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Review

Operational Parameters of Biogas Plants: A Review and Evaluation Study

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Received: 28 May 2020; Accepted: 16 July 2020; Published: 22 July 2020

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Abstract: The biogas production technology has improved over the last years for the aim of reducing the costs of the process, increasing the biogas yields, and minimizing the greenhouse gas emissions. To obtain a stable and efficient biogas production, there are several design considerations and operational parameters to be taken into account. Besides, adapting the process to unanticipated conditions can be achieved by adequate monitoring of various operational parameters. This paper reviews the research that has been conducted over the last years. This review paper summarizes the developments in biogas design and operation, while highlighting the main factors that affect the efficiency of the anaerobic digestion process. The study's outcomes revealed that the optimum operational values of the main parameters may vary from one biogas plant to another. Additionally, the negative conditions that should be avoided while operating a biogas plant were identified.

Keywords: biogas plants; anaerobic digestion; plant monitoring; bioenergy; process optimization

1. Introduction

To meet the increased demand for energy needs and to reduce greenhouse gas emissions, the capacity of worldwide installed renewable energy systems has been doubled over the last decade [1–5]. This also applies to biogas as a source of renewable energy, where the number of biogas plants installed in Europe has been increased from 6227 in 2009 to reach 18,202 by the end of 2018 [6]. The total produced electricity from biogas reached 88 TWh in 2017, 40% of which was generated in Germany [4]. Hence, Germany is a leading country in this field [6]. Biogas can be utilized—after treatment—in numerous applications, like electricity and heat generation, connection to the natural gas grid, or as biofuel in vehicles [7].

Anaerobic digestion is a biological process, in which the microorganisms degrade the complex organic matter to simpler components under anaerobic conditions to produce biogas and fertilizer [6,8]. This process has many environmental benefits, such as green energy production, organic waste treatment, environmental protection, and greenhouse gas emissions reduction [2,9–13]. The biodegradation of the complex organic matter undergoes four main steps. Namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis [3].

Biogas consists mainly of CH_4 and CO_2—the share of CH_4 is determined by the type of the feedstock fed into the biogas plant [2]. The different operational conditions also have significant effects on the biogas production potentials. In order to obtain the optimum biogas production with the lowest costs, the biogas plant design has to be optimized as per the needs and potentials. The design criteria of biogas plants (explained in the following section) should be considered for their construction [3]. Additionally, several parameters have to be controlled to prevent problems causing inhibition in biogas plants (Figure 1). Temperature, pH value, retention time, and organic loading rate have a direct effect on the microbial activity. Moreover, the physical features of the feedstock can vary, and it may contain toxic substances which can influence the microbial activities [4,14].

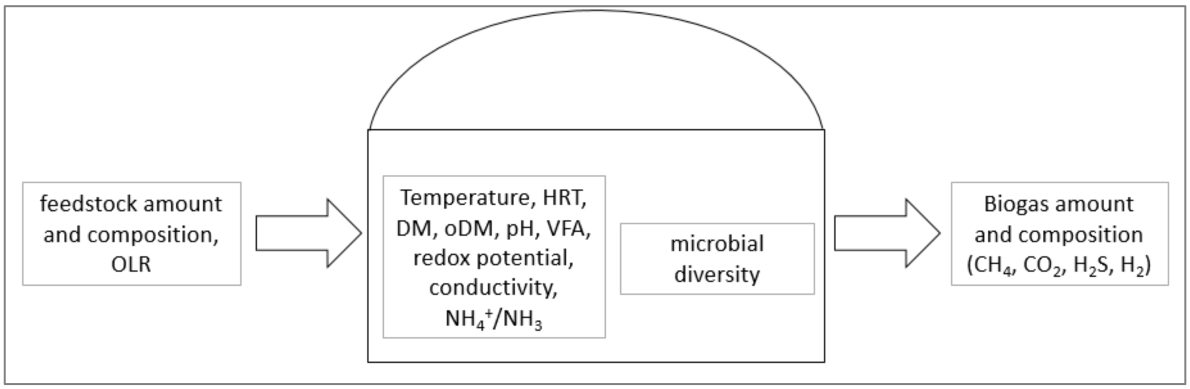

Figure 1. Operational parameters of the biogas plant. Adapted from Theurel and coauthors [9]. OLR: Organic Loading Rate, HRT: Hydraulic Retention Time, DM: Dry Matter, oDM: organic Dry Matter, VFA (Volatile Fatty Acids).

