Scale-Up Operations for Biogas Production

Achinas, Spyridon; Longinos, Sotirios ; Achinas, Vasileios ; Euverink, Gert-Jan

Published in:
Biogas Production

DOI:
10.1007/978-3-030-58827-4_12

Scale-Up Operations for Biogas Production: Analysis on Critical Factors Governing Large-Scale Operations

Spyridon Achinas, Sotirios Longinos, Vasileios Achinas, and Gerrit Jan Willem Euverink

Abstract Anaerobic digestion (AD) is a unique process where different microbial species decompose organic materials in the absence of oxygen and has been widely practiced in full-scale facilities all over the world. Several AD techniques have been applied to convert livestock manures, wastewaters, and solid lignocellulosic waste into biogas. Despite the progress on the engineering of AD systems, several challenges exist for the economically and environmentally efficient way to recover carbon in the form of renewable biogas fuel. The complexity of the challenges poses constraints into the understanding of the factors associated to the scale-up of the AD operations. This study aims to review the critical factors of biogas plant project development.

Keywords Anaerobic digestion · Biogas plant · Large-scale operations · Bioreactors · Sustainability

1 Introduction

A main reason for increasing interest in biogas production from AD is the necessity for displacing the limited energy resource fossil fuels that play a big role in global warming due to greenhouse gas emissions while being processed (Davis 2018; Achinas et al. 2017). Another main environmental problem is the overproduction of organic wastes from industry, households, and agriculture. Organic wastes,

S. Achinas (✉) · G. J. W. Euverink
Faculty of Science and Engineering, University of Groningen, Groningen, Netherlands
e-mail: s.achinas@rug.nl

S. Longinos
Department of Petroleum and Natural Gas Engineering, Middle East Technical University, Ankara, Turkey

V. Achinas
Solid Waste Management Agency of Attica Region, Special Inter-Grade Association, Athens, Greece

N. Balagurusamy, A. K. Chandel (eds.), *Biogas Production*,
https://doi.org/10.1007/978-3-030-58827-4_12

together with animal manure, are both alarming waste sources but can be treated by AD to form biogas. The waste product from the AD is digestate that, in return, can be used as natural fertilizer for agriculture (RedCorn et al. 2018; Sahajwalla 2018).

Energy and environmental policies prevent global warming by prioritizing sustainable waste management and European targets of renewable energy production. Both policies can indirectly solve the main environmental issues on limited fossil fuels and waste material and besides indirectly support the biogas production by AD industry (Wen-Wei and Han-Qing 2016). Biogas production from AD releases CO_2, but compared to fossil fuels, carbon atoms in biogas originate from the short carbon cycle, which refers to photosynthesis that took place much more recent. Besides, emissions of methane and nitrous oxide are reduced during the biogas production by AD so it contributes to mitigate global warming. Other positive returns from biogas production by AD are a reduction of odors and flies that are present in stored waste sources, an increase of local economic capabilities, and improved veterinary safety due to the application of digestate as fertilizer instead of untreated manure as fertilizer (Al Seadi et al. 2008; Chen 2017a).

2 System Context Biogas Production of AD

The industry in biogas production of AD has many reasons for its promising potential. The causal loop diagram (CLD) depicted in Fig. 1 indicates the factors of the general system that contribute to the worldwide interest in biogas production by AD. The interrelations in the general system are explained in the next three paragraphs. According to Sterman (2000), the positive loops reinforce (R) change, while negative loops (B) are self-correcting; they oppose disturbances. Figure 1 shows several possible loops of which two are explained in order to understand the interrelations.

he GHG-photosynthesis-vegetable biomass-AD production-net GHG loop is a balancing loop. This is explicable by the closed (short) carbon cycle that occurs during biogas production of AD, which was explained in a previous paragraph. The gas fossil fuels-GHG-global warming-water shortages-process water loop is a reinforcing loop because water shortages will cause the need for water-saving energy production solutions. Subsequently, gas production from fossil fuels is not preferred as it requires big amounts of water during processing, while biogas production from AD does not. The loops reinforce and ultimately outweigh gas production from fossil fuels if water shortages exist. The above given context can be traced back to a system that approaches benefits and describes simplified technical aspects that influences the AD process. Anaerobic digestion of waste can improve the quality of life. The produced biogas can be used for cooking, heating water, or generation of electricity for onsite use (Wang et al. 2018). It can also mitigate deforestation by using biogas instead of firewood, and it can mitigate waste accumulation by waste processing. These factors can result in reduced public health concerns, specifically

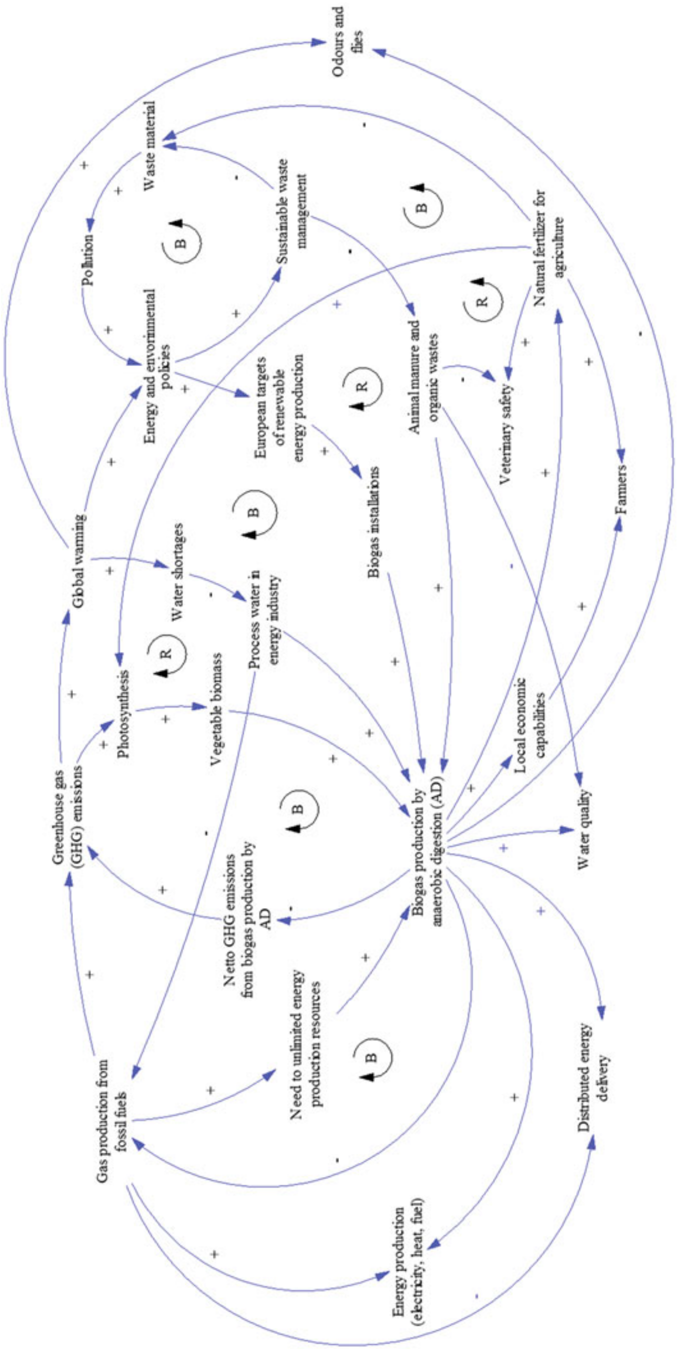

Fig. 1 Causal loop diagram on system context of biogas production from AD

children and women who are disproportionally affected by air pollution because of cultural and social expectations and prejudices.

