Chapter 18
Anaerobic Digestion: Factors Affecting Anaerobic Digestion Process

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Abstract Anaerobic digestion (AD) is a biological decomposition process that occurs in the absence of oxygen. The decomposition of organic matter is a multi-step process of series and parallel reactions namely hydrolysis, acidogenesis, acetogenesis and methanogene. Most of the control in anaerobic digestion is undertaken directly by the microorganisms themselves; however, the operational conditions such as temperature, pH, essential trace nutrients and toxicants can play a major role in modifying reaction rates of individual sub-processes. The energy performance of the anaerobic digestion is depending mainly on the biogas production technology, raw materials and geographic location (ambient temperature). Since the feedstocks coming to anaerobic digestion have usually lower heating value as received, the usual energy efficiency calculation used for incineration plant is not useful. Most commonly used method is the input/output method, and the estimation is dependent upon the chosen system boundary.

Keywords Anaerobic digestion · Operational conditions · Reaction rate
Energy performance · System boundary

1 Introduction

Anaerobic digestion (AD) is a biological process that occurs in the absence of oxygen when organic materials are available. The process is accomplished with a consortium of microorganisms such as fermentative bacteria, hydrogen-producing acetogenic bacteria, hydrogen-consuming acetogenic bacteria, carbon

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dioxide-reducing methanogens and aceticlastic methanogens (Appels et al. 2008). AD process makes use of these anaerobes to breakdown organic substances to biogas mainly composed of methane (CH_4) and carbon dioxide (CO_2). The amount of excess sludge production is very small (Mittal 2011).

Biogas from organic waste usually contains 60–70% methane, 30–40% carbon dioxide and <1% nitrogen (Jonsson et al. 2003) in an ideal condition, whereas some amount of hydrogen sulphide and ammonia is also produced otherwise (Jansen and Jensen 2000).

The energy performance of AD is mainly dependent on the biogas production technology (wet or dry technology, mesophilic or thermophilic) and geographic location (ambient temperature). The used feeding materials have also an effect because the biogas yield is varying from different feeding materials. Moreover, the process of obtaining the feeding materials and types of digestion technology, for instance, wet digestion can consume significant amount of energy.

2 AD of Organic Material into Methane

The decomposition of organic matter is a multi-step process of series and parallel reactions. This successive degradation process occurs in four stages, namely (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis and (iv) methanogenesis as shown in Fig. 1. A brief discussion of each stage is presented below.

2.1 Hydrolysis

Hydrolysis of the complex organic matter is an important step of the anaerobic biodegradation process. During hydrolysis, the first stage of anaerobic digestion, bacteria transform the insoluble complex organic substrate (carbohydrates, proteins, lipids, etc.) into soluble monomers and polymers. This process is catalysed by enzymes like cellulase, protease and lipase excreted by the microorganisms responsible for fermentation for the conversion of proteins to amino acids; lipids to long-chain fatty acids (LCFA), polysaccharides, to simple sugars (Parawira 2012; Ostrem et al. 2004). This group of microorganisms is considered to be composed of a large group of facultative bacteria that can thrive with or without oxygen (Botheju et al. 2010; Schluter et al. 2008). Hydrolysis is the rate-limiting process for the overall digestion of substrates with high suspended solids (SS)/chemical oxygen demand (COD) ratio. It is usually not due to a lack of enzyme activity but to the availability of free accessible surface area of the particles and the overall structure of the solid substrate (Zeeman and Sanders 2001; Van Lier et al. 2008). Moreover, at low temperature, hydrolysis may limit the overall process (Lew et al. 2011) and thereby determining the required reactor design. The products of hydrolysis are the substrates for acidogenic bacteria. Equation (1) shows an example of hydrolysis