In this paper, a description of the anaerobic process that takes place in biogas plants is presented. Also, the operational conditions and the available technologies—including their advantages and disadvantages—are thoroughly discussed. Specifically, parameters defining the reactor's design, the operational conditions, and the monitoring procedures are summarized and discussed. The aim is to assess the different parameters affecting the biogas production for an optimized biogas plant design and operational conditions. The study was conducted by means of a literature review on articles, books, regulation agencies, and internet documents.

2. Reactor Design Considerations and Operational Conditions

To choose the optimum biogas reactor's design, following criteria should be considered.

- Dry matter (DM) content of the substrate: Wet digestion (DM < 12%) and dry digestion (DM > 12%)
- Mode of material feeding: Intermittent (no substrate addition during the dwell time), semi-continuous (at least once per working day) and continuous (flow)
- Number of process phases: Single-phase (all steps take place in the same reactor) and two-phase (hydrolysis and methanogenesis take place in separate reactors)
- Process temperature: Psychrophilic (<25 °C), mesophilic (37 to 42 °C) and thermophilic (50 to 60 °C) [3].

2.1. Substrates

In Europe, the biogas is mainly produced by the anaerobic digestion of agricultural residuals, manure, and energy crops. Additionally, the sludge of wastewater treatment plants, organic fraction of the municipal solid waste, or solid waste buried in landfills are possible feedstock sources [10,13,15]. The anaerobic digestion is an efficient method to treat the organic fraction of the municipal solid waste for energy production while mitigating the greenhouse emissions [16–18]. The anaerobic digestion of food waste is more sensitive than that of agricultural waste, where the volatile fatty acids (VFA) are rapidly produced in the initial stage, negatively affecting the anaerobic digestion process [19–21]. Generally, the fermentation technology depends on the utilized substrate [11]. When the biodegradable substrate has a dry matter content of ≤12% (in some research, 15%), then the wet fermentation process is conducted. Otherwise, the dry fermentation process is used. Around 90% of the biogas plants in Germany operate under wet fermentation conditions [3,12]. Figure 2 summarizes the mass fraction of substrates that are utilized in the biogas plants in Europe according to a study done by Scarlat and coauthors [22]. As shown in Figure 2, the highest share of the utilized feedstock in Europe is represented by energy crops, agricultural waste, and organic waste. In some European countries (e.g., France, Norway, Portugal, Spain, and the UK), the landfill gas signifies a tangible share of the utilized feedstock [22,23].