In addition, and likewise mentioned in the CLD, the effluent contains primary nutrients that initiate agronomic benefits such as fertilizer use for improved plant growth. The main properties that influence performance of an anaerobic digester are substrate characteristics, design of a digester, and determination of operating conditions (Al Seadi et al. 2008). These AD stability performance influencers include the reason for the absence of a screening tool.

The casual loop diagram is a depiction in order to understand possible parameters that influence the AD process. Biogas production of anaerobic digestion should meet several basic conditions to guarantee efficient substrate degradation. These conditions are related to some typical process parameters examined in biotechnological processes, like temperature, mixing, and pH. Moreover, the features of the employed substrate should be analyzed and secured because it influences the abovementioned parameters. Besides, the digester operation and design is of great importance and should be thoroughly assessed to understand the ideal settings for a digester. As one of the knowledge questions emphasizes, the conceptual model should distinguish scaling sizes to understand the most significant parameters in upscaling (Wen-Wei and Han-Qing 2016; Chen 2017b; Macedonio and Drioli 2017; Moron et al. 2018).

3 AD Systems Based on Operation Mode

3.1 Batch Reactors

Batch reactors are filled with a single batch of substrate after which the AD takes place and biogas is produced without intermediate feeding or removing of liquid to or from the digester. Next, after the whole substrate batch is converted into biogas, the digester is emptied and refilled. A bit of the reactor content is left during the emptying phase to prevent the removal of necessary microbial communities. Benefits of batch reactors are the easy process control, high process flexibility in terms of cycle time, and the robustness toward dry and coarse feedstock. A main drawback is the irregular biogas production in batch reactors (Bharathiraja et al. 2016). It is stated that larger feedstock volumes result in lower biogas yield in batch mode digesters (Weiland 2006).

3.2 (Semi-)continuous Reactors

In comparison with batch reactors, (semi-)continuous reactors are applied in industrial scale.

The most common and simple reactor configuration for biogas plants are the CSTR type. Almost 90% of the existing biogas plants are CSTRs (Sanjay and Vijay

Table 1 Advantages and disadvantages of batch and CSTR operation modes in anaerobic digesters (Bharathiraja et al. 2016; Weiland 2006; Sanjay and Vijay 2012)

Mode	Advantages	Disadvantages
Batch	• Easy process control: no mixing, stirring, and pumping required • High flexibility in terms of cycle time • Low input in terms of process and mechanical demands • Robustness toward dry and coarse feedstocks • Low capital costs	• Lower and irregular biogas yield • Channeling and clogging • Large volume
CSTR	• Simplicity in design and operation • Seldom technical failure • Low setup time • Intensified process so more biogas production per time unit • Low investment and operation costs	• High HRT • Rapid acidification due to VFA accumulation • Foaming and scum formation

2012). The feedstock in CSTRs is continuously fed into the reactor, and there is a constant production of biogas. A continuous stirred digester can be horizontal, vertical, or multiple tank systems. Depending on the mixing conditions, continuous stirred digesters can be completely mixed or plug flow. The low investment and operating costs corresponding to the simple reactor design of CSTRs are a main advantage. Other benefits of CSRTs are seldom technical failure, ease of operation, less setup time, intensified processes so more production per time unit, and increased process control. Disadvantages are the high residence time and the possibility of foaming and scum formation (Weiland 2006).

Several operating modes exist in reactor industry of which batch and continuous reactors are assessed in the literature review. Batch reactors are filled with a single batch of substrate after which the AD takes place and biogas is produced without intermediate feeding or removing of liquid to or from the digester. CSTRs are continuously fed with feedstock so there is a consistent production of biogas. Benefits and drawbacks of both operation modes applied in AD are listed in Table 1. Moreover, extra survey was performed on both operation modes, however, these sections are assessed to be out of the scope of important literature findings.

4 AD Systems Based on Scale

4.1 Small-Scale AD Systems

Household digesters with an operating volume of 2–10 m^3 are small-scale digesters and mostly located in rural areas in Asia and other developing countries (Chen 2016; Manni et al. 2017). Currently, the most common small-scale anaerobic digesters are fixed dome digesters, floating drum digesters, and tubular digesters. All three digesters lack mechanical heating and mixing systems. The produced biogas from household digesters is mainly used for stoves and lamps. To illustrate, if a stove is used twice a day for a family of five, 1500–2400 L biogas is required, which requires manure from 130 chickens, 5 cows, or 1 pig (Bond and Templeton 2011).

Benefits of small-scale AD systems are agricultural, energy, environmental, health, and social benefits. These benefits are associated with burning a more environmental fuel and stabilizing residues, creating both a fertilizer and fuel source at the same time, better livestock management resulting in improved water quality, and reducing deforestation by preventing firewood from being a fuel source (Chen 2016). A drawback of a small-scale AD system is the relative high price, usually less than 800 EUR (€), in these rural areas. Therefore, countries like the Netherlands support the construction of these systems by governmental legislations or nonprofit companies that subsidize installation. These grants led to the installation of 700,000 small-scale biogas plants by 2015, impacting 3.5 million people (REN21 2017) (Table 2).

4.2 Large-Scale AD Systems

Large-scale digester size differs between hundreds to thousands cubic meters. Large-scale AD systems are popular in developed countries, since they require high capital investment and larger infrastructure. Therefore, Europe is a pioneer in large-scale AD systems (Davis 2018). The produced biogas is often upgraded to use as a transport fuel, but it is used for combined heat and power (CHP) in most of the cases (Achinas and Achinas 2017).

