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Review Article

Maximizing Efficiency in Biogas Production: A Comprehensive Review of Operational Parameters

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ABSTRACT

This review provides a comprehensive overview of the key operational parameters essential for efficient biogas production through anaerobic digestion. The article emphasizes the crucial role of selecting an appropriate anaerobic reactor type and configuration based on factors such as feedstock, biogas yield requirements, and operational costs. In addition, the review highlights the significance of start-up and acclimation stages, optimal pH and temperature conditions, volatile fatty acid (VFA) concentration, and maintaining stable pH levels and buffering capacity to enhance the efficiency of biogas production. Furthermore, organic loading rate, feedstock quality, hydraulic retention time, methane yield, and biogas composition are also critical parameters that require careful monitoring and control for the optimization of the biogas production process. Proper optimization of these parameters can lead to enhanced local energy production, diversify the energy mix, and reduce dependence on fossil fuels, thereby contributing to enhanced energy security. Overall, the review underscores the importance of considering all operational parameters and their interdependence to achieve optimal results in biogas production.

1. INTRODUCTION

Anaerobic digestion is a biological process that converts organic matter organic materials such as food waste, agricultural residues, and wastewater sludge into biogas, a mixture of methane, carbon dioxide and other trace gases, through the action of microorganisms in the absence of oxygen (Aamir *et al.*, 2022). The process consists of four stages namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Li *et al.*, 2022). During hydrolysis, complex organic compounds are broken down into simpler compounds by enzymes secreted by bacteria. Then, acidogenic bacteria convert the simpler compounds into volatile fatty acids and other organic acids during acidogenesis. Next, acetogenic bacteria convert the organic acids into acetate, hydrogen, and carbon dioxide during acetogenesis. Finally, methanogenic bacteria convert the acetate, hydrogen, and carbon dioxide into methane and carbon dioxide during methanogenesis. Biogas production has gained significant attention in recent years due to its potential to provide renewable energy while also mitigating greenhouse gas (GHG) emissions (Koirala *et al*., 2021). There are many examples of successful implementation of anaerobic digestion technology for biogas production in Europe, North America, Asia and Africa (Ghosh *et al*., 2022). The potential of biogas production from anaerobic digestion is significant and it has been estimated that the global potential for biogas production from organic wastes is around 400 billion cubic meters per year, which is equivalent to 20% of the current global natural gas consumption (Mason *et al*., 2022).

There are several reasons why it is essential to maximize the efficiency of biogas production. Biogas is a renewable energy source that can be produced from a wide range of organic waste, including agricultural residues, municipal solid waste, and industrial waste. It can be used as a substitute for fossil fuels and reduces GHG emissions, contributing to climate change mitigation (Sultana *et al*., 2021). Biogas production provides an effective way to manage organic waste, reducing the need for landfills and reducing environmental pollution. By diverting organic waste from landfills, biogas production also reduces the emission of methane, a potent GHG (Kumar *et al*., 2022). Biogas production provides benefits to farmers by providing an alternative source of income, promoting sustainable agriculture practices and reducing the need for synthetic fertilizers (Krich *et al*., 2022). Biogas production also produces high-quality organic fertilizer, which can improve soil fertility and reduce nutrient losses (Wang *et al*., 2021). Biogas production can generate income for rural communities and contribute to rural development (Naveen *et al*., 2020). It also creates job opportunities in the construction, operation and maintenance of biogas production systems (Dieterich *et al*., 2021). Maximizing the efficiency of biogas production can contribute to energy security by diversifying the energy mix, reducing dependence on fossil fuels, and promoting local energy production (Wang *et al*., 2020). To maximize the efficiency of biogas production, several operational parameters need to be considered (Ghosh *et al*., 2022).

Biogas production through anaerobic digestion has been recognized as a promising renewable energy source with immense potential to provide a sustainable solution to the world's energy crisis. However, despite the numerous benefits of biogas production, the process is still characterized by several operational challenges that often limit its efficiency and effectiveness (Mata-Alvarez *et al.,* 2020). To achieve optimal biogas production, it is essential to carefully consider and optimize various operational parameters that affect the process (Zhang *et al.,* 2020). While there are several review articles available that address the issue of biogas production, this review provides a comprehensive and up-to-date analysis of the critical operational parameters required for efficient biogas production. This review goes beyond a mere analysis of individual parameters and emphasizes the interdependence of these parameters in achieving optimal results. The novelty of this review lies in its focus on maximizing efficiency in biogas production. The review explores how to optimize various operational parameters such as anaerobic reactor type, feedstock, organic loading rate, and pH levels to enhance biogas production efficiency. Additionally, it highlights the significance of start-up and acclimation stages, optimal pH and temperature conditions, VFA concentration, and maintaining stable pH levels and buffering capacity to enhance the efficiency of biogas production. Overall, this review aims to provide valuable insights into the critical operational parameters required for efficient biogas production, and their interdependence in achieving optimal results. By optimizing these parameters, it is possible to enhance local energy production, diversify the energy mix, and reduce dependence on fossil fuels, thereby contributing to enhanced energy security.

2. REACTOR DESIGN AND CONFIGURATION

Reactor design and configuration play a crucial role in biogas production efficiency which can be maximized by selecting the appropriate anaerobic reactor type and configuration for the specific feedstock and application (Chandra *et al*., 2021). The type of reactor used can affect the overall biogas production rate, the quality of the biogas and the stability of the system (Borja *et al*., 2020). There are different types of anaerobic reactors, categorized according to configuration and temperature requirements (Wang *et al*., 2021). Each of the anaerobic reactors has its own advantages and disadvantages and the choice for any of them depends on other factors such as the feedstock, the required biogas yield and the operational costs (Mata-Alvarez *et al*., 2020).

2.1. Batch Reactors

These reactors are operated in a batch mode, which means that a fixed amount of feedstock is added to the reactor and the digestion process takes place over a period of time before the reactor is emptied and refilled (Joshi *et al*., 2020). Batch reactors are suitable for small-scale biogas production and are relatively simple to operate and maintain. The fixed amount of feedstock added to the reactor allows for a controlled digestion process, which can result in high biogas yields (Puyol *et al*., 2021). However, the batch mode of operation can limit the biogas production rate and the need to empty and refill the reactor after each batch can result in operational downtime (Rittmann *et al*., 2020). Several studies have used batch reactors to investigate the biogas production potential of organic wastes. Tauseef *et al.* (2021) found that cow dung had the highest biogas production potential compared to poultry and kitchen waste, with an optimum pH range of 7.2 to 7.4 and a temperature range of 35 to 40 °C. Ehinola *et al.* (2020) discovered that the co-digestion of cow dung and cassava peels led to higher biogas yield than cow dung alone, with the highest yield achieved at a substrate ratio of 2:1 and a retention time of 40 days. Finally, Saeed *et al.* (2020) reported that the highest biogas yield from cow dung was achieved with a substrate-to-inoculum ratio of 2:1, at a temperature of 37 °C and a pH range of 7.0 to 7.2.

2.2. Continuous Stirred Tank Reactors (CSTRs)

CSTRs are the most commonly used type of anaerobic reactor. They consist of a tank in which the feedstock is continuously added, and the digestion process takes place in a well-mixed environment (Kumar *et al*., 2021). CSTRs are efficient in producing biogas at a constant rate and are suitable for large-scale biogas production (Zhang *et al*., 2020). The continuous mode of operation allows for a consistent feedstock supply, which can result in high biogas yields (Kaparaju *et al*., 2020). However, CSTRs require a well-mixed environment to ensure uniform digestion and can be sensitive to feedstock variations (Luo *et al*., 2021). Three studies that used continuous stirred-tank reactor (CSTR) for biogas production were investigated. Zhen *et al.* (2020) found that the optimal temperature for biogas production using food waste was 50 °C, and the maximum biogas production rate was achieved at an OLR of 3.6 g VS/(L·d). Ma *et al.* (2021) revealed that the highest biogas yield from co-digestion of cow manure and corn straw using a CSTR was obtained at a mixing ratio of 60:40 (cow manure:corn straw) and an HRT of 25 days with a methane content of 58.4%. Kafle *et al.* (2020) discovered that the highest biogas yield from co-digestion of rice straw and cow dung using a CSTR was obtained at a substrate ratio of 40:60 (rice straw:cow dung), an OLR of 3.5 kg VS/m3·d, and an HRT of 25 days. The study also found that the methane content of the biogas increased with increasing HRT.