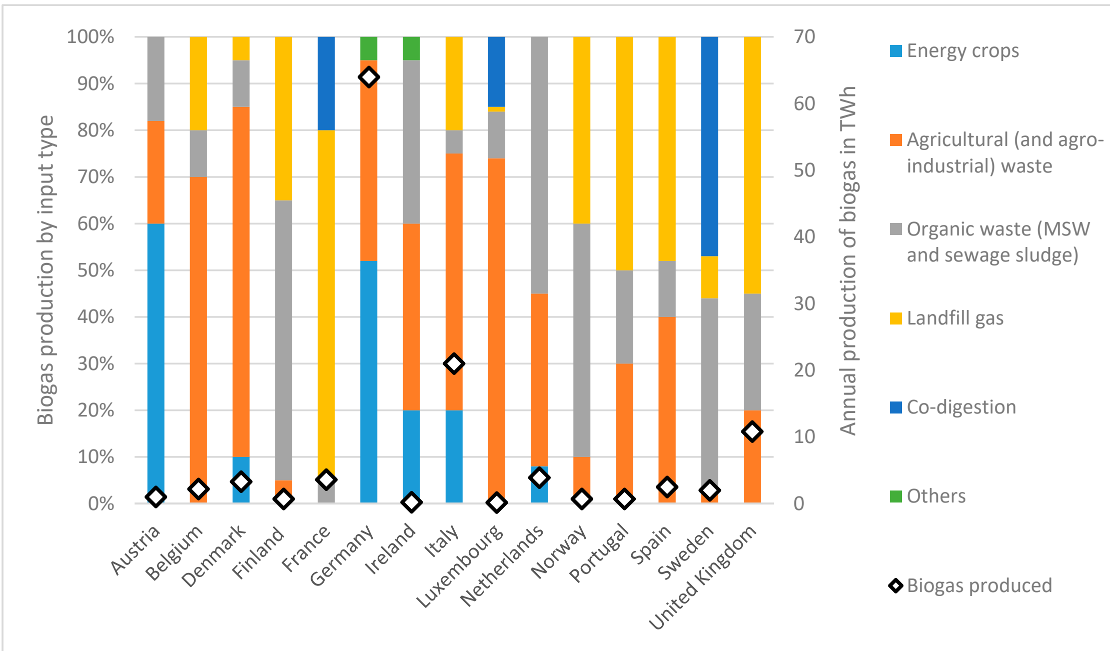

Figure 2. Mass fraction (wt.%) of utilized substrates in Europe. The white boxes represent the total annual biogas production in TWh [22,23].

The feedstock quantity and composition can affect the anaerobic digestion process as follows:

- The stirring technology is dependent on the dry matter content and the viscosity of the biodegradable feedstock [24,25].
- The feedstock's composition determines the content of the volatile solids as well as the ammonia concentration inside the reactor [26].
- Based on the feedstock quality and quantity, sedimentation and floating layers could be obtained [27,28]. The high amount of impurities in the substrates leads to sedimentation. The size of the substrate and its biodegradability are factors which determine sedimentation potentials. The floating layers can be created by the surfactants.
- The anaerobic digestion stability is dependent on the feedstock, because of their different chemical and physical properties. Therefore, suitable feeding is required to ensure the anaerobic digestion process [29].
- The technology used for the anaerobic digestion, as well as the digester's size and shape, are defined by the feedstock's properties, e.g., DM, oDM, biogas formation potentials, as well as carbon to nitrogen

ration (C:N ratio) [30]. Table 1 summarizes the main agricultural substrates that are globally utilized and their main properties.

Table 1. Main types of agricultural substrates utilized by the biogas plants worldwide. FM: Fresh Matter. NL: normal liter, FM: fresh matter, t: ton.

Substrate	DM %	oDM % (In DM)	Biogas Yield NL kg^{-1} FM	Methane Content NL kg^{-1} FM	Electricity Produced kWh t^{-1} FM	References
Pig slurry	4–19	73–86	20–35	10–21	40–71	[3,31,32]
Cattle slurry	6–11	75–82	20–30	11–19	40–61	[3]
Cattle manure	20–25	68–76	60–120	33–36	112–257	[3,26]
Poultry manure	34–50	60–75	130–270	70–140	257–551	[3,33]
Maize silage	28–39	85–98	170–230	68–120	347–469	[3,26,31,33,34]
Grass silage	15–50	70–95	102–200	46–109	208–408	[3,26,31,33]
Sugar beets	13–23	84–90	120–140	65–113	245–286	[3,26,34]
Olive pomace	57–90	55–86	92–147	65–104	188–300	[35]
Wheat straw	91–94	87–92		135–237	146–266	[36,37]
Corn (corn stover)	66–89	83–99		261–402	293–451	[33,34,38]
Rye	62–93	84–87	130	70	265	[33,34]

Using a mixture of different substrates enhances the content of nutrients, supplements, and phosphorus, while providing a balanced C:N ratio [35,39]. The increase in the C:N ratio results in a rapid consumption of the nitrogen before carbon digestion. Hence, methane potential drops [35,40]. However, the decrease in the C:N ratio leads to microorganisms' inhibition, as a result of ammonium accumulation [35]. The literature showed varying optimum C:N ratios for different substrates. The majority reported that the optimum C:N ratio is within the range of 20–30:1 for different substrates and different temperature conditions [41–47]. However, Guarino and coauthors [48] suggested a broader range of 9–50:1. Substrate biodegradability is another factor that affects the kinetics of the biodegradation process and consequently, the size of the digester [49].