Currently, the two most popular large-scale digester operations are the farm-scale digesters and the centralized digesters. Farm-scale digesters usually have a capacity between 200 and 1200 m^3 and are generally constructed in swine or dairy farms. They tread agricultural residues from one till three farms. Germany is the current leader in farm-scale digesters as they have 9000 plants operating, while the country aims at extra implementation of 10.000–12.000 digesters (Wilkinson 2011). The centralized digesters have an even larger capacity of up to 8000 m^3. Denmark, the leading country in this technology, has only 20 centralized digesters running due to very high investment costs. They are willing to increase this amount to 30 centralized digesters. Another large-scale AD system is a wastewater treatment plant, which is well-established in the United States as it has 1250 wastewater treatment plants producing biogas (ABC 2016; Nelson et al. 2017).

Table 2 Benefits, drawbacks, and design and operation parameters of small-scale digesters (Achinas and Euverink 2019a, b; Achinas and Achinas 2017; Wilkinson 2011; ABC 2016; Nelson et al. 2017; Garfi et al. 2016; Choorit and Wisarnwan 2007; Chae et al. 2008; Mao et al. 2015; Verma 2002; Kigozi et al. 2014, 2014; Buekens 2005, 2005; Wang et al. 2014, 2014, 2006; Bowen et al. 2014; Karim et al. 2005; Burton and Turner 2003; Stroot et al. 2001; Gomez et al. 2006; Pinho et al. 2004; Olivet et al. 2005; Grady et al. 1999; Beccari et al. 1996; Gerardi 2006; Yu and Fang 2002; Schnurer and Jarvis 2010, 2010; Dussadee et al. 2017; Parawira et al. 2006; Guwy et al. 1997; Moller et al. 2004; Ahring et al. 1995; Costa et al. 2007; Rosato 2017; Pontoni et al. 2015; Yadvika et al. 2004; Braun et al. 2009; Zupancic and Grilc 2011; Deublein and Steinhausez 2008; Kayhanian 1999; Ariunbaatar et al. 2015; Shi et al. 2017; Rabii et al. 2019; Świątek et al. 2018; Solarte-Toro et al. 2018; Benato and Macor 2019; Oreggioni et al. 2017; Lindkvist et al. 2019; Baccioli et al. 2019; Florio et al. 2019; Lauer and Thrän 2018; Achinas 2014; Carlini et al. 2017; Dell'Antonia et al. 2013; Chen et al. 2018; Chiumenti et al. 2018; Fauzianto et al. 2014; Valenti and Porto 2019; Watts and Wiles 2007)

Parameter	Fixed dome digester	Floating drum digester	Tubular digester
Digester design, material	Fixed dome, bricks, and concrete (local materials)	Steel drum and concrete	Tubular, PVC, or polyethylene
Covering	–	Steel drum	Simple roof to protect the plastic top
Temperature range (°C)	Psychrophilic (<25 °C) Mesophilic (25–40 °C)	"	"
Total volume (m^3)	10–20	1.6–10	6–70
Hydraulic residence time (days)	~55	–	20–125
Lifespan (years)	~20	~15	5–10
Benefits	Cheap digester, interchangeable construction materials	Maintains a constant produced gas pressure	Ease of implementation and handling
Drawbacks	Produced gas pressure fluctuates much, no stirring and heating so in	High construction price, expensive construction, no stirring and heating	Reactor surface, no stirring and heating, short lifespan

5 Critical Factors for the Biogas Plant Operation

5.1 Process Operation Parameters

Anaerobic digestion should meet several conditions to guarantee efficient substrate degradation. These conditions are related to some typical process parameters examined in biotechnological processes, like temperature, mixing, pH, organic loading rate (OLR), hydraulic retention time (HRT, days), total alkalinity (TA, as equivalent mg $CaCO_3$), volatile fatty acids (VFAs, as equivalent mg acetic acid), VFAs/TA ratio (or FOS/TAC), redox potential, and ammonia (Garfi et al. 2016). Moreover, the features of the employed substrate should be analyzed because it influences the parameters mentioned above. Examples are the content of volatile solids (VS), total solids (TS), and the carbon-to-nitrogen ratio (C/N).

5.1.1 Temperature

Performance of AD and survival and growth of microbial consortia rely very much upon reactor temperature. Anaerobic digestion can operate in different temperature ranges that are classified as psychrophilic (<20 °C), mesophilic (20–45 °C), and thermophilic (45–70 °C) (Choorit and Wisarnwan 2007). The most occurring temperature ranges are either mesophilic temperatures or thermophilic temperatures. The operating temperature preferably does not change because mesophilic to thermophilic temperature switches (or vice versa) can result in immediately reduced biogas production until the involving microbes have increased in the required amount. Chae et al. (2008) found a significant reduction in biogas production while changing the temperature from 35 to 30 °C and 30 to 32 °C.

Several modern biogas plants operate at thermophilic temperatures due to several advantages such as reduced retention time, improved digestibility, effective destruction of pathogens, and consequently higher biogas yield compared to mesophilic temperatures. However, some outweighing disadvantages cause mesophilic temperature ranges being the most occurring process temperature range. The temperature of the thermophilic process initiates ammonia inhibition or the so-called toxicity of ammonia. Moreover, thermophilic AD requires increased energy demand and high investment costs, and there is an increased risk of process imbalance, e.g., acidification (Davis 2018; Mao et al. 2015) (Table 3). Thus, a decrease in temperature results in higher richness in microorganisms and better process stability. The optimal conditions for the AD will, therefore, be a combination of both ranges: thermophilic ranges for hydrolysis + acidogenesis, and mesophilic for acetogenesis and methanogenesis, which is convenient for a two-stage AD.

Table 3 performance comparison between mesophilic and thermophilic temperature range operation (Choorit and Wisarnwan 2007; Chae et al. 2008; Mao et al. 2015; Verma 2002; Kigozi et al. 2014; Buekens 2005; Wang et al. 2014; Bowen et al. 2014)

Performance characteristics	Mesophilic digestion	Thermophilic digestion
Biogas production	Low	High
Process stability	High	Low
Pathogens destruction	Low	High
Energy requirement	Low	High
HRT	High	Low
Effluent quality	High	Low
Odor production	Low	High
Investment costs	Low	High

5.1.2 Mixing

Most anaerobic digesters are equipped with an impeller to mix the reactor content. Mixing ensures efficient transfer of the organic compounds to the present microbial biomass. It also releases trapped gas bubbles and prevents sedimentation of dense material. The employed mixing method can differ significantly per digester (Karim et al. 2005). It can occur continuously or intermittent and activated for a few times per day. The energy input varies from 10 to 100 Whm^{-3}, depending on the type of impeller, the total solids in the digester, and the kind of reactor (Burton and Turner 2003). Currently, two types of mixing equipment are applied in Europe: a screw in a central tube that creates downward movement and an impeller attached to a central draught tube that creates upward movement.