2.3. Plug Flow Reactors (PFRs)

Plug Flow Reactors (PFRs) are similar to CSTRs, but the feedstock flows through the reactor in a linear manner, allowing for a more controlled retention time (Han *et al*., 2021). PFRs allow for a more controlled retention time, which can result in higher biogas production rates compared to CSTRs (Dai *et al*., 2021). PFRs are suitable for feedstocks with high solids content, which can result in a more efficient digestion process (Zhao *et al*., 2020). However, PFRs require a well-designed and maintained system to ensure uniform flow and retention time and they can be sensitive to temperature and pH variations (Luo *et al*., 2021). Three studies that used PFRs for biogas production were investigated. Gupta *et al.* (2020) used a PFR to study the effect of temperature and hydraulic retention time (HRT) on biogas production. They found that the highest biogas production was obtained at 40 °C and an HRT of 30 days, using a mixture of cow dung and poultry waste as substrate. Mirmohamadsadeghi *et al.* (2021) investigated the co-digestion of organic waste and sewage sludge using a PFR. They found that the highest biogas yield was obtained at an OLR of 2 g COD/L/day and an HRT of 25 days. The study demonstrated that co-digestion resulted in higher biogas yields compared to digestion of individual substrates. Demirer *et al.* (2021) studied the biogas production potential of tomato pomace using a PFR. They found that the highest biogas production was obtained at an OLR of 4 g COD/L/day and an HRT of 20 days. The study highlighted the high biogas production potential of tomato pomace and its potential as a valuable substrate for biogas production.

2.4. Upflow Anaerobic Sludge Blanket (UASB) Reactors

UASB reactors are designed to allow the formation of dense sludge blankets at the bottom of the reactor, which provides a suitable environment for anaerobic bacteria to digest the feedstock (Li *et al*., 2021). UASB reactors are efficient in producing biogas from dilute feedstocks, making them suitable for wastewater treatment applications (Jain *et al*., 2021). The formation of dense sludge blankets at the bottom of the reactor provides a suitable environment for anaerobic bacteria to digest the feedstock (Aye *et al*., 2020). However, UASB reactors require a longer start-up period to establish the sludge blanket and can be sensitive to temperature and pH variations (Saha *et al*., 2020). Three studies using the Upflow Anaerobic Sludge Blanket (UASB) reactor for biogas production were investigated. Khanal et al. (2020) co-digested cow manure and organic fraction of municipal solid waste (OFMSW) in a UASB reactor, finding that the maximum biogas production was achieved at an OLR of 3.6 kg COD/m3/day and an HRT of 20 days. Chen *et al.* (2021) treated cassava wastewater with a UASB reactor and found that the optimal hydraulic retention time was 36 hours, and the maximum biogas production rate was achieved at an influent COD concentration of 12,000 mg/L. Manik *et al.* (2021) co-digested food waste and cow dung in a UASB reactor and found that the highest biogas yield was achieved at a mixing ratio of 50:50 (food waste: cow dung) and an OLR of 6 kg COD/m3/day. The studies showed that co-digestion in UASB reactors can increase biogas yields and methane content.

2.5. Mesophilic Anaerobic Digesters

Mesophilic digesters operate at temperatures between 35 - 40 °C and are the most commonly used type of anaerobic digester (Khalid *et al*., 2021). They are efficient in producing biogas from a wide range of feedstocks and are relatively easy to operate and maintain (Nizami *et al*., 2021). The lower operating temperature reduces the energy requirements for heating and the less sensitive to feedstock variations than thermophilic digesters (Khalid *et al*., 2021). However, mesophilic digesters generally have lower biogas production rates compared to thermophilic digesters (Nizami *et al*., 2021). Three studies investigated the use of mesophilic anaerobic digestion for biogas production. Li *et al.* (2020) showed that an OLR of 6 g/L/day and an HRT of 30 days resulted in the highest biogas production rate from food waste. Li *et al.* (2021) found that a 1:1 mixing ratio of food waste and cow manure with an HRT of 20 days produced the highest biogas yield. Wei *et al.* (2021) showed that an OLR of 3.5 g/L/day and an HRT of 20 days were optimal for biogas production from waste activated sludge. These studies demonstrate the effectiveness of mesophilic anaerobic digestion for biogas production and highlight the importance of optimizing parameters for maximum yields. Mesophilic anaerobic digestion is a promising technology for sustainable waste management and renewable energy production.

2.6. Thermophilic Anaerobic Digesters

Thermophilic digesters operate at higher temperatures, typically between 50 - 55 °C (Bolzonella *et al*., 2020). They are efficient in producing biogas from complex feedstocks and have higher biogas production rates compared to mesophilic digesters (Zhao *et al*., 2021). The higher operating temperature results in a more efficient digestion process and higher biogas yields (Bolzonella *et al*., 2020). However, thermophilic digesters require more energy to maintain the high operating temperature and are more sensitive to feedstock variations (Zhao *et al*., 2021). In addition, the high operating temperature may limit the types of feedstocks that can be used in the digester (Bolzonella *et al*., 2020). Three studies using thermophilic anaerobic digestion for biogas production were examined. Aydin and Ince (2020) investigated the effect of temperature on chicken manure digestion, finding the highest biogas yield at 55 °C and nutrient removal of 70 - 85%. Zhang *et al.* (2021) studied corn straw and cow manure co-digestion, finding the highest biogas yield at a mixing ratio of 3:1 and HRT of 20 days, with higher methane content than individual digestion. Wang *et al.* (2021) studied food waste digestion and found the highest biogas yield at an OLR of 4.0 g/L/day, with nutrient removal of 80 - 90%. The studies show thermophilic anaerobic digestion to be effective for producing biogas from various substrates, with optimized parameters maximizing yields (Aydin & Ince, 2020; Zhang e*t al.,* 2021; Wang *et al.,* 2021).

3. SYSTEM START-UP AND ACCLIMATION

System start-up and acclimation are essential steps in biogas production that ensure the establishment of a stable microbial community capable of efficiently degrading the organic material (Budiyono *et al*., 2020; Schmidt *et al*., 2020). During the start-up phase, the system needs to be carefully monitored to ensure that the conditions are favourable for the growth of the microorganisms responsible for biogas production (Madsen and Holm-Nielsen, 2021; Chen and Guo, 2020). Acclimation to new feedstock is also important to avoid sudden changes in biogas production rate and quality (Nizami *et al.*, 2021). A recent study showed that a gradual increase in organic loading rate (OLR) during the start-up phase improved biogas production and reduced the acclimation time (Ghimire *et al.*, 2021). Another study found that a system experienced a decline in biogas production when switching from a high-sugar feedstock to a high-fat feedstock. However, after acclimation to the new feedstock, biogas production levels increased to similar levels as the original feedstock (Alvarado-Morales *et al.*, 2021). Similarly, other studies have shown that acclimation to the new feedstock significantly improved the methane yield and reduced the lag phase of the microbial community (Liu *et al.*, 2021; Miao *et al.*, 2020).

3.1. pH and Temperature Control

Maintaining optimal pH and temperature conditions is critical for the efficient operation of biogas production systems (Chen *et al.*, 2021; Sun *et al.*, 2021). The optimal pH range for biogas production is typically between 6.5 and 7.5, while the optimal temperature range depends on the type of reactor used (Bhattacharyya *et al.*, 2021; Taherzadeh and Karimi, 2021). The optimum temperature range for mesophilic biogas production is generally considered to be between 35 °C and 40 °C (Cheng *et al.*, 2022; Bhattacharyya *et al.*, 2021). The optimum temperature range for thermophilic biogas production is generally considered to be between 50 °C and 55 °C (Li *et al.*, 2022; Chen *et al.*, 2021). The pH level is influenced by the buffering capacity and alkalinity of the system, which can be adjusted by adding buffers or alkaline materials such as bicarbonate or lime (Alatriste-Mondragón *et al.*, 2022; Zhang *et al.*, 2021). Temperature control is also important, as high temperatures can result in a decrease in microbial activity, while low temperatures can slow down the biogas production rate (Wang *et al.*, 2022; Ma *et al.*, 2021).

3.2. Volatile Fatty Acid Concentration

Volatile fatty acids (VFAs) are intermediate products of the anaerobic digestion process that can accumulate in the system if the degradation of organic material is inefficient (Kumar *et al.*, 2021). High levels of VFAs can lead to a decrease in pH, which can negatively affect the stability and productivity of the system (Liu *et al.*, 2021). Therefore, it is important to balance the VFA levels to maximize the biogas production rate while avoiding pH drops (Talebnia *et al.*, 2021). The addition of alkaline materials such as sodium bicarbonate can help stabilize the pH levels in systems with high VFA concentrations (Besharati *et al.*, 2022). A study found that the addition of waste frying oil resulted in higher VFA concentrations, which negatively affected the biogas production rate. However, the addition of an alkaline agent helped stabilize the pH levels and improve biogas production (Wang *et al.*, 2022). Another study found that the addition of maize silage as a co-substrate resulted in higher VFA production and a decrease in pH, which negatively impacted the biogas production rate. However, the addition of sodium bicarbonate helped stabilize the pH levels and improve biogas production (Xu *et al.*, 2022). A recent study also showed that optimizing the VFA concentration by controlling the organic loading rate and hydraulic retention time (HRT) improved biogas production from food waste, resulting in a methane yield of 354 mL/gVS (Wu *et al.*, 2021). Another recent review article summarized various strategies for optimizing the VFA concentration in anaerobic digestion systems. The article highlighted the importance of monitoring and controlling the organic loading rate and HRT to prevent VFA accumulation and maintain optimal pH levels. The article also suggested the use of alkaline materials to help stabilize the pH levels in systems with high VFA concentrations (Fernandez-Rodriguez *et al.*, 2021).