2.2. Process Phases

The biogas plants can be operated in a single-stage mode or two-stage (multi-stage) anaerobic systems [50,51]. The decision of operating the biogas plant under single- or multi-stage systems can be made after evaluating the advantages and disadvantages of each choice. The decision criteria on the operational mode of the biogas plant are summarized below (Figure 3).

- Cost: the installation and maintenance of the multi-stage system are more expensive than that for the one-stage system [51].
- Operational conditions: the optimal operation conditions (e.g., temperature and pH) for the microorganisms in the multi-stage systems are more demanding than that for single-stage systems, since the operational parameters in the different stages are diverse. On the other hand, due to the separation of the phases, there is a better process control.
- The stability of the anaerobic digestion process is improved through using the multi-stage systems. The methanogenesis step is very sensitive to the changes in the organic load rate, the heterogeneity of the biodegradable feedstock, and the changes in the environmental conditions. Hence, the multi-stage is more advantageous than the single-stage system, where the control of these conditions is more efficient, and the flow of the biodegradable feedstock from the first digester to the others is more homogeneous in quantity and quality [51–57].
- The multi-stage systems have higher performance than single-stage systems in terms of the removal efficiency of the volatile solids and improving the biogas quality (methane content) [51,52,54,56,58–61].

- The single-stage systems are still the most used due to their simplicity [10].

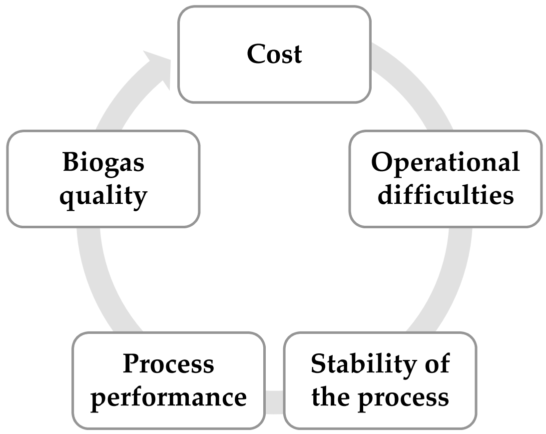

Figure 3. Decision-making criteria for selecting the mode of biogas plant operation under single- or multi-stage systems.

2.3. Process Temperature

Temperature is a significant parameter inside the reactor, which has a direct effect on the microbial performance. Biogas plants can be operated under psychrophilic (<25 °C), mesophilic (32 to 42 °C), or thermophilic (50 to 57 °C) conditions, defined based on the microorganism group used in the process [62]. Among all types, methanogens are defined as the most sensitive microorganisms to environmental conditions [63]. There is not a clear discrimination between the species living at different temperature ranges and the highest number of species within their optimum is observed under mesophilic conditions at 37 °C [64].

Not only the microorganisms but also reaction kinetics are affected by the temperature inside the reactor [65]. In the range of optimum temperatures, increasing the temperature leads to an increase in the enzymatic activities. Nevertheless, surpassing these defined optimum temperatures may lead to inhibition of enzymatic reactions. 37 °C is the optimum temperature for most of the mesophilic enzymes [64,66,67]. According to Streitwieser [68], the thermophilic range is a better option for easily degradable substrates, which leads to an increase in biogas production as well as an increase in the reaction rates. Besides, shorter start-up time is needed for the new operating biogas plants at thermophilic conditions [69–71]. To supply stable biogas production, the temperature should be maintained stable [72].

Several studies examined the effect of temperature changes, including both stepwise and abrupt changes. Wu and coauthors [73] studied the effects of sudden temperature decreases in lab-scale reactors to simulate the possible heating failures. Decreasing the temperature from 55 to 20 °C for 1, 5, 12, and 24 h in different reactors almost stopped the biogas production, which could be recovered after adjusting the temperature back to 55 °C. Other studies were conducted to examine the effect of abrupt temperature changes in thermophilic temperature conditions. The results showed that the recovery with daily temperature fluctuations under thermophilic conditions (below 60 °C) can be attained, however, temperatures above 60 °C have an adverse impact on hydrolysis and acidogenesis stages due to the high ammonia concentrations generated in the process [74–76]. The process microbiology was examined by Pap and coauthors [77], who observed the replacement of acetolastic methanogens by hydrogenotrophic archaea after changing the temperature conditions from mesophilic to thermophilic. Similar studies, conducted under mesophilic conditions, examined temperature fluctuation in the mesophilic conditions (35 to 30 °C, after 170 h to 32 °C) [78]. Recovery of the process was possible after 40 h. While a lower number of methanogenic archaea is observed at high temperatures, acidogenic bacteria are less affected by temperature changes [74,79].