The stirring intensity of the impeller is an important topic in digester optimization. A certain degree of mixing is essential for contact between the substrate and the microbes and therefore biogas production; however, excessive mixing can diminish biogas production. Low-speed stirring improved digester performance and stabilized an unstable continuously mixed digester (Stroot et al. 2001). Furthermore, low-speed stirring conditions better allow a digester to absorb the disturbance of shock loading compared to high-speed stirring conditions (Gomez et al. 2006).

The precise reason for this adverse effect is unclear, but the formation of anaerobic granules changed during intensive mixing and had a considerable influence on anaerobic digestion performance. Excessive stirring can disrupt the granule structure that reduces the oxidation rate of fatty acids, which might result in digester instability. Thus, low-speed mixing conditions can provide a suitable environment for the granular microbial communities (Pinho et al. 2004).

Hydrodynamic studies estimate the optimal stirring rate and determine if a digester vessel operates at its full mixing capacity (Olivet et al. 2005). In anaerobic digestion, hydrodynamics uses the nontoxic molecule Li^+, which concentration profiles can create a residence time distribution curve that reveals dead zones or areas that are not mixed well. It also reveals short channeling or circuiting where feedstock takes a more direct route between input and output instead of being distributed throughout the whole digester working volume.

5.1.3 pH

pH is the measure for acidity/alkalinity of a solution (a substrate mixture for the AD) and is an essential parameter for maintaining functional AD. Anaerobes are highly pH dependent, and methanogens are even influenced to a greater extent by pH (Grady et al. 1999). Beccari et al. (1996) established that methanogenesis is strongly affected by the pH with an optimum range between pH 6.8 and pH 7.2. If the pH value of the anaerobic digester is outside the optimum range, the activity of the methanogens decreases (Gerardi 2006). Usual progress of the pH value during AD is a decrease over time as a result of the accumulation of volatile fatty acids. Although methanogens do not prefer a lower pH value, acidogens do. The optimum pH of hydrolysis and acidogenesis is stated to be in between 5.5 and 6.5 (Yu and Fang 2002). An important reason for separate reactors (two-stage AD) for hydrolysis + acidogenesis and acetogenesis + methanogenesis is the variety in pH preferences of the anaerobes. Overall, pH control is a problematic and interactive process, whereas reduction of ammonia toxicity due to an increased concentration of free ammonia (FA) is another factor that prefers a stable monitored pH (Mao et al. 2015).

5.1.4 Alkalinity (Buffer Capacity)

Alkalinity is often known as buffer capacity and is a measure of the number of alkaline compounds (i.e., the equilibrium of bicarbonate ions and carbon dioxide) in the digester. The substrates influence alkalinity due to the ammonia that is being released by decomposition of protein- and amino acid-rich feedstocks. The ionized form of ammonia reacts with carbonate ions (i.e., dissolved carbon dioxide) to form ammonium bicarbonate ions (Schnurer and Jarvis 2010). Thus, the alkaline chemicals provide resistance to changes in pH as they neutralize the produced acids. The concentration of the alkaline chemicals is proportional to the buffering capacity (Dussadee et al. 2017, 2017). According to Parawira et al. (2006), it is of great importance that the buffering capacity of the digester remains high to stabilize the pH caused by fluctuations in VFA concentration. In the case of a stable pH (e.g., 7.0), the alkalinity is considered equivalent to the concentration of ammonia, bicarbonate, and hydrogen sulfide, which results in efficient AD (Parawira et al. 2006). Achinas and Euverink suggested the co-inoculation of the bioreactor and showed positive effect on the degradation of the organic matter (Achinas and Euverink 2019b). Alkalinity measures are more reliable process balance measures than pH measures because the accumulation of VFA will reduce the alkalinity significantly before the pH decreases. If the alkalinity shows low amounts (e.g., <4000 mg L^{-1} bicarbonate) the best-suited solution for increasing alkalinity will be reducing OLR. Alternatively, more rapid approaches are adding bicarbonate, carbonate salts, or strong bases to the digester (Guwy et al. 1997).

5.1.5 Volatile Fatty Acids (VFAs)

A low concentration of intermediate products like VFAs (e.g., acetate, butyrate, and propionate) indicates the stability of the AD process (Moller et al. 2004). The intermediate compounds are produced during acidogenesis and have a carbon chain of up to six atoms. Most of the time, an unstable AD will result in accumulation of VFAs which results in a drop of the pH. However, if the buffer capacity in the digester is high enough (i.e., a surplus of alkalinity), a pH drop will not occur. A similar concentration of VFA can be ideal for one type of digester but inhibitory for a different type. Therefore, the VFA concentration cannot be used as a stand-alone AD process monitoring parameter (Davis 2018).

Ahring et al. (1995) demonstrated that monitoring VFAs indicates process stability as increasing VFA can be indicative of an overload of the OLR. The reason here is that methanogens are not able to metabolize the produced acetate by acetogenic bacteria until the number of methanogenic archaea increased sufficiently. The total alkalinity to volatile fatty acids ratio (also referred to as FOS/TAC in German literature) is another indicator for the buffer capacity of a digester. If the two major groups of intermediary microorganisms (i.e., acidogens and methanogens) are active in the same physical space, the ideal VFA/TA ratio is between 0.1 and 0.5 for a stable AD (Costa et al. 2007). If the ratio exceeds 0.5, corrective action should be undertaken. A solution might be the addition of sodium bicarbonate to increase the amount of total alkalinity and stabilize the ratio. As it is assumable that VFA accumulation occurs due to feeding, the VFA/TA ratio is likely to increase (Rosato 2017).

5.1.6 Carbon/Nitrogen Ratio

Anaerobic digestion is sensitive to the C/N ratio as it represents the relationship between the quantity of contained carbon and nitrogen in organic matter, which illustrates the nutrient levels anaerobes require for growth (Kigozi et al. 2014). Methanogens use nitrogen to meet their protein demand. A high C/N ratio of above 40:1 initiates fast depleted nitrogen by microbes such that it will not react with the excess carbon in the feedstock, which reduces the biogas yield (Kigozi et al. 2014). In addition to the low protein solubilization rate, a high C/N ratio induces low FA and total ammonia to nitrogen concentrations within the anaerobic digester. Therefore, ammonia inhibition in the AD process can be avoided by optimizing and stabilizing the C/N ratio. Maintaining the C/N ratio can either be done by explicitly monitoring or by merely being aware of the entering waste types in the anaerobic digester and the relative composition of the wastes (Buekens 2005). The optimal C/N ratio is claimed to be in between 20:1 and 30:1, with a ratio of 25:1 being the most frequently used (Mao et al. 2015; Kigozi et al. 2014; Buekens 2005). Wang et al. (2014) tested C/N ratios of 15:1 and 20:1 at a mesophilic and thermophilic temperature resulting in excessive ammonia inhibition. Similarly, approximately threefold cumulative biogas yield was obtained from C/N ratios of 25:1 and 30:1 compared to 15:1.