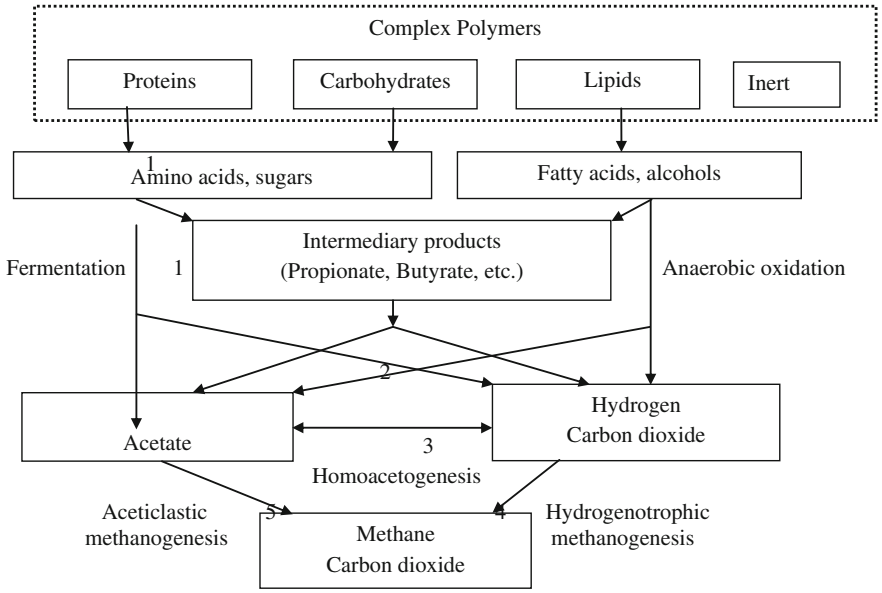

Fig. 1 Reaction of the anaerobic digestion of polymeric materials (numbers indicate the bacterial groups involved): (1) Hydrolytic and fermentative bacteria (2) Acetogenic bacteria (3) Homo-acetogenic bacteria (4) Hydrogenotrophic methanogens (5) Aceticlastic methanogens. Adapted from Gujer and Zehnder (1983)

reaction where organic waste is broken down into a simple sugar, in this case, glucose (Ostrem et al. 2004).

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \quad (1)$$

2.2 *Acidogenesis*

In the second stage, the hydrolysis products (amino acids, LCFA and simple sugars) which are relatively soluble compounds are converted into variety of small organic compounds mainly volatile fatty acids (VFAs), that is, acetate (CH_3COOH) and organic acids such as propionate (CH_3CH_2COOH), butyrate ($CH_3CH_2CH_2COOH$), valeric ($CH_3CH_2CH_2CH_2COOH$), formic ($HCOOH$), lactic ($C_3H_6O_3$) as well as H_2, CO_2 and ammonia (Zeeman et al. 1996; Ostrem et al. 2004; WtERT 2014). This process is mainly performed by a fermentative microorganism, and the nature of end products depends on the conditions of reactor medium. For instance, acetate will be the main end product if H_2 is effectively removed by H_2-scavenging organisms such as methanogens (Van Lier et al. 2008). However, if methanogenesis is retarded and H_2 accumulates, more reduced products such as propionate and

butyrate are likely to appear. Therefore, effluents of overloaded or disturbed anaerobic reactors often contain these more reduced intermediate products and become acidic (Van Lier et al. 2008). Out of acidogenesis product, hydrogen, carbon dioxide and acetic acid will skip the acetogenesis process and be utilized directly by the methanogenic microorganisms in the final stage as shown in Fig. 1. Equations (2) and (3) represent typical acidogenic reactions where glucose is converted into acetic acid and propionate, respectively (Ostrem et al. 2004; Bilitewski et al. 1997).

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (3)$$

2.3 Acetogenesis

In the third stage, the short-chain fatty acids (SCFA), other than acetate that is produced in the acidogenesis steps, are further converted to acetic acid, carbon dioxide and hydrogen by the acetogenic bacteria as shown in Fig. 1. There are two types of acetogenic bacteria namely hydrogen-producing acetogens and homoacetogens (Parawira 2012; Cavinato 2011). Equations (4) and (5) show the production of acetic acid from butyrate and propionate and by utilizing hydrogen-producing bacteria (Ostrem et al. 2004).

$$CH_3CH_2CH_2COOH + 4H_2O \rightarrow CH_3COOH + 2CO_2 + 6H_2 \quad (4)$$

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \quad (5)$$

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O \quad (6)$$

Homoacetogenesis is the generation of acetic acid from dissolved H_2 and CO_2 by homoacetogens as shown in Eq. (6).