On the other hand, stepwise temperature changes were examined to obtain a stable process in spite of the temperature fluctuations. The temperature change from 37 to 55 °C in 41 days was studied by Bousková and coauthors [80]. Results showed that 70 days was sufficient for process recovery. Thermophilic bacteria, which already exists in the mesophilic inoculum, can become a dominant group in the thermophilic conditions [81].

According to several studies reviewed, it was concluded that temperature fluctuations (i.e., more than ±3 °C d (day)$^{-1}$ under mesophilic conditions and more than ±1 °C d^{-1} under thermophilic conditions) should be avoided [82–86].

2.4. Mixing

The stirring (mixing) system inside the biogas plants has significant importance on the anaerobic process [87]. The core responsibilities of the stirring system are:

- Ensure the homogeneity of biodegradable substrates, temperature, and pH value inside the digester by mixing the fresh substrates with the existing one [26,27,88–90].
- Enhance the metabolism of the microorganisms and enhance the anaerobic process stability. Moreover, the mixing assists the gas-bubbles to flow upwards from the biodegradable feedstock at high total solids values [26,91,92].
- Reduce the creation of sediments on the bottom of the digesters to ensure the highest available volume for the anaerobic digestion process and reduce the need to clean the digester (on average, it is once every 4 to 7 years) [93].
- Break the foam layer on the top of the biodegradable substrate. The creation of this layer can inhibit 20% to 50% of the biogas production [94]. "Foam is generally a dispersion of a gas in a liquid consisting of a large proportion (approximately 95%) of gas. The liquid phase is located in a thin film which is present between the gas bubbles" [28,94]. Two groups of surface-active compounds are considered to be in charge of the foam formation, which are the surfactants and bio-surfactants. The surfactants are compounds inflowing the digester with the feeding, while the bio-surfactants are considered to be the outcomes of the activities of the microorganisms [27,28]. These foam layers have to be destroyed because their formation leads to a drop in the biogas yield, high-cost losses, and equipment damage, as well as operational disturbances [27,28,95–97].

Choosing the most suitable mixing technology relies on the conditions and requirements such as the value of the total solids of the biodegradable feedstock, the type of the used feedstock, the hydraulic retention time, and the size of the digester. Biogas plants operate with or without mixing, defined by the digester's structural concept: complete mix, plug flow, or batch concept [29]. The complete mix digesters are mainly used for biogas plants with biodegradable substrates with total solid values in the range of 2% to 10%, while plug-flow digesters are suitable for the range of 11% to 13% [98]. The completely mixed concept is a widely applied type in Germany. The complete mix concept contains a gas tight cover to collect the formed biogas inside a vertical cylindrical digester, which has walls from concrete, steel, or reinforced concrete [3]. The necessity of using a mixing system inside the digesters increases with increasing the total solid values of the biodegradable substrate [88–90].

The major mixing technologies used in the large-scale biogas plants are mechanical, pneumatic, and hydraulic mixing technologies [99]. The pneumatic (gas-lift) mixing is dependent on the formed biogas itself to move the biodegradable substrate [100]. The three types of pneumatic mixing are: The free gas-lift, the limited gas release from the bottom of the digester, and the creation of piston pumping by the use of big bubbles [101]. The main advantage of this mixing technology is the absence of any moving parts inside the digesters. This leads to a maximum utilization of the digester's volume for the biodegradable substrates. Additionally, it decreases the complexity and cost of maintenance [86,100]. The main disadvantage of this mixing technology is the inability to mix in the entire digester, especially near the bottom and the top. This results in sediments formation, and disability to break the floating layers. The poorly mixed zone might cover up to one-third of the digester [86,100–102].

The hydraulic mixing needs pumps (mainly airlift pumps) to mix the biodegradable substrates inside the digesters [26,100]. This technology has the advantage of installing the mixing components outside of the digesters. The main disadvantage of this technology that it is only suitable for small-scale digesters. Otherwise, sediments, floating layers, and poorly mixed zones will be obtained [3].