5.1.7 Organic Loading Rate (OLR)

The organic loading rate shows the number of volatile solids fed into a digester per unit time (usually per day) under continuous feeding (Pontoni et al. 2015). The optimum OLR is hard to define because it is specific to the operating temperature of the digester and the substrate. Increased OLR will increase biogas production to a greater extent. However, the stability and productivity of the AD process can be severely disturbed as well. Too high OLR rate will exacerbate the methanogenic activity in a digester as hydrolysis and acidogenesis have more active bacteria than methanogens. This oblique activity results in VFA accumulation that eventually leads to irreversible acidification. Subsequently, the pH decreases, further hydrolysis is inhibited, and methanogens are not able to convert VFA into biogas anymore (Mao et al. 2015). The usual calculation followed for OLR is depicted in Eq. (1) (Davis 2018):

$$B_R = \frac{m * c}{V_r} \tag{1}$$

with $B_R = \mathrm{OLR}\left(\frac{kg}{d*m^3}\right), m =$ mass of substrate fed$\left(\frac{kg}{d}\right)$, $c =$ concentration organic matter (%), $V_R =$ digester volume(m^3).

5.1.8 Hydraulic Retention Time (HRT)

The hydraulic retention time is the average time spent by the fed substrate inside the digester. The HRT is valuable as it indicates the available time for the microorganism to grow in the reactor before they are washed out. Eventually, it establishes the conversion of the organic matter to biogas (Yadvika et al. 2004). The effect of an altered HRT on AD biogas yield is hard to determine because it is very substrate dependent. However, Yadvidka et al. (2004) state that shorter retention time is likely to face washout of active microorganisms, while longer retention time desires a large digester volume and hence more investment and equipment costs. On average, AD of lignocellulosic material needs an HRT of around 10 days (Braun et al. 2009). The HRT is defined as the ratio between digester volume and substrate volume fed per unit time (Eq. 2) (Mao et al. 2015).

$$\mathrm{HRT} = \frac{V_R}{V} \tag{2}$$

with HRT (d), V_R= digester volume (m^3), $V =$ volume fed per unit time $\left(\frac{m^3}{d}\right)$.

5.1.9 Redox Potential

Redox potential (i.e., reduction oxidizing potential) has been shown as a successful monitoring parameter in many AD systems due to redox reaction-catalyzed enzymes that degrade the organic materials in the anaerobic environment (Wang et al. 2006). The strictness of the anaerobic environment is well known, which is indicated by a redox potential of ≤ -200 mV (Zupancic and Grilc 2011). Preferably, the redox potential is between -300 and -330 mV for optimal AD process environment. If the redox potential becomes too low (more negative), adding oxidizing agents such as nitrates, nitrites, oxygen, or sulfates into the digester increases the redox potential

(Deublein and Steinhausez 2008). If the redox potential is initially too high, the facultative anaerobic microorganisms in the reactor consume the oxygen dissolved in the water and decrease the redox potential to the level required by important obligatorily anaerobic microorganisms (mostly methanogens).

5.1.10 Ammonia

Decomposition of nitrogenous matter, e.g., proteins and urea, leads to the formation of ammonia. It is an essential nutrient that serves as a precursor for the synthesis of proteins and enzymes required by the microorganisms in the reactor to survive. Ammonia is also used as a fertilizer for the growth of plants to generate feedstock (Kayhanian 1999). The total ammonia nitrogen is primarily composed of ammonium ion (NH_4^+) and free ammonia (NH_3) (i.e., free ammonia nitrogen (FAN)). The equilibrium of these two components mainly relies on process temperature and pH (Schnurer and Jarvis 2010). To illustrate, if the temperature or pH increases, the equilibrium steadily shift toward FAN. Furthermore, the FAN is the most toxic species of total ammonia nitrogen (TAN). FAN can penetrate a bacterial cell membrane resulting in a proton imbalance, altering intercellular pH, inhibiting specific enzyme activities, and increasing maintenance energy requirements (Ariunbaatar et al. 2015).

Too high ammonia content will lead to process inhibition, which Al Seadi et al. (Davis 2018) stated, where after they came up with a maximal ammonia concentration of 0.80 g L^{-1} to keep the process stable. However, Shi et al. (2017) reported that maximally allowable ammonia concentrations seem to depend on the substrate, inoculum, and environmental conditions, fluctuating from 53 mg L^{-1} to 1450 mg/L and 1500–1700 mg L^{-1} (Shi et al. 2017). Zupanic and Grilc (2011) also concluded that the allowable maximum is 2200 mg L^{-1}. The most well-known and established methods to reduce ammonia inhibition during AD are chemical (struvite precipitation) and physical (air stripping) methods. They were both effectively applied to wastewater treatment and sewage sludge AD that contained high ammonia concentrations.

5.2 Microbial Ecology

Anaerobic digestion requires an equal rate of degradation due to the sensitivity of the process. However, the dynamics of the separate microbes are complex and interactive, so equal degradation is hard to achieve (Rabii et al. 2019). Especially, disproportionate amounts of microbial groups influence the degradation stability. For example, complete degradation during hydrolysis is complex because organic compounds like fats and proteins are depolymerized into monomers within several days, whereas carbohydrates are depolymerized within a few hours. Additionally, if hydrolysis runs too fast, acid augmentation will occur, resulting in a lower pH and process failure (Świątek et al. 2018). As mentioned, the four steps during AD engage in syntrophic interrelation so to illustrate, if the growth rate of hydrolytic bacteria is low, the rates of the other three steps decrease, resulting in a lower biogas yield. Thus, the microbial population dynamics influence the stability of the degradation steps, and in return, the microbial population dynamics are affected by chemical conditions (e.g., alkalinity, VFA concentrations, TAN, TOC), operating parameters (e.g., OLR, pH, HRT, and temperature), and substrate characteristics (type of lignocellulosic biomass). Operating parameters and substrate characteristics control the chemical conditions. It is described that among the microbial groups involved in AD, methanogens are the key microbes for biogas production, which are the most sensitive to changes in operating parameters and are the rate-limiting step of the whole process.

