digestion (HS-AcoD) has proven to be an effective strategy to overcome several of these limitations. By combining substrates with complementary compositions, such as nitrogen-rich and carbon-rich materials, operators can achieve an optimized C/N ratio (ideally 20–30), diluting inhibitors and enhancing overall methane production. This synergistic approach not only stabilizes the digestion process but also improves biogas yield across diverse waste feedstocks. A comparison of reactor configurations further reveals that continuous systems (Dranco, VALORGA, Kompogas) offer consistent biogas output, while batch systems (BEKON, Biocel) provide cost-effective alternatives, particularly for smaller scale applications. Future research should prioritize improving mass transfer in high-viscosity environments, optimizing feedstock combinations, and advancing two-stage digestion systems to handle complex organic fractions more effectively. In conclusion, HS-AD and HS-AcoD represent a compelling pathway toward sustainable waste-to-energy conversion, offering both environmental and economic benefits when properly optimized and scaled.

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Both the authors contributed equally on collection of literature to writing this manuscript.

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AI tool usage declaration

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