The dominant technology used in Germany is the mechanical mixing [91]. Different types of stirrers can be installed: submersible, long-axis, axial, and paddle stirrers [3]. The digester's form and size as well the used substrates are the main parameters used to choose the most suitable technology [3,103,104]. The previously mentioned mechanical stirrers vary, mainly according to their impeller velocities and sizes as well as the power consumption [91]. In the case of high viscosity of the biodegradable substrate (the total dry matter content is high as well), slow and large impellers (stirrers) are used. Yet, for low viscosities, the most suitable stirrers are the small and fast ones [33].

The researchers have been trying to discover the optimum stirring system and conditions in the anaerobic digesters for a long time. In 1982, the research of Hashimoto [105] focused on evaluating the stirring period inside the digesters. He found that stirring for only 2 h per day is more efficient than continuously stirring under laboratory thermophilic conditions. The results, however, showed similarities in the amount of biogas formed for the two different stirring conditions in pilot-scale anaerobic digesters. Table 2 summarizes the findings of different studies in the field of mixing inside the digesters.

On the basis of the information presented in Table 2, the optimal stirring inside the digester depends on several factors, as follows:

- The size of the digester,
- The operating temperature inside the digesters,
- The used mixing technology,
- The used feedstock and the DM value of the biodegradable feedstock.

Table 2. Findings of various studies conducted on the mixing characteristics of various biogas plants. 0: reference value (or no changes in the anaerobic process), +: improvement in the anaerobic process, −: worsening the anaerobic process, X: dependent on the stirring intensity, COD: chemical oxygen demand, MSW: municipal solid waste.

Scale of The Plant	Substrate	Stirring Period Daily (h)				Stirring Intensity		Temperature (°C)	Remarks	References
		0	1–8	9–23	24	High	Low			
A	Beef cattle waste		0		–			55		[105]
B	Beef cattle waste		0		0			55		[105]
A	Castor cake	0	+		+			30	Loading rates 4 and 8 g L^{-1} d^{-1}	[106]
A	Castor cake	0	–		–			37	Loading rates 4 and 12 g L^{-1} d^{-1}	[106]
A	Castor cake	0	+		+			37	Loading rate 8 g L^{-1} d^{-1}	[106]
B	Refuse-derived fuel and primary sludge	0			–			35		[107]
A	Water hyacinth and cattle dung	0	+		–			37		[108]
A	Unmodified olive mill wastewater	0		–		–	0	35		[109]
A	Fermented olive mill wastewater	0		0		0	0	35		[109]
A	Sewage sludge	0			–			28	Loading rates 2.4, 4.8, and 7.2 g COD L^{-1} d^{-1}	[110]
B	Animal manure	0			+			35		[111]
A	Dog food	0			–			35 & 55	Batch fed	[112]
A	Manure slurry	0			+			35		[88]
A	Animal waste	0			–	–	0	35	Biogas recirculation, low DM values	[89]
A	Cow manure	+	0		–			55		[113]
B	Cow manure		X		0	0	+	54		[113]
A	Lipid-rich waste	0			+			37	Batch reactor	[114]
A	Corn silage	0			+			37	Continuous reactor	[114]
A	Rice straw					+	0	35		[115]
A	Manure and MSW	0			+			55		[116]
B	Natural water, cow dung, rice straw and water hyacinth	0			+			31		[117]
A	MSW	0			X	–	+	33		[118]
C	Cow dung		X			+	–	27	Optimum mixing was for 3 h daily with 60 rpm	[119]
B	Cow manure and maize straw	0			X	–	+		Different DM and C:N ratios	[120]
A	Cow manure and vegetable waste	0	+							[121]
A	Cattle manure, tea waste	0			+			37		[122]
A	Municipal solid waste	–	+				0	34		[123]