2.4 Methanogenesis

The final stage of overall anaerobic conversion is called methanogenesis in which stage the degradable organic material is finally converted to a gaseous form that automatically leaves the reactor system. Acetoclastic and hydrogenotrophic methanogens are responsible for this conversion (Parawira 2012; Cavinato 2011). Acetoclastic methanogenesis is the final stage of anaerobic digestion in which acetic acid is converted into CH_4 and CO_2 by a group of archaea known as acetoclastic

methanogens. This is responsible for the production of about two-third of methane as shown in Eq. (7) (Cavinato 2011; Ostrem et al. 2004).

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{7}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{8}$$

Hydrogenotrophic methanogenesis is the production of CH_4 from dissolved H_2 and CO_2 by a group of slow-growing hydrogenotrophic methanogens. These methanogens produce the remaining one-third of methane by the reaction shown in Eq. (8) (Cavinato 2011; Ostrem et al. 2004). Methanogenic microorganisms may compete with sulphate-reducing microorganisms if sulphate is present at sufficiently high concentrations (Speece 1996).

3 Factors Affecting the Rate of Anaerobic Digestion

Each of the four sub-processes has different rates depending on operating conditions and substrate concentration. The overall rate of stabilization therefore will be limited by the slowest or rate-limiting step. The rate-limiting step may change from one sub-process to another with time within a system dependent upon the substrate characteristics (Ma et al. 2013; McCarty and Mosey 1991). In the case of high solid content, an initial hydrolysis step to convert particulate matter into soluble substrate is required to obtain efficient AD. The hydrolysis step is appreciably affected by temperature and is usually the rate-limiting step for low-temperature conditions (Xia et al. 2016; Lew et al. 2011; Zeeman 1991).

For predominantly dissolved organic waste, the rate-limiting steps are the acetogenesis and the methanogenesis as these bacteria groups have the slowest growing rates (Xia et al. 2016; Gujer and Zehnder 1983). Most of the control in anaerobic digestion is undertaken directly by the microorganisms themselves. The environmental conditions such as temperature, pH, essential trace nutrients and toxicants can play a major role in modifying reaction rates of individual sub-processes (Xia et al. 2016; Mckeown et al. 2012; Cavinato 2011). The international water association (IWA) task group for mathematical modelling of anaerobic digestion processes defined two categories of inhibition for microorganism: biocidal and biostatic inhibition. Biocidal inhibition describes the toxicity experienced by the microorganism due to normally irreversible conditions, whereas, in biostatic inhibition, the growth of the microbes ceases during exposure to inhibitory conditions, but resumes growth after re-establishment (Batstone et al. 2002). Some of the inhibition factors are discussed below.

3.1 pH

Acetoclastic methanogenesis is particularly vulnerable to low-pH conditions and quickly inhibited the process if the pH drops below 6.5 (Van Lier et al. 2008), which halts the removal of acids from the system. This happens when there is an increase in acid-producing rate (due to high organic loading rate) and decrease in acid-removing rate (decrease in buffer) causing souring (Yuan and Zhu 2016; Speece 1996).

There are three principal bacteria types involved in biogas production: bacteria responsible for hydrolysis, fermentative bacteria and methane-producing archaea. The fermentative bacteria can function in pH range from 8.5 down to pH 4 with their optimal pH range of 5.0–6.0 (Hwang et al. 2004); on the other hand, methanogenic archaea can function in pH interval from 5.5 to 8.5 with an optimal range of 6.5–8.0 (Boe 2006). pH inhibition occurs as a result of disruption of homeostasis and increase levels of non-dissociated VFA (Batstone et al. 2002). The bicarbonate produced by the methane-producing bacteria normally neutralizes the pH reduction caused by acid-producing bacteria (Liu and Tay 2004).