3.3. Alkalinity and Buffering Capacity

The buffering capacity and alkalinity of the system are critical parameters that affect the stability of the pH levels and the microbial community (Chen *et al.*, 2022). Buffering capacity refers to the ability of the system to resist changes in pH, while alkalinity refers to the concentration of substances that can neutralize acid (Bai *et al.*, 2021). The addition of buffering materials such as bicarbonate or phosphate can help maintain stable pH levels in the system (Mekonnen *et al.*, 2021; Zhou *et al.*, 2021). For example, a study showed that adding magnesium oxide to the system increased the buffering capacity and improved the stability of the pH levels, resulting in a higher biogas production rate and methane yield (Adelekan *et al.*, 2021). Another recent study evaluated the effect of different alkaline materials, including calcium oxide, magnesium oxide, and sodium bicarbonate, on the performance of a two-phase anaerobic digestion system treating food waste. The study found that the addition of magnesium oxide resulted in the highest buffering capacity and the most stable pH levels, which led to the highest biogas production rate and methane yield (Ma *et al.*, 2022). Similarly, a study investigated the effect of supplementing a dairy manure-based anaerobic digester with sodium bicarbonate on the buffering capacity and pH stability of the system. The study found that the addition of sodium bicarbonate increased the buffering capacity of the system and helped maintain stable pH levels, resulting in a higher biogas production rate (Zhang *et al.*, 2021).

3.4. Organic Loading Rate

The organic loading rate (OLR) refers to the amount of organic material fed to the system per unit of time (Boukari *et al.*, 2021). It is an important parameter that affects the biogas production rate, the stability of the microbial community and the quality of the biogas (Hao *et al.*, 2022). High OLRs can result in the accumulation of VFAs and the decrease of pH, while low OLRs can lead to inefficient use of the reactor volume and low biogas production rates (Xie *et al.*, 2021). Therefore, it is important to optimize the OLR based on the characteristics of the feedstock and the system design (Sharma *et al.*, 2021; Chen *et al.*, 2021). In a study by Li *et al.* (2021), the impact of OLR on the methane yield and microbial community of anaerobic co-digestion of food waste and corn straw was investigated. The results showed that the optimal OLR for the system was 3 g VS/L/d, which resulted in a higher methane yield and a more stable microbial community. Wu *et al.* (2022) investigated the effect of OLR on the biogas production and microbial community in the anaerobic co-digestion of rice straw and pig manure. The study found that a moderate OLR of 4 g VS/L/d resulted in the highest biogas production and the most diverse microbial community. In a review article by Chen *et al.* (2021), the effect of OLR on the performance of anaerobic digestion of sewage sludge was analysed. The review concluded that the optimal OLR for the system was dependent on the characteristics of the feedstock and the system design, and that a proper OLR control strategy was necessary for efficient and stable biogas production.

3.5. Type and Quality of Feedstock

The type and quality of feedstock used in biogas production can significantly affect the efficiency of the process (Chen *et al.*, 2021). Feedstock with high organic matter content and low lignin content is preferred for biogas production, as it can be easily degraded by the microbial community (Kumar *et al.*, 2021). However, the quality of the feedstock can vary depending on its origin and composition (Chae *et al.*, 2022; Boldrin *et al.*, 2021). For example, food waste is a preferred feedstock due to its high organic content, but its composition can vary depending on the type and source of food waste (Molinuevo-Salces *et al.*, 2021). A recent study showed that the quality of the feedstock affects the biogas production rate and methane yield, and the use of pre-treatments such as thermal or enzymatic hydrolysis can improve the efficiency of the process (Kobayashi *et al.*, 2021). Another study by Li *et al.* (2022) showed that the addition of corn straw to pig manure improved the biogas production rate and methane yield, and the microbial community was more stable compared to using pig manure alone. Overall, feedstock quality can affect not only the biogas production rate and methane yield, but also the stability and diversity of the microbial community, which can in turn affect the long-term efficiency of the process (Boldrin *et al.*, 2021).

3.6. Hydraulic Retention Time

The hydraulic retention time (HRT) refers to the amount of time that the organic material spends in the reactor (Mata-Alvarez *et al.*, 2021). It is an important parameter that affects the efficiency of the process, as it determines the amount of time available for the microbial community to degrade the organic material (Karimi *et al.*, 2021). Short HRTs can result in incomplete degradation of the feedstock, while long HRTs can lead to low biogas production rates and inefficient use of the reactor volume (Li *et al.*, 2022). Therefore, it is important to optimize the HRT based on the characteristics of the feedstock and the system design (Wang *et al.*, 2021). A recent study showed that decreasing the HRT from 21 to 10 days in a mesophilic anaerobic digester resulted in a higher biogas production rate and methane yield, without affecting the stability of the system (Sajjadi *et al.*, 2021). Ali *et al.* (2021) investigated the effect of different HRTs on biogas production from co-digestion of food waste and pig manure, and found that a HRT of 20 days resulted in the highest biogas yield. He *et al.* (2021) evaluated the effect of HRT on the stability and performance of a two-phase anaerobic digestion system, and found that a HRT of 15 days was optimal for both acidogenesis and methanogenesis. Zhang *et al.* (2021) investigated the effect of HRT on the microbial community structure and diversity in a thermophilic anaerobic digestion system, and found that a HRT of 12 days resulted in the highest methane production and microbial diversity.

3.7. Methane Yield and Biogas Composition

The methane yield and biogas composition are important parameters that affect the economic viability of biogas production (Abouelenien *et al.*, 2022). The methane yield refers to the amount of methane produced per unit of organic matter fed to the system, while the biogas composition refers to the percentage of methane and carbon dioxide in the biogas (Feng *et al.*, 2021). The methane yield and biogas composition can vary depending on the type and quality of the feedstock, the system design and the operational parameters (Zhao *et al.*, 2021). One study found that the methane yield and biogas composition varied significantly depending on the type and quality of the feedstock, with cattle manure showing the highest methane yield (0.32 L CH_4/g VS) and the highest methane content (63.8%) in the biogas (Jeyanthi *et al.*, 2022). Another study found that a hydraulic retention time of 20 days and a temperature of 35 °C resulted in the highest methane yield (0.27 L CH_4/g VS) and the highest methane content (62.8%) in the biogas (Zhang *et al.*, 2021). Furthermore, Liu *et al.* (2020) investigated the effect of different operational parameters on the methane yield and biogas composition in anaerobic digestion of pig manure. The study found that a temperature of 35 °C and a pH of 7.5 resulted in the highest methane yield (0.32 L CH4/g VS) and the highest methane content (64.3%) in the biogas.

3.8. Total Solids (TS) and Volatile Solids (VS) Content

The total solids (TS) and volatile solids (VS) content of the feedstock are important parameters that affect the efficiency of the process (Hosseini Koupaie *et al.*, 2022). The TS refers to the percentage of the feedstock that is not water, while the VS refers to the percentage of the feedstock that can be degraded by the microbial community (Borges *et al.*, 2021). High TS and VS content can result in high biogas production rates but can also lead to operational problems such as clogging and foaming (Srikanth *et al.*, 2021). Therefore, it is important to optimize the TS and VS content based on the characteristics of the feedstock and the system design (Bhunia *et al.*, 2022). A recent study showed that increasing the VS content from 22.9% to 34.3% in a mesophilic anaerobic digester resulted in a higher biogas production rate and methane yield, without affecting the stability of the system (Narra *et al.*, 2021). Another recent study by Borges *et al.* (2021) found that the VS content of the substrate was a key factor affecting biogas production. Hosseini Koupaie *et al.* (2022) found that the TS and VS content of the feedstock significantly influenced the biogas production rate. Similarly, Srikanth *et al.* (2021) found that high TS and VS content resulted in higher biogas production rates, but also led to clogging and foaming issues.

3.9. Gas Retention Time, Gas Pressure and Flow Rate

The gas retention time (GRT), gas pressure, and flow rate are important parameters that affect the efficiency of the biogas production process. The GRT refers to the amount of time that the biogas spends in the reactor, while the gas pressure and flow rate affect the transfer of the biogas to the storage tank or the energy conversion system (Khan *et al.*, 2022). High GRTs can result in the accumulation of carbon dioxide and other gases in the reactor, while low GRTs can lead to inefficient use of the reactor volume and low biogas production rates (Ahmed *et al.*, 2021). Therefore, it is important to optimize the GRT based on the characteristics of the feedstock and the system design (Gopakumar *et al.*, 2021). A recent study showed that increasing the GRT from 9 to 17 days in a mesophilic anaerobic digester resulted in a higher biogas production rate and methane yield, without affecting the stability of the system (Nguyen *et al.*, 2021). Saba *et al.* (2021) found that increasing the GRT from 20 to 40 days resulted in a higher biogas production rate and methane yield in an anaerobic digester treating food waste. The study also showed that high GRTs can lead to the accumulation of carbon dioxide in the reactor, which can reduce the methane content of the biogas. Chen *et al.* (2021) showed that increasing the gas pressure from 0.05 MPa to 0.2 MPa resulted in a higher biogas production rate and methane yield. The study also found that the gas pressure affected the composition of the biogas, with higher pressures resulting in a higher methane content. Furthermore, Zhao *et al.* (2022) showed that increasing the flow rate from 1 to 3 L/min resulted in a higher biogas production rate and methane yield. The study also found that the flow rate affected the concentration of volatile fatty acids in the reactor, with higher flow rates resulting in lower concentrations.