2.5. The Energetic Potential of the Biogas Plants

The energetic potential of the biogas plants depends mainly on the operational parameters mentioned in the previous sections. In Table 1, the biogas formation potential for the primary agricultural substrates was presented. These values indicate the amount of biomehtane/biogas produced per one gram of fresh substrate. It is worth mentioning that the biogas has an average low calorific value (LCV) of 10 MJ kg^{-1} [124], and an average high calorific value (NCV) of 20–21 MJ kg^{-1} at methane content of 55% [75,125,126], where the methane has an NCV of 50 MJ kg^{-1} [127]. Table 1 adapts the calculation method used by Achinas and coauthors [126] in their research to estimate the electricity produced from fresh material (estimating 35% electrical efficiency combined heat power, heating value of 21 MJ m^{-3}, 55% methane content, 3.6 MJ $(kWh)^{-1}$). To evaluate the energy efficiency of the biogas plants, the researchers used different approaches, including or excluding the energy used for the cultivation, transport, and treatment of the substrates in the calculations. The internal electricity consumption of the biogas plants varies on average in the range of 4.9–9.3% [33,128]. The main sources of the electricity consumption are the stirring system, the feeding system, the combined heat and power unit, and the heating system. To optimize the electricity efficiency, researchers improved the stirring system (Table 2), others considered the temperature inside the digesters (Table 2), and others optimized the energy production unit. Further researchers were able to optimize the biogas yield through optimizing the mixing ratio of the substrates, the environmental conditions for the microorganisms, as well as the monitoring system.

3. The Conditions Inside the Reactor

3.1. Oxygen

Strictly anaerobic microorganism groups of acetogens and methanogens can be affected by an oxygen leak in the reactor, which can lead to inhibition [129]. On the other hand, micro-aeration can improve the efficiency of the hydrolysis step in the anaerobic digestion process [130–132]. Moreover, a micro oxygen injection to 50 L anaerobic digestion reactors provided a decrease in the H_2S concentration in the biogas (from 6000 to 30 ppm) [132]. Both experimental and simulation results of the study conducted by Botheju and coauthors [129] showed that an increase in the oxygen loads causes a decrease in the methane potential. More than 0.1 mg L^{-1} of oxygen concentration has caused inhibition of obligate anaerobic methanogenic archaea [3].

3.2. PH

There are various kinds of microbial groups taking part in the anaerobic digestion process, which have diverse optimum pH values for their optimal growth rates. For example, a pH range of 5.0 to 6.0 is suitable for acidogens, while pH from 6.5 to 8.0 is more convenient for the methanogens group [133]. The combined effect of pH and temperature were studied on the anaerobic digestion of grass silage by Sibiya and Muzenda [134]. Results showed that the highest efficiency was achieved at 45 °C and a pH value of 6.5. Usually, the biogas plants operate within a pH range of 6.5 to 8.4 [135,136]. Mpofu and coauthors [137] summarized the optimum temperatures and pH values for many acetogenic and methanogenic bacteria. The pH value is highly dependent on the VFAs, the ammonium content, and the alkalinity concentrations. The increase of the VFAs leads to a drop in the pH value. On the other hand, an increase in the alkalinity sources causes an increase in pH [33,62,138–143].

3.3. Dry Matter Content of the Biodegradable Feedstock

The total solids or dry matter content of the biodegradable substrate is highly connected to the feedstock. As mentioned earlier, these values play a crucial role in determining the fermentation technology (dry or wet fermentation), the digester or reactor design, as well as the stirring technology.

- The researchers consider that the wet fermentation process occurs at dry matter content of less than 15%, while the dry fermentation takes place at higher DM values.
- The mixing inside the digesters (technology as well as duration) is highly dependent on the dry matter content, as mentioned in Section 2.4. The dry matter content of the biodegradable feedstock is a critical factor in controlling the Bingham viscosity and the yield stress [144].
- The biogas formation potential might be dependent on the dry matter content of the biodegradable feedstock [145,146]

Most large-scale biogas plants operate in wet fermentation conditions, where the dry matter content is less than 12%. By the end of 2019, the worldwide cumulative installed biogas plants had the capacity of 19.5 TW_{el} [147,148]. The majority of the biogas plants are still adopting wet fermentation technology [149].

3.4. Organic Loading Rate (OLR)

Obtaining optimum biogas production with reasonable cost cannot be achieved without a well-planned organic loading rate (OLR). OLR represents the number of volatile solids fed per unit volume of digester per unit of time, as described in Equation (1) [3]:

$$OLR = \frac{m * c}{V_R * 100} \left(kg\ oDM\ m^{-3}\ d^{-1}\right) \tag{1}$$

where m is the amount of substrate fed in a unit of time (kg d^{-1}), c is the concentration of organic dry matter (% oDM), and V_R is the reactor's volume (m^3).