The greatest risk for digester failure is a result of acid accumulation which would occur if the amount of volatile solids loaded into the digester increased sharply. The acidogenic bacteria would then flourish, producing high volumes of organic acids and further lowering the pH to below 5.0 which is lethal to methanogens. pH values above 8 are toxic to most anaerobic organisms which results in the inhibition of biological functions. High pH could be due to prolific methanogenesis, resulting in a higher concentration of ammonia that would impede acidogenesis (Lusk 1999). This can now be opposed by adding a greater amount of fresh feedstock (Ostrem et al. 2004).

Systems with low potential for generating alkalinity through metabolism may necessarily add alkalinity in the form of lime (CaO), carbonate, hydroxide or bicarbonate for buffering digestion (Speece 1996).

3.2 Temperature

Anaerobic process can occur in a wide range of temperature that is psychrophilic (<20 °C), mesophilic (25–40 °C) and thermophilic (45–60 °C) (Khalid et al. 2011; Mathew et al. 2014). The anaerobic process temperature of the reactor has influence to the physical and chemical properties of the substrate which in turn affects the thermodynamic and kinetic reaction of the biological processes. There are several advantages with increasing temperatures (Abdelgadir et al. 2014; Van Lier et al. 1996), for instance, increase hydrolysed soluble product which in turn makes them more accessible for microorganism, increase reaction kinetics in both chemical and biological process that shorten the reaction time and hence the hydraulic retention time (HRT) of the reactor, and it also makes physical–chemical properties of the

soluble substrate favourable and improves diffusivity, increase liquid-to-gas transfer rate because of lower gas solubility and improve liquid–solid biomass separation (Van Lier et al. 1996). Moreover, increased temperature also increases death rate of pathogenic bacteria, reducing time required for pathogen destruction in AD process (Bendixen 1994; Smith et al. 2005). However, high temperature (thermophilic) can have negative effects as well. Increasing temperature increases the fraction of free ammonia (NH_3) that is inhibitory to microorganisms. Ammonia inhibition could result process disturbance in thermophilic process. The stability of the mesophilic process makes it more acceptable in current AD facilities, but achieved at longer retention times (Ostrem et al. 2004).

3.3 C:N Ratio

All microorganisms present in anaerobic digestion process need essential elements for their growth. One of the main nutrient elements is nitrogen that is required for the synthesis of amino acids, proteins, etc., which in turn could be converted into ammonia, a buffer compound for the neutralization of the acidification process. Thus, all feedstock should contain nutrients and essential trace elements for the efficient anaerobic digestion process. It is reported that C:N:P ratio of 100:3:1 is suitable for high methane yield (Rajeshwari et al. 2000). Significantly deviation of C:N:P ratio could lead to deficiency of buffering capacity or insufficient nutrients for microorganism growth.

3.4 Effect of Moisture Content in Feedstock

The amount of moisture content in feedstock can have influence in anaerobic digestion process and methane yield. A study on the effect of moisture content ranged from 97 to 89% on anaerobic digestion of sludge showed that the amount of methane yield was decreased from 330 to 280 mL/g-VSS (Fujishima et al. 2000). The reason behind this reduction of methane yield was the decreased in removal efficiency of carbohydrate from 71 to 28% due to decrease in moisture content in the feedstock during anaerobic digestion process (Fujishima et al. 2000). This suggests that optimum level of moisture content is necessary for AD process.

3.5 Effect of Particle Size

The particle size of feedstock has strong influence in process kinetics of anaerobic digestion process. A study on the effect of particle size increased from 1.02 to 2.14 mm on anaerobic thermophilic food waste digestion carried out by Kim et al.

in 2000 showed that a strong effect on the substrate utilization rate coefficient which is decreased from 0.0033 to 0.0015 h^{-1}. This clearly indicated that the smaller the particle size the better the kinetic process and hence methane yield.