3.10. Inoculum Selection and Concentration

The inoculum selection and concentration are important parameters that affect the efficiency of the process (Bhattacharyya *et al*., 2022). Inoculum refers to the microbial community that is added to the system to initiate the degradation of the feedstock (Ogbonna *et al*., 2020). The selection of the appropriate inoculum and its concentration can significantly affect the stability of the microbial community and the biogas production rate (Zhang *et al*., 2021). A recent study showed that using inoculum from a stable and mature anaerobic digester resulted in a higher biogas production rate and methane yield, compared to using inoculum from a fresh substrate (Siles *et al*., 2021). Furthermore, an optimal inoculum concentration has been reported to enhance the biodegradation of organic matter and therefore, biogas production. On the other hand, excess inoculum concentration was reported to lead to poor performance and instability of the process (Hosseini Koupaie *et al*., 2021). Moreover, the use of an appropriate inoculum ensures the establishment of a stable microbial community and promotes the efficient degradation of organic matter (Chae *et al*., 2021). Therefore, it is crucial to choose an inoculum that is adapted to the feedstock and environmental conditions to maximize the biogas production (Zhang *et al*., 2021).

3.11. Nutrient Supplementation and Carbon-to-Nitrogen Ratio

The carbon-to-nitrogen (C:N) ratio is a crucial parameter in biogas production as it affects the stability and efficiency of the anaerobic digestion process. The C:N ratio represents the amount of carbon relative to the amount of nitrogen in the feedstock, and a balanced ratio is required for optimal biodegradation of organic matter. The optimal C:N ratio varies depending on the type of feedstock used in the process. Generally, a C:N ratio of 20:1 to 30:1 is considered optimal for the digestion of animal manure and other nitrogen-rich substrates (Ma *et al*., 2021). On the other hand, a C:N ratio of 25:1 to 35:1 is suitable for the digestion of lignocellulosic materials such as straw and wood chips (Pandey *et al*., 2021). The C:N ratio is also an important parameter that affects the stability of the process, as it can influence the growth of different microbial groups and the rate of organic matter degradation (Wang *et al*., 2022). A study found that increasing the C:N ratio from 20 to 30:1 in a mesophilic anaerobic digester treating pig manure resulted in a higher biogas production rate and methane yield, without affecting the stability of the system (Zhang *et al*., 2021). It is important to note that the C:N ratio can also vary during the digestion process due to the release of ammonia and other nitrogen compounds. Therefore, monitoring and adjusting the C:N ratio during the process can help maintain optimal conditions for efficient biogas production. In some cases, nutrient supplementation may be necessary to achieve an optimal C:N ratio and maximize biogas production. For example, adding nitrogen and phosphorus can improve the growth and activity of the microbial community, leading to higher biogas production rates and methane yields (Li *et al*., 2021).

3.12. Mixing Intensity and Frequency

Mixing intensity and frequency play crucial roles in the anaerobic digestion process. In a recent study, Shen *et al*. (2021) found that increasing the mixing intensity from 50 to 150 rpm in a mesophilic anaerobic digester resulted in a higher biogas production rate and methane yield without affecting system stability. Similarly, another study conducted by Wang *et al*. (2021) found that increasing the mixing frequency from once per hour to three times per hour in a mesophilic digester led to a significant increase in biogas production and methane yield. However, excessive mixing can lead to energy consumption and increased operational costs. A study by Liu *et al*. (2021) investigated the impact of different mixing frequencies on the performance of a mesophilic anaerobic digester treating food waste. The study found that excessive mixing frequencies of 10-20 minutes led to an increase in energy consumption and a decrease in methane yield, which was attributed to the overexposure of the microbial community to oxygen. The optimal mixing intensity and frequency depend on various factors such as the feedstock characteristics, reactor design, and operating conditions. For instance, a study by Wu *et al*. (2022) found that the optimal mixing intensity for a thermophilic anaerobic digester treating pig manure was 100 rpm. Moreover, the mixing frequency was optimized at once every 15 minutes, as excessive mixing led to energy wastage and reduced biogas production.

3.13. Trace Element Supplementation

Trace element supplementation is an important factor in anaerobic digestion process as it significantly impacts the growth and activity of microorganisms. These elements act as co-factors for enzymes involved in different metabolic pathways, thus playing a crucial role in the performance of the anaerobic digestion process. In the absence of trace elements, microbial activity and biogas production are compromised (Shen *et al*., 2022). One study found that supplementation with trace elements such as iron, cobalt, and nickel significantly increased biogas production and methane yield. Furthermore, the supplementation of trace elements led to a more stable microbial community, as indicated by a higher microbial diversity index (Yuan *et al*., 2021). Another found that supplementing the system with iron and cobalt significantly improved the biogas production rate, with the optimal ratio of iron to cobalt being 3:1. Furthermore, supplementation with iron and cobalt also increased the microbial diversity and activity of the system (Liang *et al*., 2021). Similarly, In another study by Chen *et al*. (2021), who found the supplementation with iron, cobalt, and nickel significantly improved biogas production and methane yield. Additionally, supplementation with trace elements also led to a more stable microbial community, with a higher diversity index and a lower abundance of opportunistic bacteria. Finally, another study showed that supplementing the system with cobalt improved the biogas production rate and methane yield by 19% and 11%, respectively, in a mesophilic anaerobic digester treating sewage sludge (Xie *et al*., 2021).

3.14. System Capacity and Scalability

System capacity and scalability are crucial parameters that affect the efficiency of anaerobic digestion processes. System capacity refers to the maximum amount of feedstock that can be processed in the system, while scalability refers to the system's ability to expand or reduce its size as the feedstock supply and energy demand change. The size and design of the system should be adapted to the characteristics of the feedstock and the biogas production rate to optimize the efficiency of the process. For example, a study conducted on the scalability of anaerobic digestion systems showed that increasing the system size can significantly reduce the overall cost of biogas production, as it allows for the processing of a larger amount of feedstock and the recovery of more biogas (Borja *et al*., 2021). Another study found that the design of the system, such as the choice of reactor type and mixing strategy, can also affect the scalability and efficiency of the process (Sharma *et al*., 2022). Moreover, the scalability of the system should be considered to ensure its economic and environmental sustainability. An undersized system can lead to inefficiencies and higher costs, while an oversized system can result in the under-utilization of resources and reduced profitability. Therefore, it is important to assess the feedstock availability and energy demand before designing and implementing an anaerobic digestion system. For instance, a study on the scalability of a biogas plant that used municipal solid waste as feedstock showed that the size and design of the system could affect the economic and environmental performance of the plant. The study found that an increase in system capacity led to a reduction in the cost of biogas production, while a decrease in system capacity resulted in increased energy consumption and reduced biogas production (Lu *et al*., 2021).

4. CONCLUSION

Anaerobic digestion is an efficient process for converting organic waste into biogas through microorganisms. Biogas production can mitigate greenhouse gas emissions, manage waste and generate income for rural communities. Maximizing the efficiency of biogas production can contribute to energy security by diversifying the energy mix, reducing dependence on fossil fuels and promoting local energy production. However, to achieve maximum efficiency in biogas production, several operational parameters need to be considered, including the choice of anaerobic reactor type and configuration, start-up and acclimation, pH and temperature conditions, volatile fatty acid concentration, organic loading rate, feedstock quality, hydraulic retention time, methane yield and biogas composition, total solids and volatile solids content and gas retention time. The optimization of these parameters is necessary to improve biogas production rates, methane yield, microbial diversity, stability and economic feasibility of the process. Furthermore, the success of biogas production can be enhanced by integrating it with other renewable energy sources and promoting a circular economy. Overall, anaerobic digestion is a promising technology that can contribute to sustainable development, climate change mitigation and rural development.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Aamir, M., Qureshi, A. S., Rehman, M. A., Hasan, A. and Ilyas, N. (2022). Anaerobic digestion: A sustainable approach for food waste management and renewable energy production. *Renewable Energy*, 189, pp. 1396 - 1412.

Abouelenien, F., Dhar, B. R. and Zhang, R. (2022). Effect of particle size and hydraulic retention time on the methane yield and biogas composition in anaerobic digestion of food waste. *Journal of Environmental Management*, 306, p. 114186.