6 Critical Factors for the Large-Scale Biogas Plant Investments

6.1 The Need for Renewable Gas Production

The population growth will create more need for reliable and stable energy – energy for homes, transportation, business, and industry (Solarte-Toro et al. 2018). In European level, the shifting to a low carbon economy remains a challenge. There is a consensus that CO_2 emissions have to be eliminated in order to move to a green economy. Plain gas has the lowest CO_2 emission among the fossil fuels. However, countries attempt to decarbonize the energy produced. Biogas production is regarded a way to shorten the carbon cycle. The carbon cycle of biogas is only as long as it took for the organic material to grow. The CO_2 absorbed by this organic material is released again upon combustion of the gas, but no additional CO_2 is emitted to the atmosphere. The shortage of renewable electricity can be offset by the exploitation of wastes.

6.2 Subsidy for Biogas Production

Besides the revenues of selling electricity and/or heat, biogas producers can also benefit from the subsidies (Benato and Macor 2019). Subsidizing renewable electricity production from biogas will reinforce the bioeconomy and the sustainable development. Subsidies and green policy scheme can realize the green value of the biogas and stimulate its large-scale production (Oreggioni et al. 2017). In practice the shortage of subsidy is much larger, since the subsidies scheme is not available in all the European countries.

6.3 Biogas Production

The green value of an end product can forecast the business project viability. It is essential to understand the economic drivers for the biogas project and provide financial and technical assurance for biogas-based project business case (Lindkvist et al. 2019). It is more expensive to produce biomethane instead of biogas due to the upgrading procedure (Baccioli et al. 2019). It may therefore be essential to use biogas directly to satisfy local power and heat demand. However, the subsidy policy for biomethane rather than biogas induces the biogas producers to upgrade the biogas in biomethane (Florio et al. 2019), in spite of the fact that CHP biogas plants may be a more optimal solution (Lauer and Thrän 2018).

6.4 Digestate

The digestate produced from the degradation of organic mass is a valuable end product. This product can be used as fertilizer in the agricultural land. Nitrogen, potassium, and phosphorus remain in the digester and are essential nutrients for plant growth. Besides the environmental benefit, the use of digestate is also economically essential. For instance, it avoids waste disposal costs. Nevertheless, there are stringent regulations with regard to manure use as soil conditioner in Europe (Achinas 2014). Digestate can contain various amount of hazardous matter. Hazardous matter can pose risks to human and animal health or can cause environmental pollution. There is a maximum amount of minerals that is allowed to be applied to the crops. In that case, farmers must often pay third parties to get rid of their excess manure, and subsequently additional operation costs arise.

6.5 Feedstock of Dependency of Producers

The availability and cost of waste streams is a key role for the investment success. The waste streams are often considered freely available to biogas producers during the biogas project execution (Carlini et al. 2017). As soon as an anaerobic digester is built, this can create an advantage to the supplier of waste streams for further bargain of the waste availability. The supplier has the option to not deliver the waste for free, and subsequently the owner can decide if it can proceed with the biogas production or not. At the start-up phase, it is therefore necessary to agree on long-term contracts for input material (Dell'Antonia et al. 2013).

These contracts contain at least the duration, guaranteed quality of the biomass, guaranteed amount of feedstock supply, and payments based on delivered quality and quantity. It is needed to include the available amount of feedstock before the size of the plant, based on the desired amount of output, is adjusted. Therefore, it is important to investigate the amount of feedstock that can be delivered by suppliers.

6.6 Permitting Process

In order to build a biogas plant, a permit from the local authorities is mandatory. New biogas producers must adhere to strict regulations, and thus it takes a long time to obtain a permit to build the digester. The permitting process renders the difficult expansion of biogas business projects. Every country has his own regulations for criteria, documentation, and procedure that are needed to get permission to install a biogas plant. Investors must document the conformity of the project with national legislation in order to get the permit for building a biogas plant. Topics that are discussed in the document are, for instance, exhaust emissions, impact on groundwater, protection of land, noise and odors, recycling and handling of organic wastes and manure, building safety, and work safety. Besides the building permit, several legislations are also taken into consideration during the permission process of biogas projects. This is specified in the environmental protection law, by-product instruction, nature protection, supply law, procedure law, environmental protection act, and land use planning law.

6.7 Acceptability of Using Biomass for Energy Production

In late study of the institution “Natuur en Milieu” (nature and environment), a resolution has been done concerning the sustainable development of green gas. The inference of this study is that even though the expression green gas proposes that gas has been generated from biological substances is a positive fact for the environment. The study suggests that sewage waste, landfills, and organic waste from residential houses are steadily sustainable sources for biogas generation (Chen et al. 2018; Chiumenti et al. 2018). The study also explains that for different organic substances, it should be contemplated if they cannot be used for influent or for food, or other petitions, with which there is a larger additional value. If this study is broadly obtained, large-scale production of biogas will not be material due to more decrease of the accessible feedstock. The utilization of biomass for energy generation does not give the highest benefits (Fauzianto et al. 2014). As general opinion, energy production is placed not in the initial benefits for biomass in this study (Valenti and Porto 2019). Pharmaceuticals must be the first choice of biomass use, following food, then for generation of various chemicals, and only after it is not appropriate for all the previous uses, it should be used for energy production. In a complete market, this distribution of biological substances to the output with the highest benefits would ipso facto occur. This procedure might, nevertheless, be perverted by subsidies. We have already known it from biofuel production, where high fundings were provided hence to augment biofuel production. This motive has an outcome, the augmentation of food prices, making the food not accessible for the unprivileged.

6.8 Technological Upscaling of AD Process

Upscaling bioreactors is relatively easy due to the possibility to run them parallel in high quantities without modifying the individual reactors. If one reactor runs at a desired steady state, its operating settings can be copied to other reactors such that the same steady state is reached in these reactors. Bioreactor upscaling, which Watts and Wiles (Watts and Wiles 2007) refer as scale-out, does not involve changes in hydrodynamics and reaction kinetics during the reactor process, while conventional bioreactor upscaling does. It involves a complicated iterative process during upscaling due to significantly changing hydrodynamics and reaction kinetics. The indicated difference between the described scale-up procedures is summarized in Fig. 2.