3.6 Organic Loading Rate (OLR)

The degree of starvation of microorganisms in biological systems is dependent on the OLR. At a high OLR, a fast microbial growth (but intoxication may occur with high quantities of organic matter) takes place whereas at a low OLR microorganism starvation takes place. However, if the applied OLR is too high, microorganism could not use up all produced organic acids and causes acidic state of the digester (Liu and Tay 2004). OLR is mainly determined based on feeding materials and reactor temperature.

3.7 Solid Retention Time (SRT)

SRT is a key parameter that affects biochemical properties of organic materials. The SRT plays an important role in anaerobic digestion especially for methanogens at low operational temperatures (Halalsheh et al. 2005). The SRT should be long enough to provide sufficient methanogenic activity. Methanogenesis starts at SRT between 5 and 15 days at 25 °C and between 30 and 50 days at 15 °C (Halalsheh et al. 2005); however, it again depends on characteristics of feeding materials.

3.8 Sulphate Reduction

The effect of sulphate reduction on anaerobic systems is complicated by the fact that the reduced product sulphide has an inhibitory effect on almost all the microbial groups (Batstone et al. 2002). The methanogenic microorganism competing with sulphate-reducing microorganism for the common intermediate acetic acid, due to the presence of sufficiently high concentrations of sulphur (Speece 1996).

However, reduction of sulphate leads to an increase of pH and the buffer capacity and leaves the system with H_2S gas as shown in Eqs. (9) and (10), respectively (Arceivala and Asolekar 2007).

$$SO_4^{--} + 4H_2 \rightarrow H_2S + 2H_2O + 2OH^- \tag{9}$$

$$SO_4^{--} {}_+ CH_3COOH \rightarrow H_2S + 2HCO^{3-} \tag{10}$$

3.9 Denitrification

Denitrifying microorganisms have a higher cell growth yield per unit substrate consumed than methanogenic microorganism and compete for the same carbon source and electron source (e.g. acetate or H_2). Thus in anaerobic digestion, the presence of nitrate has significant impact in the form of microbial competition which leads to inhibition of CH_4 production. The reaction (Eq. 11) shows the overall reduction of nitrate by acetic acid to produce N_2 (Batstone et al. 2002; Foxon et al. 2006).

$$5CH_3COOH + 8NO_3^- + 8H_2 \rightarrow 4N_2 + 10CO_2 + 19H_2O \quad (11)$$

3.10 Ammonia

Nitrogen in the form of NH4-N is required by bacteria for their cell mass synthesis. The major nitrogen compound is obtained from nitrogenous materials available in organic matter usually proteins and urea. Ammonia is produced during hydrolysis of proteins and urea. Urea is readily hydrolysed to ammonia and carbon dioxide by the enzyme urease present in organic matter (Arceivala and Asolekar 2007). Urea is decomposed by bacteria via the following enzymatic catalysed reaction as shown in Eq. (12) (Fidaleo and Laveccio 2003).

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \quad (12)$$

Also, hydrolytic bacteria further hydrolyse amino acids to form ammonia, H_2, CO_2 and VFAs (Tchobanoglous et al. 2003). The release of ammonia through the decomposition of urea, hydrolysis of amino acids is the primary parameter that causes a rise in the bicarbonate-ammonia buffer (alkalinity) and controlling the pH and the process stability of the digester (Shanmugam and Horan 2008). Consequently, a dramatic pH falls below 6 as a critical value hardly occurs (Wendland 2008). Even if the formation of VFA (HAc-acetic acid) decreases the buffer capacity but the formation of NH_4^+ increases the bicarbonate concentrations and the process stabilities.

Ammonia inhibits predominantly the methanogenesis (Wendland 2008). Acetate utilizing methanogenic bacteria was found to be more sensitive to ammonia than hydrogen-consuming ones (Fotidis et al. 2013). Two different mechanisms were attributed to ammonia inhibition: firstly methanogens are directly inhibited by free ammonia, and secondly in the bacterial cell wall, free ammonia is rapidly converted to ammonium ion as shown in Eq. (13) (Kadam and Boone 1996).

$$NH_3 + H_2O \rightarrow NH_4^+ + H_2O \quad (13)$$

4 Energy Performance of AD

4.1 Methods Used

The energy performance of the anaerobic digestion is depending mainly on the biogas production technology (wet or dry technology, mesophilic or thermophilic) and geographic location (ambient temperature). The feedstock of course has also an effect because the biogas yield is varying. In addition when utilizing cultivated feedstock, the processes of obtaining the feedstock can consume significant amount of energy. Especially when utilizing wet digestion technology, the main part of the parasitic energy demand is the heat required for heating the feedstock to the desired temperature (Havukainen et al. 2014).