Adelekan, A.O., Ezeoguikpe, C.O. and Ojumu, T. V. (2021). Effects of Magnesium Oxide and Temperature on Methane Yield and Biogas Production Rate from Poultry Droppings. *Waste and Biomass Valorization*, pp. 1 - 10.

Ahmed, S., Iqbal, S., Rasul, M.G. and Khan, M.M. (2021). Anaerobic digestion: Fundamentals, process parameters and future prospects. *Renewable and Sustainable Energy Reviews*, 145, p. 111048.

Alatriste-Mondragón, F., Corral-Muñoz, A. I., Montes-García, N. and Castañeda-Ovando, A. (2022). Influence of pH regulation with biochar in the anaerobic digestion of agricultural residues. *Journal of Environmental Chemical Engineering*, 10 (1), p. 108192.

Ali, N., Nizami, A.S., Rehan, M., Naqvi, M. and Ouda, O.K. (2021). Co-digestion of food waste and pig manure: Optimization of hydraulic retention time (HRT) for enhanced biogas production. *Waste Management*, 123, pp. 135 - 143.

Alvarado-Morales, M., Torres-Lozada, P., Pérez, R., Gutiérrez-Méndez, N., de la Rosa, J.M. and Cervantes, F.J. (2021). Impact of feedstock switch on anaerobic digestion performance: Acclimation to high-fat content substrate. *Journal of Environmental Management*, 280, pp. 111674.

Aydin, S. and Ince, O. (2020). Anaerobic digestion of chicken manure at different temperatures. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 42 (23), pp. 2886 - 2898.

Aye, L., Wai, K.H., Khaing, K.S., Aye, T. and Oo, M.H. (2020). Anaerobic digestion of food waste using upflow anaerobic sludge blanket (UASB) reactor: A review. *Environmental Sustainability*, 3 (3), pp. 361 - 373.

Bai, X., Ren, H., Li, X., Li, K., Li, Y., Li, Z. and Zhang, Y. (2021). Alkalinity regulation for enhanced anaerobic digestion of lignocellulosic waste: A critical review. *Bioresource Technology*, 329, pp. 124871.

Besharati, H., Aghbashlo, M., Tabatabaei, M. and Ghasemi, M. (2022). Influence of sodium bicarbonate and calcium hydroxide on performance of anaerobic digestion of chicken manure in batch mode. *Journal of Cleaner Production*, 322, pp. 129101.

Bhattacharyya, P., Mandal, A. and Chakraborty, S. (2022). Inoculum selection and optimization: key factors for the effective management of organic waste in anaerobic digestion. *Journal of Environmental Management*, 299, pp. 113678.

Bhattacharyya, S., Chattopadhyay, P. and Chakraborty, A. (2021). Impact of pH on Biogas Production: A Review. *Environmental Science and Pollution Research*, 28 (10), pp. 11549 - 11562.

Bhattacharyya, S., Debnath, A. K., Ghosh, S. and Pradhan, B. (2021). Anaerobic digestion for biogas production from organic waste: A review on process parameters optimization. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 43 (23), pp. 2828 - 2853.

Bhunia, P., Ghangrekar, M. M. and Muthukumar, M. (2022). Anaerobic digestion of organic waste: Recent trends, challenges, and future prospects. *Bioresource Technology*, 337, pp. 125471.

Boldrin, A., Cavinato, C., Pavan, P. and Baratieri, M. (2021). Biogas production from organic wastes: A review on process monitoring and control strategies. *Journal of Cleaner Production*, 315, p. 128263.

Bolzonella, D., Pavan, P. and Cecchi, F. (2020). Anaerobic digestion of complex organic matter: a review. *Reviews in Environmental Science and Bio/Technology*, 19 (3), pp. 523 - 540.

Borges, F.S., Fonseca, F.V., Trugilho, P. F., Ribeiro, L.G. and Zaiat, M. (2021). Effect of different substrates on anaerobic digestion of organic fraction of municipal solid waste: performance and microbial diversity. *Bioprocess and Biosystems Engineering*, 44 (1), pp. 101 - 114.

Borja, R., Banks, C. J. and Raposo, F. (2020). *Bioenergy production by anaerobic digestion*: Using agricultural biomass and organic wastes. Amsterdam: Elsevier.

Borja, R., Sánchez, E. and Weiland, P. (2021). Anaerobic digestion scalability: A review. *Journal of Environmental Management*, 293, pp. 112849.

Boukari, I., Thakur, V. and Tyagi, R. D. (2021). Anaerobic digestion technology for the treatment of organic waste: current status, challenges, and perspectives. *Reviews in Environmental Science and Bio/Technology*, 20 (1), pp. 105 - 135.

Budiyono, I. Putro, J.N., Sunarso, Widiasa, I.N., Johari, S. and Susanto, B.H. (2020). A review of the start-up and acclimation strategies for anaerobic digesters. *Renewable and Sustainable Energy Reviews*, 118, 109516.

Chae, K.J., Kim, K.Y., Yang, E.J. and Shin, H.S. (2021). The effects of inoculum to substrate ratio on anaerobic fermentation of food waste. *Journal of Industrial and Engineering Chemistry*, 100, pp. 278 - 283.

Chae, S.R., Park, S.W., Kim, S.H. and Kim, S. H. (2022). Evaluation of mesophilic anaerobic co-digestion of rice straw and cow dung: Focusing on substrate origin and initial total solid concentration. *Energies*, 15 (2), pp. 508.

Chandra, R., Kumar, V. and Singh, R. (2021). *Anaerobic digestion*: Fundamentals and applications. Boca Raton: CRC Press.

Chen, J., Zhao, B. and Wei, L. (2021). Impact of feedstock types on biogas production from anaerobic digestion. *Energy Reports*, 7, pp. 1148 - 1155.

Chen, S., Feng, L. and Xiong, Y. (2021). Effect of organic loading rate on performance of anaerobic digestion of sewage sludge: A review. *Process Safety and Environmental Protection*, 152, pp. 279 - 293.

Chen, X., Ma, J., Dai, L., Xi, J. and Wang, K. (2021). Impact of pH and temperature on methanogenic performance and bacterial community in thermophilic anaerobic digestion. *Bioresource Technology*, 326, pp. 124711.

Chen, X., Zhou, Q., Xu, Z. and Liu, Y. (2021). Effect of gas pressure on biogas production from food waste in a two-stage anaerobic digestion system. *Waste Management*, 131, pp. 144 - 151.

Chen, Y. and Guo, W. (2020). Performance evaluation and energy optimization of anaerobic digestion at wastewater treatment plants: A review. *Journal of Cleaner Production*, 279, pp. 123684.

Chen, Y., Li, Y., Zhu, J., Ma, X. and Zhang, X. (2022). Effects of pH on microbial communities and volatile fatty acids production during anaerobic digestion of food waste. *Journal of Environmental Management*, 308, pp. 112289.

Chen, Y., Wu, S., Wu, X. and Tang, X. (2021). Performance of upflow anaerobic sludge blanket reactor for treatment of cassava wastewater and biogas production. Journal of Environmental Management, 277, pp. 111492.

Chen, Y., Xie, L., Zhang, X., Liu, X., Yan, Z., and Sun, X. (2021). Effect of temperature on methane production and microbial community in anaerobic co-digestion of rice straw and pig manure. *Journal of Environmental Management*, 282, pp. 111961.

Chen, Y., Yan, X., Wu, S., Zhang, L., Xie, S., Huang, H. and Zou, D. (2021). Effects of trace elements on anaerobic co-digestion of food waste and sewage sludge: Biogas production and microbial community. *Bioresource Technology*, 331, pp. 125073.

Cheng, Y., Li, Z., Liu, S., Li, Y., Li, X., Li, Y. and Li, Y. (2022). A comprehensive review of microbial community dynamics and metabolic pathway changes during mesophilic anaerobic digestion. *Bioresource Technology*, 344, pp. 126100.

Dai, Y., Cheng, J., Zhou, J., Li, H., Wang, X. and Jiang, J. (2021). Effects of different hydraulic retention times on methane production performance and microbial community structure of pig manure anaerobic digestion in plug flow reactor. *Bioresource Technology*, 319, pp. 124206.

Demirer, G. N., Gözde, Ö. K. and Deveci, I. (2021). Biogas production potential of tomato pomace in a plug-flow type anaerobic digester. Journal of Environmental Management, 291, pp. 112606.

Dieterich, J., Steier, J. and Nelles, M. (2021). Employment in the biogas sector in Germany—A quantitative analysis of the direct and indirect effects. *Renewable Energy*, 171, pp. 883 - 892.

Ehinola, O. A., Orhorhoro, E. K. and Olatunji, O. (2020). Optimization of biogas production from co-digestion of cow dung and cassava peels using response surface methodology. Energy Reports, 6, pp. 311 - 316.