Basic design goals for a digester are a maximum volume production of biogas; to allow for a continuous, high, and sustainable organic loading rate; and to minimize reactor volume (Garfi et al. 2016). The digester size is based on the available amount of organic wastes, and the digester design preferably considers the construction practicalities of both mixing and heat loss (Achinas and Euverink 2016). To illustrate, square and rectangular underground digesters are easier to build, however, mixing will be suboptimal as flow will be stagnant in right-angled corners, resulting in a buildup of refractory compounds that will reduce the effective operating volume of the digester over time. The outlined situation might lead to process failure leading to extra downtime and maintenance. Besides, the heat loss (e.g., due to surrounding

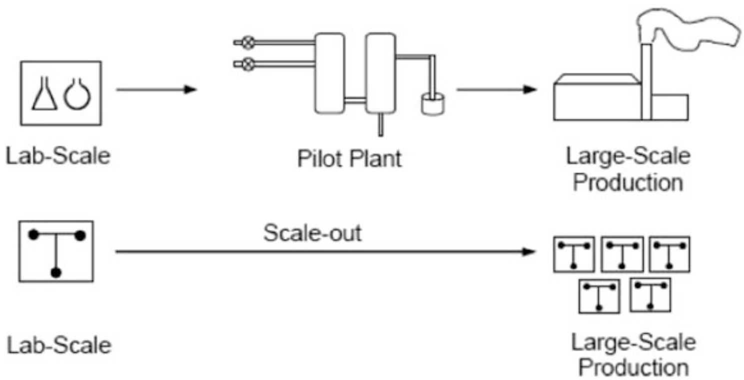

Fig. 2 Comparison between upscaling conventional bioreactors (top) and mini/micro bioreactors (bottom) (Watts and Wiles 2007)

climate conditions) influences decisions on the digester shape, material, location, and operating mode. A wide spectrum of operating modes have been applied since 1859 such as batch digesters, continuously stirred tank digesters, plug-flow digesters, and sludge bed digesters. Additionally, digesters can operate in either a one-stage or multiple-stage digestion, depending upon the scale of operation and feeding characteristics (Dussadee et al. 2017).

References

ABC (2016) Operational biogas systems in the U.S. American Biogas Council
Achinas S (2014) Material flow analysis (MFA) for waste management in olive oil industries sector in South Europe. J Sustain Dev 5(1):29–23
Achinas S, Achinas V (2017) Biogas combustion: an introductory briefing. In: Vico A, Artemio N (eds) Biogas: production, applications and global developments. Nova Science Publishers, New York, pp 179–193
Achinas S, Euverink GJW (2016) Consolidated briefing of biochemical ethanol production from lignocellulosic biomass. Electron J Biotechnol 23:44–53
Achinas S, Euverink GJW (2019a) Feasibility study of biogas production from hardly degradable material in co-inoculated bioreactor. Energies 12:1040
Achinas S, Euverink GJW (2019b) Effect of combined inoculation on biogas production from hardly degradable material. Energies 12:217
Achinas S, Achinas V, Euverink GJW (2017) A technological overview of biogas production from biowaste. Engineering 3(3):299–307
Ahring B, Sandberg M, Angelidaki I (1995) Volatile fatty-acids as indicators of process imbalance in anaerobic digesters. Appl Microbiol Biotechnol 43:559–565
Al Seadi T, Rutz D, Prassl H, Kottner M, Finsterwalder T, Volk S, Janssen R (2008) Biogas handbook, technical report, University of Southern Denmark Esbjerg. Esbjerg, Denmark
Ariunbaatar J, Scotto Di Perta E, Panico A, Frunzo L, Esposito G, Lens PNL, Pirozzi F (2015) Effect of ammoniacal nitrogen on one-stage and two-stage anaerobic digestion of food waste. Waste Manag 38:388–398
Baccioli A, Ferrari L, Guiller R, Yousfi O, Vizza F, Desideri U (2019) Feasibility analysis of bio-methane production in a biogas plant: a case study. Energies 12:473
Beccari M, Bonemazzi F, Majone M et al (1996) Interactions between acidogenesis and methanogenesis in the anaerobic treatment of olive mill effluents. Water Res 186(30):183–189
Benato A, Macor A (2019) Italian biogas plants: trend, subsidies, cost, biogas composition and engine emissions. Energies 12(6):979
Bharathiraja B, Sudharsana T, Jayamuthunagai J et al (2016) Biohydrogen and Biogas – an overview on feedstocks and enhancement process. Fuel 185:810–828
Bond T, Templeton M (2011) History and future of domestic biogas plants in the developing world. Energy Sustain Dev 15:347–354
Bowen E, Dolfing J, Davenport R, Read F, Curtis T (2014) Low-temperature limitation of bioreactor sludge in anaerobic treatment of domestic wastewater. Water Sci Technol 69:1004–1013
Braun R, Weiland P, Wellinger A (2009) Bioenergy from energy crop digestion. Energy from biogas and landfill gas. IEA Bioenergy Report 37
Buekens A (2005) Energy recovery from residual waste by means of anaerobic digestion technologies. Proceedings of the future of residual waste management in Europa, pp 17–18
Burton C, Turner C (2003) Manure management treatment strategies for sustainable agriculture, 2nd edn. Silsoe Research Institute

Carlini M, Mosconi EM, Castellucci S et al (2017) An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. Energies 10:1165

Chae K, Jang A, Yim S, Kim I (2008) The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresour Technol 99:1–6

Chen J (2016) A bright future for sustainable development: ushered in by innovation. Engineering 2 (1):16–18

Chen JF (2017a) Green chemical engineering for a better life. Engineering 3(3):279

Chen JF (2017b) Green chemical engineering. Engineering 3(3):283–284

Chen P, Anderson E, Addy M et al (2018) Breakthrough technologies for the biorefining of organic solid and liquid wastes. Engineering 4(4):574–580

Chiumenti A, Boscaro D, da Borso F, Sartori L, Pezzuolo A (2018) Biogas from fresh spring and summer grass: effect of the harvesting period. Energies 11:1466

Choorit W, Wisarnwan P (2007) Effect of temperature on the anaerobic digestion of palm oil mill effluent. Electron J Biotechnol 10:376–385

Costa R, Tavares C, Cossich E (2007) Stabilization of swine wastes by anaerobic digestion. Environ Technol 28:1145–1151

Davis LA (2018) The shale oil and gas revolution. Engineering 4(4):438–439

Dell'Antonia D, Cividino SRS, Carlino A et al (2013) Development perspectives for biogas production from agricultural waste in Friuli Venezia Giulia (Nord-East of Italy). J Agr Eng 44:569–572

Deublein D, Steinhausez A (2008) Biogas from waste and renewable resources. Weinheim

Dussadee N, Ramaraj R, Cheunbarn T (2017) Biotechnological application of sustainable biogas production through dry anaerobic digestion of Napier grass. Biotech 7:47

Fauzianto R, Achinas S, Achinas V (2014) Sustainable biomass production for energy strategies in Asia: a review for legal and social aspects. J Agric Sustain 7(1):1–26

Florio C, Fiorentino G, Corcelli F, Ulgiati S, Dumontet S, Güsewell J, Eltrop L (2019) A life cycle assessment of biomethane production from waste feedstock through different upgrading technologies. Energies 12:718

Garfi M, Marti-Herrero J, Garwood A, Ferrer I (2016) Household anaerobic digesters for biogas production in Latin America: a review. Renew Sust Energ Rev 60:599–614