The energy performance of AD is difficult to calculate similarly to incineration since the lower heating value as received (LHV_{as}) can be even negative especially with feedstock coming for wet digestion. This means that the energy efficiency defined as produced energy (electricity and/or heat) divided by the fuel energy of the incoming waste would be negative. Therefore, other methods have needed to be developed to ascertain the energy performance of AD. Table 1 describes some methods which have been used in obtaining information about the different methods which have been used for energy performance calculation. These studies on energy performance include waste as well as energy crops as feedstocks and have used varying system boundaries. Energy performance has been calculated as energy output divided by energy input (Prade et al. 2012; Tanaka 2008) as well as energy input divided by energy output. However, it seems that the output/input is most commonly used method among these studies.

Energy output divided by energy input has been used for example by Berglund and Börjesson (2006). Berglund and Börjesson (2006) studied the energy performance of wet anaerobic digestion operating at mesophilic temperature of energy crops, harvest residues, manure, industrial organic waste and municipal organic waste. The input/output range was calculated by using the primary energy used for the unit processes as input and biogas energy content as output. The input/output ratios ranged from 20 to 50% being lowest for grease trap sludge and highest for ley crops. The differences were mainly due to varying properties of raw materials, system design and allocation method. The heat and electricity consumption of biogas production was responsible for approximately 40–80% of the net energy consumption. Similarly, Pöschl et al. (2010) used primary energy to calculate primary energy input output (PEIO) ratio wet digestion at mesophilic digestion in two-stage digester. The feedstocks include agricultural waste, energy crops, municipal solid waste and food industry residues. PEIO was 11–64% for single feedstock digestion and 34–55% for co-digestion.

Salter and Banks (2009) used output/input ratios for estimating energy performance of anaerobic digestion of energy crops (maize, fodder beet, lupin and

Table 1 Methods for calculating energy balance of anaerobic digestion

Method	Inputs and outputs included	Result	References
Input/output 1	Input: Primary energy for obtaining raw material, transport, operation of biogas plant Output: Biogas energy content	20–40%	Berglund and Börjesson (2006)
Input/output 2	Input: Crop cultivation, collection, transport, biogas plant operation, digestate processing Output: Energy produced from biogas	10.5–64%	
Input/output 3	Input: Production of inputs, cultivation, digestion, biogas processing and transport fuel delivery Output: Biomethane energy	22–37%	Tuomisto and Helenius (2008)
Output/input 1	Output: Methane Input: Energy for cultivation, transport, fertilizer and pesticides	7–25	Gerin et al. (2008)
Output/input 2	Output: Heat, power and biomethane Input: Crop production, transport, biogas production and upgrading	3.5–8.2	Seppälä et al. (2008)
Output/input 3	Output: Heat, power and biomethane Input: Crop production and digestion, biogas and digestate use (direct and indirect energy)	1.8–3.3	Salter and Banks (2009)
Output/input 4	Output: Heat, power and biomethane Input: Crop production and processing, reactor	4.04–6.5	Salter et al. (2005)
Output/input 5	Output: Electricity and heat Input: Cultivation, harvesting, digestion, digestate	5.5–6.8	Navickas et al. (2012)
Biomethane yield (BMY)	BMY_1 = (methane potential of input biomass − methane potential of the digestate)/methane potential of the input biomass BMY_2 = effective specific methane produced/biomethane potential of input	BMY_1 and BMY_2 84–93%	Schievano et al. (2011)
Energy efficiency	Mechanical energy of the tractor/(biogas energy + energy produced outside system, e.g. electricity, diesel)	5.8–13%	Lacour et al. (2012)
Relative biogas yield	Measured biogas yield/theoretical biogas yield	90–161%	Djatkov et al. (2012)
Total annual efficiency	(produced electricity + used heat)/biogas energy	30.5–73%	Laaber et al. (2007)
Electricity use	Parasitic electricity use/produced electricity	30.4%	Banks et al. (2011)