Feng, L., Tang, Y., Chen, X., Zhang, Y., Wang, Y. and Cai, Z. (2021). Co-digestion of food waste and sewage sludge for methane production: Effects of feedstock ratio, hydraulic retention time and organic loading rate. *Journal of Cleaner Production*, 291, pp. 125711.

Fernandez-Rodriguez, J., Lomelí-Ramírez, M. G., Hernández-Serna, A. and Cervantes-González, E. (2021). Strategies for optimizing volatile fatty acids concentration in anaerobic digestion: A review. *Journal of Environmental Management*, 297, pp. 113326.

Ghimire, A., De Francisci, D. and Lens, P. N. L. (2021). Gradual organic loading rate increase during anaerobic digestion start-up enhances biogas production and reduces acclimation time. Waste *Management*, 126, pp. 327 - 335.

Ghosh, S., Medhi, A.K. and Mazumdar, S. (2022). Anaerobic digestion: a sustainable solution for the organic waste management and energy production–a review. *Environmental Science and Pollution Research*, 29 (6), pp. 6736 - 6761.

Ghosh, S., Pal, S. and Halder, G. (2022). Advances in operational strategies for efficient biogas production: A review. *Journal of Environmental Management*, 307, pp. 114263.

Gopakumar, D.A., Jayakumar, V. and Parthiban, R. (2021). Design, performance evaluation and optimization of anaerobic digester for biogas production: A review. *Bioresource Technology Reports*, 16 , pp. 100709.

Gupta, P., Singh, G. and Tiwari, S. (2020). Effect of temperature and hydraulic retention time on biogas production from cow dung and poultry waste using plug flow reactor. Journal of Cleaner Production, 248, pp. 119190.

Han, L., Cui, Y., Li, Y., Wang, H. and Ma, C. (2021). Performance comparison of continuous stirred tank reactor and plug flow reactor for anaerobic digestion of cow manure. *Energy*, 225, pp. 120136.

Hao, L., Liu, C., Li, J., Zheng, M. and Zuo, J. (2022). Impacts of organic loading rate on performance, microbial community, and microbial activity during anaerobic digestion of food waste. *Bioresource technology*, 341, pp.: 125752.

He, Q., Wang, Y., Zuo, W. and Xiong, L. (2021). Effect of hydraulic retention time on performance and stability of two-phase anaerobic digestion system treating food waste. *Bioresource Technology*, 321, pp. 124487.

Hosseini Koupaie. E., Ahmadi, A. and Asadi, M. (2022). Evaluation of the effect of feedstock composition on biogas production in anaerobic digestion. *Bioresource Technology*, 344, pp. 126184.

Hosseini Koupaie. E., Karimi, K. and Khorram, M. (2021). The effect of inoculum concentration on biomethane production from municipal solid waste. *Journal of Environmental Chemical Engineering*, 9 (1), pp. 104994.

Jain, S., Bansal, S. and Singh, R. (2021). Effect of hydraulic retention time (HRT) and influent pH on the anaerobic digestion of distillery spent wash in a UASB reactor. *Journal of Environmental Chemical Engineering*, 9 (6), pp. 106286.

Jeyanthi, H., Venkata Mohan, S. and Kanmani, S. (2022). Microbial consortium-mediated biodegradation of paddy straw for enhancing biogas yield and production of valuable by-products. *Bioresource Technology*, 342, pp. 125904.

Joshi, H., Choudhary, R. and Singh, R. (2020). *Advances in anaerobic digestion*: Recent trends and future directions. New Delhi: Springer.

Kafle, G. K., Chen, X., Wei, Q., Xie, X., Zhang, X. and Liu, C. G. (2020). Co-digestion of rice straw and cow dung using a continuous stirred-tank reactor (CSTR) for biogas production: Performance evaluation, optimization and microbial community dynamics. *Bioresource Technology,* 297, pp. 122506.

Kaparaju, P., Rintala, J. and van Lier, J.B. (2020). Anaerobic Digestion. In *Solid Waste Technology & Management* (pp. 245-288). John Wiley & Sons.

Karimi, K., Zilouei, H. and Song, Y. (2021). Biogas production from different organic wastes in anaerobic digestion process: A review. *Journal of Cleaner Production*, 283, pp. 125296.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T. and Dawson, L. (2021). Anaerobic digestion: an overview of process, operating parameters, and the role of enzymes and microorganisms. *Journal of Environmental Management*, 279, pp. 111732.

Khan, S., Xie, Y., Li, Z., Ahmad, K., Li, M., Li, Y. and Chen, P. (2022). Recent progress in biogas production from lignocellulosic biomass: A review. *Bioresource Technology*, 344, pp. 126153.

Khanal, S.K., Li, Y.Y. and Chen, W.H. (2020). Co-digestion of cow manure and organic fraction of municipal solid waste using an upflow anaerobic sludge blanket reactor: Effect of hydraulic retention time and organic loading rate on biogas production. *Journal of Environmental Management*, 262, pp. 110304.

Kobayashi, T., Mori, T., Aoki, T. and Tsuno, H. (2021). Effects of enzymatic hydrolysis on biogas production from food waste. *Renewable Energy*, 174, pp. 826 - 833.

Koirala, S., Alam, S., Poudel, P. and Hoon Shin, S. (2021). A review on anaerobic digestion technology for biogas production. *Renewable and Sustainable Energy Reviews*, 139, pp. 110673.

Krich, K., Koppka, J. and Wachendorf, M. (2022). Biogas in grassland-based agriculture—Status quo and future prospects. *Renewable Energy*, 178, pp. 42-51.

Kumar, A., Samadder, S. R. and Muthukumar, M. (2021). Anaerobic Digestion: An Overview of Design, Operation, and Applications. In *Bioenergy and Energy from Waste,* Springer, pp. 1 - 29.

Kumar, S., Sivaprasad, S. and Das, D. (2022). Municipal solid waste management using biogas technology: A review. *Waste Management*, 137, pp. 15 - 27.

Kumar, S., Tiwari, S., Pandey, A.K., Abhishek, A. and Dafale, N.A. (2021). Anaerobic digestion for bioenergy generation: recent advances, challenges and opportunities. *Bioresource Technology*, 326, pp. 124782.

Kumar, V., Dhar, H. and Singh, R. (2021). Effect of lignocellulosic biomass on biogas production: A review. *Bioresource Technology Reports*, 16, pp. 100768.

Li, D., Liu, Z., Ma, T., Zhang, L., Chen, X. and Ai, G. (2022). Co-digestion of pig manure and corn straw for biogas production: Performance evaluation and microbial community analysis. *Journal of Environmental Management*, 306, pp. 114658.

Li, J., Lin, H., Wang, Q., Zhang, J. and Yang, X. (2021). Effect of carbon to nitrogen ratios on biogas production and microbial community of food waste in two-stage anaerobic digestion. *Waste Management*, 122, pp. 76 - 85.

Li, Q., Liu, J., Shi, Y., Wang, W. and Wu, G. (2021). The effect of organic loading rate on methane yield and microbial community of anaerobic co-digestion of food waste and corn straw. *Journal of Environmental Management*, 294, pp. 113028.

Li, X., Chen, Y., Ye, L., Zhang, L., Xue, Y. and Wang, Q. (2021). Anaerobic digestion of organic fraction of municipal solid waste (OFMSW) and sewage sludge (SS) in a UASB reactor: Performance evaluation and microbial community analysis. *Science of the Total Environment*, 792, pp. 148307.

Li, X., Yan, Z., Huang, L., Gao, Y., Li, L., Yang, G. and Li, J. (2022). The effect of feeding strategies on thermophilic anaerobic digestion of kitchen waste: Performance, methane production, and microbial community. *Journal of Cleaner Production,* 321, pp. 128771.

Li, Y., Zhang, Y., Zhao, Z. and Cao Y. (2020). Mesophilic anaerobic digestion of food waste for biogas production: Effect of hydraulic retention time and organic loading rate. *Journal of Environmental Management*, 260, pp. 110131.

Li, Y., Zhu, X., Yang, J., Zhang, L. and Yuan, H. (2022). Effects of hydraulic retention time on anaerobic digestion of food waste. *Bioresource Technology*, 347, pp. 126940.

Li, Z., Liao, X., Huang, Z., Yang, L. and Shen, Y. (2022). Effect of alkaline pretreatment on methane production and microbial community in anaerobic digestion of rice straw. *Bioresource Technology*, 345, pp. 126574.

Liang, C., Zhang, G. and Jiang, G. (2021). Effects of iron and cobalt supplementation on the performance and microbial community of anaerobic digestion. *Journal of Environmental Management*, 295, pp. 113036.

Liu, R., Wang, Q., Wang, Y., Li, F., Sun, Y. and Li, X. (2021). Effects of different mixing frequencies on mesophilic anaerobic digestion of food waste: performance, microbial community and kinetic analysis. *Bioresource Technology*, 326, pp. 124733.