Gerardi M (2006) Wastewater bacteria. Wiley-Interscience, New Jersey

Gomez X, Cuetos M, Cara J, Moran A, Garcia A (2006) Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes – conditions for mixing and evaluation of the organic loading rate. Renew Energy 31:2017–2024

Grady LC, Daigger G, Lim H (1999) Biological wastewater treatment, 2nd edn. CRC Press

Guwy A, Hawkes F, Wilcox S, Hawkes D (1997) Neural network and on-off control of bicarbonate alkalinity in a fluidized-bed anaerobic digester. Water Res 31:2019–2025

Karim K, Hoffmann R, Klasson K, Al-Dahnan M (2005) Anaerobic digestion of animal waste: effect on mode of mixing. Water Res 39:3597–3606

Kayhanian M (1999) Ammonia inhibition in high-solids biogasification: an overview and practical solutions. Environ Technol 20:355–365

Kigozi R, Muzenda E, Aboyade A (2014) Biogas technology: current trends, opportunities and challenges. University of Johannesburg, pp 1–8

Lauer M, Thrän D (2018) Flexible biogas in future energy systems—sleeping beauty for a cheaper power generation. Energies 11(4):761

Lindkvist E, Karlsson M, Ivner J (2019) Systems analysis of biogas production—part I research design. Energies 12(5):926

Macedonio F, Drioli E (2017) Membrane engineering for green process engineering. Engineering 3 (3):290–298

Manni M, Coccia V, Cavalaglio G et al (2017) Best practices for recovering rural abandoned towers through the installation of small-scale biogas plants. Energies 10:1224

Mao C, Feng Y, Wang X et al (2015) Review on research achievements of biogas from anaerobic digestion. Renew Sustain Energy Rev 45:540–555

Moller H, Sommer S, Ahring B (2004) Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure. J Environ Qual 33:27–36

Moron M, Morales L, Mora C et al (2018) OMW spillage control tool based on tracking p-Coumaric acid degradation by HPLC. Environ Technol 40:1–16

Nelson MJ, Nakhla G, Zhu J (2017) Fluidized-bed bioreactor applications for biological wastewater treatment: a review of research and developments. Engineering 3(3):330–342

Olivet D, Valls J, Gordillo M, Freixo A, Sanchez A (2005) Application of residence time distribution technique to the study of the hydrodynamic behavior of a full-scale wastewater treatment plant plug-flow bioreactor. J Chem Technol Biotechnol 80:425–432

Oreggioni GD, Lesh Gowreesunker B, Tassou SA et al (2017) Potential for energy production from farm wastes using anaerobic digestion in the UK: an economic comparison of different size plants. Energies 10:1396

Parawira W, Murto M, Zvauya R, Mattiasson B (2006) Comparison of the performance of a UASB reactor and an anaerobic packed-bed reactor when treating potato waste leachate. Renew Energy 31:893–903

Pinho S, Ratusznei S, Rodrigues J, Foresti E, Zaiat M (2004) Influence of the agitation rate on the treatment of partially soluble wastewater in anaerobic sequencing batch biofilm reactor. Water Res 38:4117–4124

Pontoni L, Panico A, Salzano E, Frunzo L, Iodice P, Pirozzi F (2015) Innovative parameters to control the efficiency of anaerobic digestion process. Chem Eng Trans 43:2089–2094

Rabii A, Aldin S, Dahman Y et al (2019) A review on anaerobic co-digestion with a focus on the microbial populations and the effect of multi-stage digester configuration. Energies 12(6):1106

RedCorn R, Fatemi S, Engelberth AS (2018) Comparing end-use potential for industrial food-waste sources. Engineering 4:371–380

REN21 (2017) Renewables 2017: global status report. Secretariat, Paris

Rosato M (2017) Redimensioning the importance of the VFA/TA (FOS/TAC) method for the optimization of biogas plants, pp 1–5

Sahajwalla V (2018) Green processes: transforming waste into valuable resources. Engineering 4 (3):309–310

Sanjay P, Vijay V (2012) Biogas production, upgradation and slurry management. Narosa Publication, New Delhi, pp 116–121

Schnurer A, Jarvis A (2010) Microbiological handbook for biogas plants. Swedish Waste Management 207

Shi X, Lin J, Zuo J, Li P, Li X, Guo X (2017) Effects of free ammonia on volatile fatty acid accumulation and process performance in the anaerobic digestion of two typical bio-wastes. J Environ Sci 55:49–57

Solarte-Toro JC, Chacón-Pérez Y, Cardona-Alzate CA (2018) Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material. Electron J Biotechnol 33:52–62

Sterman J (2000) Business dynamics; System thinking and modeling for a complex world, Chapter 5

Stroot P, McMahon K, Mackie R, Rashkin L (2001) Anaerobic co-digestion of municipal solid waste and biosolids under various mixing conditions – I. Digester performance. Water Res 35:1804–1816

Świątek M, Lewicki A, Szymanowska D, Kubiak P (2018) The effect of introduction of chicken manure on the biodiversity and performance of an anaerobic digester. Electron J Biotechnol 37:25–33

Valenti F, Porto SMC (2019) Net electricity and heat generated by reusing Mediterranean agro-industrial by-products. Energies 12:470

Verma S (2002) Anaerobic digestion of biodegradable organics in municipal solid wastes. MSc Dissertation. Columbia University

Wang L, Zhou Q, Li F (2006) Avoiding propionic acid accumulation in the anaerobic process for biohydrogen production. Biomass Bioenergy 30:177–182

Wang X, Lu X, Li F, Yang G (2014) Effects of temperature and carbon-nitrogen (C/N) ratio on the performance of anaerobic co-digestion of dairy manure, chicken manure and rice straw: focusing on ammonia inhibition. PLoS One 9:e97265

Wang J, Wang H, Fan Y (2018) Techno-economic challenges of fuel cell commercialization. Engineering 4(3):352–360

Watts P, Wiles C (2007) Micro reactors: a new tool for the synthetic chemist. Org Biomol Chem 5:727–732

Weiland P (2006) Biomass digestion in agriculture: a successful pathway for the energy production and waste treatment in Germany. Eng Life Sci 6(3):302–309

Wen-Wei L, Han-Qing Y (2016) Advances in energy-producing anaerobic biotechnologies for municipal wastewater treatment. Engineering 2:438–446

Wilkinson K (2011) A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia. Biomass Bioenergy 35:1613–1622

Yadvika S, Sreekrishnan T, Kohli S, Rana V (2004) Enhancement of biogas production from solid substrates using different techniques – a review. Bioresour Technol 95:1–10

Yu H, Fang H (2002) Acidogenesis of dairy wastewater at various pH levels. Water Sci Technol 45:201–206

Zupancic G, Grilc V (2011) Anaerobic treatment and biogas production from organic waste. Management of organic waste