Modified from Havukainen et al. (2014)

perennial ryegrass) and found that ratio was 1.8–3.3 for energy crops being lowest for lupin and highest for maize. Navickas et al. (2012) also studied energy crops (fresh grass, hay and reed canary grass), and output ratio was highest for hay (6.8) and lowest for fresh grass (5.5).

4.2 System Boundary

The comparison of energy balance values in Table 1 is difficult since the system boundaries around the anaerobic digestion systems are varying a lot. The system boundary can stop to the produced biogas (Berglund and Börjesson 2006), or it can also include the energy produced from biogas (Salter et al. 2005). There are also significant differences in which energy consumptions are included. Gerin et al. (2008) excluded electricity and heat consumption of anaerobic digestion when studying energy crop biogas system, even though according to Berglund and Börjesson (2006) anaerobic digestion is the most energy-consuming process also in energy crop biogas system. In most cases, the indirect energy consumption in construction is excluded. However, at least Salter and Banks (2009) included the indirect energy use of construction and maintenance of digester and auxiliary equipment.

Comparing energy balances of different anaerobic digestion systems would require that some general system boundaries could be set. The energy performance of anaerobic digestion would be better estimated with utilizing few different system boundaries. Figure 2 presents four system boundaries which can be used in calculating the different energy performance values which can be used in following the energy performance of given anaerobic digestion system and to compare to other systems.

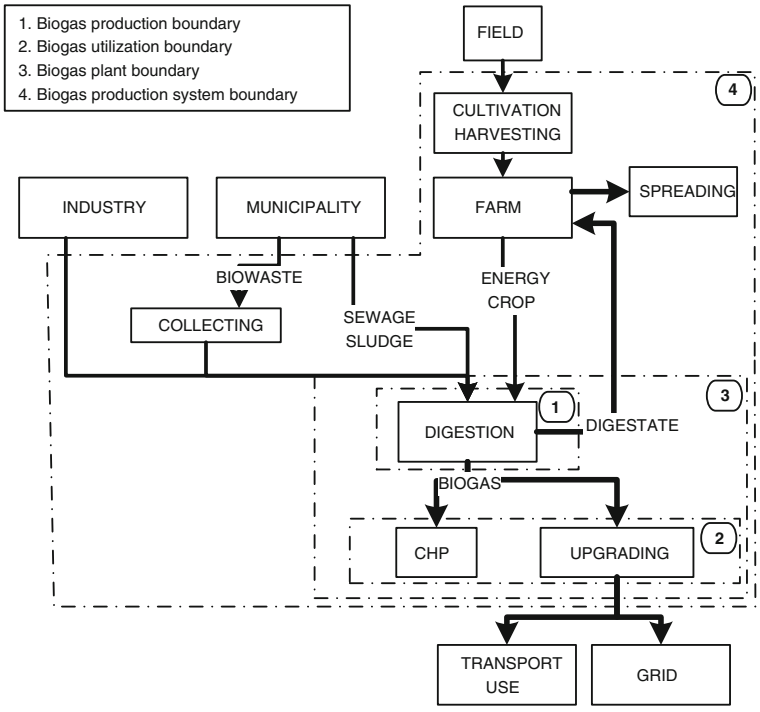

Fig. 2 Different system boundaries for estimating energy performance of anaerobic digestion system. Modified from Havukainen et al. (2014)