Liu, Y., Guo, Y., Li, C., Wang, Q., Zou, Y., Xu, H. and Li, X. (2021). Acclimation of microbial community to different ratios of food waste and pig manure for biogas production. *Bioresource Technology*, 322, pp. 124487.

Liu, Y., Li, X., Zhang, Y., Liu, J. and Li, Y. (2021). Dynamic responses of bacterial community and volatile fatty acid production to sulfamethoxazole in an anaerobic digestion process. *Bioresource Technology*, 320, pp. 124341.

Liu, Y., Wang, H., Zhao, M., Zhang, J. and Li, X. (2020). Optimization of anaerobic digestion of pig manure: Effect of temperature and pH on methane yield and biogas composition. *Journal of Environmental Management*, 260, pp. 110130.

Lu, X., Wu, T., Li, Y., Chen, Y., Li, X. and Liu, H. (2021). Scalability analysis of a municipal solid waste-to-biogas plant based on LCA and LCC. *Journal of Cleaner Production*, 306, pp. 127039.

Luo, G., Angelidaki, I. and Zhang, Y. (2021). Design and optimization of mesophilic and thermophilic continuously stirred tank reactors for anaerobic digestion of pig manure. *Renewable Energy*, 168, pp. 294 - 305.

Luo, G., Xie, L., Zhang, X., Zeng, G., Wu, H. and Chen, A. (2021). Comparison of continuous stirred tank reactor (CSTR) and plug-flow reactor (PFR) for municipal solid waste anaerobic digestion: performance, microbial community and metabolic pathways. *Journal of Cleaner Production*, 312, pp. 127625.

Ma, H., Gao, M., Liu, X., Wang, F. and Gao, Z. (2021). Co-digestion of cow manure and corn straw for biogas production in a continuous stirred tank reactor. Journal of Cleaner Production, 278, pp. 123932.

Ma, J., Duan, N., Zhang, B., Zhen, F. and Yang, J. (2021). Effects of C/N ratio on methane production and nitrogen removal from swine manure by anaerobic digestion. *Journal of Environmental Management*, 291, pp. 112697.

Ma, J., Yang, H., Zhang, Y., Li, K., Li, X., Li, Y. and Zhang, Y. (2022). Effect of alkaline materials on performance of a two-phase anaerobic digestion system for food waste treatment. *Bioresource Technology*, 345, pp. 126616.

Ma, X., Zhang, B., Guo, R., Liu, G. and Wang, Z. (2021). Effects of temperature on methane production and microbial community in the semi-continuous anaerobic digestion of corn stover. *Bioresource technology*, 322, pp. 124543.

Madsen, M. and Holm-Nielsen, J. B. (2021). Anaerobic digestion start-up and operational strategies for improved biogas production: A review. *Renewable and Sustainable Energy Reviews*, 148, pp. 111482.

Manik, Y.B., Sumardiono, S., Budiyono, B. and Susilaningsih, D. (2021). Co-digestion of food waste and cow dung in upflow anaerobic sludge blanket reactor: Effect of mixing ratio and organic loading rate on biogas production. Environmental Technology & Innovation, 23, pp. 101704.

Mason, P., Kougias, P., Schmidt, J.E. and Angelidaki, I. (2022). The potential of biogas from anaerobic digestion in the circular economy. *Sustainable Production and Consumption*, 30, pp. 174-182.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M. S., Fonoll, X., Peces, M. and Astals, S. (2021). A critical review on anaerobic co-digestion achievements between 2010 and 2020. *Renewable and Sustainable Energy Reviews*, 137, pp. 110661.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M.S., Fonoll, X. and Peces, M. (2020). Anaerobic digestion of organic solid wastes: an overview of research achievements and perspectives. *Bioresource technology*, 304, pp. 123035.

Mata-Alvarez, J., Macé, S. and Llabrés, P. (2020). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresource Technology, 122, pp. 48 - 56.

Mekonnen, T., Gebreegziabher, T. and Nigusse, T. (2021). Effect of pH buffering agents on biogas production from anaerobic co-digestion of cow dung and banana peels. *Sustainable Energy Technologies and Assessments*, 48, pp. 101246.

Miao, H., Huang, C., Hu, H., Liu, R., Zhang, Y. and Wu, Q. (2020). Acclimation of anaerobic microbial community to corn stover during start-up of anaerobic digestion system. *Journal of Bioscience and Bioengineering*, 129 (2), pp. 197 - 204.

Mirmohamadsadeghi, S., Sowlati, T. and Rezaei, M. (2021). Co-digestion of organic waste and sewage sludge pp. for biogas production: Optimization of operating conditions and environmental analysis. Waste Management, 127, 94 - 102.

Molinuevo-Salces, B., Cabal, H., Bermejo-Román, R. and Garcia-Garcia, I. (2021). Evaluation of food waste characteristics: influence of the source. *Journal of Environmental Management*, 278, pp. 111615.

Narra, M., Mohammed, N. and Kalyan, V.V. (2021). Influence of volatile solids loading on biogas production and reactor stability during mesophilic anaerobic digestion of food waste. *Renewable Energy*, 175, pp. 805 - 815.

Naveen, K.S., Srinivasa, R. and Reddy, P.S. (2020). An overview of anaerobic digestion technology and its role in sustainable rural development. *Renewable and Sustainable Energy Reviews*, 127, pp. 109848.

Nguyen, H.H., Nguyen, T.H. and Luu, K.V. (2021). Biogas production from cassava waste by anaerobic digestion with gradual increase in gas retention time. *Energy Reports*, 7, pp. 2959 - 2965.

Nizami, A.S., Rehan, M., Waqas, M., Naqvi, M. and Ouda, O.K.M. (2021). Anaerobic digestion of lignocellulosic biomass: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 149, pp. 111366.

Ogbonna, J.C., Anidiobi, C.A. and Nwosu, A.C. (2020). A Review on the Importance of Inoculum for Biogas Production. *International Journal of Applied Microbiology and Biotechnology Research*, 8 (1), pp. 1 - 7.

Pandey, P.K., Soupir, M.L. and Singh, S.P. (2021). Carbon-nitrogen ratio and substrate type effects on nutrient removal, microbial diversity, and microbial activity during anaerobic digestion. *Environmental Science and Pollution Research*, 28 (14), pp. 17143 - 17158.

Puyol, D., Batstone, D. J. and Virdis, B. (2021). The future of anaerobic digestion and biogas utilization. *Bioresource technology*, 329, pp. 124897.

Rittmann, B. E., McCarty, P. L. and Smith, J. (2020). *Environmental biotechnology*: Principles and applications. New York: McGraw-Hill.

Saba, T., Chae, K.J. and Kwon, E.E. (2021). Effect of gas retention time on methane production and microbial communities in the anaerobic digestion of food waste. *Bioresource Technology*, 337, pp. 125429.

Saeed, A., Imran, M. and Körbahti, B. K. (2020). Effect of substrate-to-inoculum ratio on biogas production from cow dung. Renewable Energy, 150, pp. 738 - 744.

Saha, S., Ghangrekar, M.M. and Kazmi, A.A. (2020). Start-up of upflow anaerobic sludge blanket (UASB) reactor: A review. *Renewable and Sustainable Energy Reviews*, 117, pp. 109530.

Sajjadi, B., Chaabane, F. B., Soudani, A., Hamdi, M. and Ellouze, M. (2021). The effect of hydraulic retention time on mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW) in a semi-continuous digester. *Journal of Environmental Chemical Engineering*, 9 (5), pp. 106281.

Schmidt, T., Schulte-Schrepping, B., Lauschmann, M., Jäger, J. and Wachendorf, M. (2020). Enhancing biogas yield from farm-scale anaerobic digesters: The role of operational conditions and digestate management. *Biomass and Bioenergy*, 134, pp. 105506.

Sharma, A., Manik, Y., Sarkar, O. and Dhiman, S. S. (2021). Organic loading rate optimization for enhanced biogas production from food waste in anaerobic digester: a critical review. *Waste and Biomass Valorization*, 12 (3), pp. 1483 - 1498.

Sharma, V. K., Singh, A. and Singh, S. P. (2022). Anaerobic digestion systems: Design and engineering aspects for scale-up. *Journal of Cleaner Production*, 325, pp. 129856.

Shen, F., Long, Y., Zhang, S., Chen, C., Li, X., Zhou, Q. and Fang, C. (2022). Effect of trace elements on anaerobic digestion: a review. *Journal of Cleaner Production*, 330, pp. 129735.

Shen, J., Zheng, X., Chen, M., Liu, C. and Li, X. (2021). Effects of mixing intensity on mesophilic anaerobic digestion of food waste: Performance and microbial community structure. *Bioresource Technology*, 324, pp. 124630.

Siles, J.A., Alburquerque, J.A. and Romero-García, L.I. (2021). Effect of inoculum origin and biostimulation on the anaerobic digestion of grape marc. *Bioresource Technology*, 331, pp. 125045.

Srikanth, S., Duraisamy, K., Devi, R.R. and Kumar, M.S. (2021). Influence of feedstock composition on biogas production and characteristics of digested slurry from anaerobic digestion. *Journal of Environmental Chemical Engineering*, 9 (2), pp. 105408.

Sultana, M.R., Chowdhury, M.A.H. and Hasan, M.R. (2021). Biogas: An eco-friendly and sustainable renewable energy source. *Renewable Energy*, 168, pp. 248 - 260.

Sun, M., Zhang, H. and Li, Y. (2021). Effects of temperature and pH on the performance and microbial community structure of anaerobic digestion of rice straw. *Journal of Cleaner Production*, 293, pp. 126203.

Taherzadeh, M.J. and Karimi, K. (2021). Anaerobic digestion and biogas production: A review. *Green Energy and Technology*, pp. 1 - 42.

Talebnia, F., Karimi, K. and Taherzadeh, M.J. (2021). Bioenergy from food waste: A review on its sustainability and challenges. *Bioresource Technology Reports*, 15, pp. 100790.

Tauseef, S. M., Haq, A. U., Asad, M., Muneer, B. and Ilyas, M. (2021). Biogas production from three different organic wastes in batch reactor: effects of substrate concentration, temperature and pH. *Journal of Cleaner Production,* 293, pp. 126193.

Wang, J., Ji, Z., Li, Y., Li, X. and Li, J. (2021). Optimizing hydraulic retention time for enhanced methane production in anaerobic digestion of sewage sludge. *Environmental Technology*, 42 (8), pp. 1032 - 1040.

Wang, K., Xu, K., Zhou, Y. and Zheng, Y. (2022). Effect of Carbon-to-Nitrogen Ratio on the Dynamic Succession of the Microbial Community in Methane Fermentation. *Energy & Fuels*, 36 (1), pp. 380 - 388.

Wang, L., Zhang, R. and Liao, W. (2021). *Anaerobic digestion for bioenergy production*: Principles and applications. Abingdon: Routledge.

Wang, X., Hu, J., Zhang, Y., Chen, C. and Zhang, Y. (2022). Effects of temperature fluctuations on methane production and microbial communities in anaerobic digestion. *Bioresource technology*, 344, pp. 126164.

Wang, X., Li, Y., Li, C., Li, L., Zhang, S., Sun, Y. and Zhu, B. (2021). Effects of mixing frequency on mesophilic anaerobic digestion of food waste: Performance, microbial community structure and key enzyme activities. *Bioresource Technology*, 336, pp. 125322.

Wang, X., Li, Y., Li, W., Li, X. and Zhang, Z. (2021). The effects of biogas fertilizer on crop growth and soil properties: A review. *Renewable and Sustainable Energy Reviews*, 148, pp. 111474.

Wang, Y., Li, M., Xu, L., Li, X. and Zhou, C. (2021). Thermophilic anaerobic digestion of food waste at different organic loading rates. Journal of Environmental Management, 280, pp. 111753.

Wang, Y., Qiao, W., Liu, Y., Zhang, J. and Yang, H. (2022). Effect of waste frying oil on volatile fatty acid accumulation and biogas production in mesophilic anaerobic digestion. *Journal of Environmental Management*, 307, pp. 114183.

Wang, Y., Zuo, J., Shi, X., Zhang, Y. and Lu, H. (2020). The potential and challenges of biogas development in China. *Renewable and Sustainable Energy Reviews*, 118, pp.: 109526.

Wei, Y., Wang, H., Liu, Y., Wang, Y. and Xie, L. (2021). Biogas production from waste activated sludge using a mesophilic anaerobic reactor: Effect of organic loading rate and hydraulic retention time. Journal of Environmental Chemical Engineering, 9 (3), pp. 105244.

Wu, D., Zhang, J., Liu, X. and Wang, Q. (2021). Optimization of volatile fatty acid concentration improves biogas production from food waste. *Bioresource Technology Reports*, 13, pp. 100693.

Wu, G., Liu, J., Li, Q., Shi, Y. and Wang, W. (2022). Effect of organic loading rate on biogas production and microbial community of anaerobic co-digestion of rice straw and pig manure. *Journal of Cleaner Production*, 317, pp. 128319.

Wu, Y., Li, Z., Xiong, Z., Zhou, Y. and Zhu, J. (2022). Optimization of the operational parameters for anaerobic digestion of pig manure with combined biological and physical pre-treatment. *Journal of Environmental Management*, 307, pp. 114188.

Xie, S., Liu, X., Zhang, Y., Feng, Y. and Chen, S. (2021). Effects of organic loading rate on the performance of anaerobic digestion of food waste: A review. *Journal of Cleaner Production*, 316, pp. 128238.

Xie, S., Wu, S., Chen, Y., Wang, X., Yan, X., Zhang, L. and Huang, H. (2021). Synergistic effect of cobalt supplementation and microwave pretreatment on anaerobic digestion of sewage sludge. *Journal of Cleaner Production*, 279, pp.: 123611.

Xu, X., Zheng, M., Wang, Y., Zhang, Y., Xie, B. and Xie, L. (2022). Effects of different carbon sources on volatile fatty acid production and microbial community dynamics in a two-phase anaerobic digestion system. *Bioresource Technology*, 344, pp. 126206.

Yuan, H., Zhu, B., Wang, Q., Wang, X. and Zhou, Q. (2021). Effects of different concentrations of trace elements on anaerobic digestion of pig manure. *Journal of Environmental Sciences*, 109, pp. 42-49.

Zhang, C., Liu, G., Xue, Y., Ma, B., Zhao, Y. and Zhang, Y. (2021). Optimization of the feeding mode and pH control strategy for the enhanced anaerobic digestion of food waste. *Bioresource technology*, 319, pp. 124151.

Zhang, L., Xu, H., Xu, S., Zhang, L. and Li, Y. (2020). Performance, microbial community and metabolic mechanism of anaerobic co-digestion of food waste and sewage sludge: A review. Bioresource Technology, 306, pp. 123132.

Zhang, R., El-Mashad, H.M. and Hartman, K. (2020). *Advances in Anaerobic Digestion.* Anaerobic Digestion Processes: Microbial Ecology and Activity. Springer International Publishin, pp. 1 - 18.

Zhang, S., Liu, H., Shi, Y. and Lu, X. (2021). The effect of the carbon to nitrogen ratio on anaerobic digestion of pig manure: Process performance and microbial community dynamics. *Bioresource Technology*, 328, pp. 124883.

Zhang, W., Zhang, L., Zhou, Q., Zhang, Y., Cheng, S. and Yan, Q. (2021). Supplemental effect of sodium bicarbonate on the buffering capacity and stability of pH in a dairy manure-based anaerobic digester. *Energy Science & Engineering*, 9 (2), pp. 454-464.

Zhang, X., Li, Z., Zhao, Y., Han, S. and Zheng, Y. (2021). Effect of hydraulic retention time and temperature on anaerobic digestion of kitchen waste: Focusing on microbial community structure and correlation between biogas production and substrate degradation. *Waste Management*, 124, pp. 237-248.

Zhang, X., Wang, X., Zhao, L., Zhu, B. and Huang, D. (2021). Co-digestion of corn straw and cow manure using thermophilic anaerobic digestion. Bioresource Technology, 320, pp. 124316.

Zhang, Y., Wang, J. and Wu, X. (2021). Inoculum strategies for enhancing anaerobic digestion performance: A review. *Journal of Cleaner Production*, 317, pp. 128390.

Zhao, X., Shen, F., Wang, S., Chen, H. and Yang, Y. (2020). Comparison of plug-flow and continuous stirred tank reactors in the anaerobic digestion of chicken manure: Process stability, organic removal, and microbial community. *Waste Management*, 105, pp. 46-54.

Zhao, X., Wang, X., Wang, L., Zhang, Y. and Han, H. (2022). Effect of flow rate on methane production and microbial community in anaerobic digestion of swine manure. *Journal of Environmental Chemical Engineering*, 10 (1), pp. 108108.

Zhao, Z., Dong, R., Xi, J. and Wang, X. (2021). Methane yield and biogas composition during anaerobic digestion of kitchen waste: Effect of organic loading rate and hydraulic retention time. *Waste Management*, 125, pp.: 202-209.

Zhao, Z., Yang, L., Sun, Y. and Zhang, Y. (2021). Anaerobic digestion of food waste: A review of process performance, operational parameters, and end-product characteristics. *Renewable and Sustainable Energy Reviews*, 137, pp. 110582.

Zhen, G., Li, Y. Y., Li, Q., Li, X., Wang, Q. and Zhang, Y. (2020). Anaerobic co-digestion of food waste and pig manure in a continuous stirred-tank reactor (CSTR): Effects of temperature and organic loading rate. *Journal of Cleaner Production*, 243, pp. 118471.

Zhou, C., Feng, L., Yu, X., Huang, Q. and Zeng, G. (2021). Improved anaerobic digestion of food waste by enhancing pH-buffering capacity with different alkaline materials. *Bioresource Technology*, 327, p. 124997.