4.3 Output/Input Ratio Calculation

The energy performance calculation can be done on biogas production alone, utilization of produced biogas from anaerobic digestion, for the anaerobic digestion plant or for the anaerobic digestion system. Energy performance of biogas production can be calculated by Eq. (14) (Havukainen et al. 2014) utilizing the system boundary 1 in Fig. 2

$$R_{\mathrm{pr2}} = \frac{E_{\mathrm{bg}}}{E_{\mathrm{el,par}} + E_{\mathrm{h,par}}} \tag{14}$$

where E_{bg} is the energy content of the produced biogas (MWh), $E_{\mathrm{el,par}}$ is the parasitic electricity used for biogas production (MWh) and $E_{\mathrm{h,par}}$ is the parasitic heat needed in biogas production processes (MWh). The energy performance of biogas utilization can be calculated by Eq. (15) (Havukainen et al. 2014) utilizing system boundary 2 in Fig. 2.

$$R_{\mathrm{ut}} = \frac{E_{\mathrm{el,prod}} + E_{\mathrm{h,prod}} + E_{\mathrm{bm}} - E_{\mathrm{el,par,CHP}} - E_{\mathrm{el,par,up}} - E_{\mathrm{h,par,up}}}{E_{\mathrm{bg}}} \tag{15}$$

where $E_{\mathrm{el,prod}}$ is the produced electricity (MWh), $E_{\mathrm{h,prod}}$ is the produced heat (MWh), E_{bm} is the energy content of produced biomethane (MWh), $E_{\mathrm{el,par,CHP}}$ is the parasitic electricity need of the (CHP) equipment (MWh), $E_{\mathrm{el,par,up}}$ is the parasitic electricity need of the upgrading process (MWh) and $E_{\mathrm{h,par,up}}$ is the parasitic heat need of the upgrading process (MWh).

Equation (16) (Havukainen et al. 2014) can be used for calculating energy performance for the anaerobic digestion plant (R_{pl}) utilizing system boundary 3 in Fig. 2.

$$R_{\mathrm{pl}} = \frac{E_{\mathrm{h,s}} + E_{\mathrm{bm}} + E_{\mathrm{el,s}}}{E_{\mathrm{el,par,pl}} + E_{\mathrm{f}} + E_{\mathrm{h,par,pl}}} \tag{16}$$

where E_{f} is the energy content of other fuels used in the production of energy in the biogas plant, $E_{\mathrm{h,s}}$ is the heat energy supplied to processes outside the biogas plant boundary, $E_{\mathrm{el,s}}$ is the electricity supplied to the grid, $E_{\mathrm{el,par,pl}}$ is the electricity need from the electricity grid and $E_{\mathrm{h,par,pl}}$ is the heat need from outside the biogas plant.

The energy performance for the whole anaerobic digestion system (R_{sy}) can be calculated with Eq. (17) (Havukainen et al. 2014).

$$R_{\mathrm{sy}} = \frac{E_{\mathrm{h,s}} + E_{\mathrm{bm}} + E_{\mathrm{el,s}}}{E_{\mathrm{t,d}} + E_{\mathrm{t,f}s} + E_{\mathrm{ch}} + E_{\mathrm{c}} + E_{\mathrm{sd}} + E_{\mathrm{el,o}} + E_{\mathrm{f}} + E_{\mathrm{h,o}}} \tag{17}$$

where the fuel need is $E_{\mathrm{t,d}}$ for transporting the digestate (MWh), E_{sd} for spreading the digestate (MWh), $E_{\mathrm{t,fs}}$ for transporting the feedstock (MWh), E_{c} for the collection of biowaste (MWh) and E_{ch} for the cultivation and harvesting of the energy crop (MWh).

4.4 Conclusion

Anaerobic digestion process is the biochemical and physic chemical process of organic materials. In the process, there are several factors that affect the biochemical as well as physiochemical process. The most important factors are temperature, pH, OLR, C:N ratio, etc., that has to be controlled to be the adequate level for the efficient anaerobic digestion process and the methane yield. As with other energy production methods, it is also necessary to determinate the energy performance of biogas plant. The output/input ratio method which can be compared to other biogas production systems or biogas plants has been chosen for this case. Since the output/input ratio results are directly dependent on the used system boundary, the estimated system boundary has to be clearly described. After this method, to calculate energy performance of biogas plants and systems, an improvement in the production systems might be possible.

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