Keeping the OLR low can cause a decrease in the biogas production efficiency. On the other hand, a high organic loading rate can be a reason for process inhibition [150,151]. In order to obtain the optimum conditions for the specific biogas plant, OLR should be determined based on the feed substrate [152]. According to a study conducted by González-Fernández and coauthors [153], increasing the OLR of microalgae from 1.0 kg tCOD (total chemical oxygen demand) m^{-3} d^{-1} to 2.5 kg tCOD m^{-3} d^{-1} did not result in process inhibition, yet it provided higher methane production. Zuo and coauthors [154] studied two-stage anaerobic digestion of vegetable waste in lab-scale reactors. Increasing the OLR improved the methane content of the biogas. In order to prevent process inhibition at high OLR operation, implementing recirculation of biodegradable feedstock—which dilutes the biodegradable feedstock and supplies pH adjustment—can be a suitable solution. Overall, OLR is an essential parameter for designing the process, but increasing the OLR can cause an accumulation in the VFAs, resulting in process interruption [150,155]. Findings of the conducted studies that dealt with the effect of OLR on the anaerobic digestion process efficiency are summarized in Table 3.

Table 3. Studies performed to evaluate the effect of organic loading rate (OLR) on the anaerobic digestion process efficiency. CSTR: continuous stirred tank reactor, semi-CSTR: semi-continuous stirred tank reactor.

OLR ($kg\ m^{-3}\ d^{-1}$)	Stable/Optimum OLR	Reactor Type	Temperature	Substrate	Reference
1.0, 2.0, 3.0 and 4.0	3 kg m^{-3} d^{-1}	CSTR, Semi-CSTR, 8 L	35 °C	Maize, rye, fodder beets	[156]
1.0 and 2.5 (COD)	1 kg COD m^{-3} d^{-1}	CSTR, 1 L	35 °C	Thermally pretreated microalgae	[153]
1.8 to 4.0 (oDM)	2 kg oDM m^{-3} d^{-1}	CSTR, 4 L	35 °C	Animal by-products from the meat processing industry	[157]
Ranged from 1.2 to 8.0 (oDM)	8 kg oDM [76] m^{-3} d^{-1}	CSTR, 1.6 m^3	35 ± 2 °C	Municipal biomass waste and waste-activated sludge	[155]
3.0, 3.6, 4.2, 4.8, 6.0, 8.0, and 12.0 (oDM)	6–8 kg oDM m^{-3} d^{-1}	CSTR, 40 L	37 ± 2 °C	Rice straw and pig manure	[150]
Ranged from 4.2 to 12.8 (oDM)	1.12 g oDM L^{-1} d^{-1}	Semi-CSTR, 10 L	37 ± 0.5 °C	Dried pellets of exhausted sugar beet cossettes and pig manure	[145]
1.22, 1.46, 1.70, and 2.0 (oDM)	<2.00 kg oDM substrate.m^{-3} d^{-1}	Completely mixed bioreactor, 300 m^3	39 ± 1 °C	Rice straw	[158]
3.7 to 12.9 (oDM)	9.2 kg oDM m^{-3} d^{-1}	Semi-CSTR, 3000 mL	37 ± 1 °C	Food waste	[159]
Ranged from 0 to 10.0 (oDM)		CSTR, 5 L	37 ± 0.5 °C	Food waste	[160]

3.5. Hydraulic Retention Time (HRT)

Hydraulic retention time (HRT) is one of the determining parameters for the volume of the digester, which defines the remaining time of the feedstock until it is discharged (Equation (2)) [3].

$$\mathrm{HRT} = \frac{V_R}{V} \quad (\mathrm{d}) \tag{2}$$

where V_R is the reactor volume (m^3), and V is the substrate volumetric feed rate in the reactor, daily ($m^3\ d^{-1}$).

Optimum biogas production can be obtained at different HRT's, depending on the used substrate [161]. Various HRTs were assessed by literature to find the optimum values for the different substrates. The adopted HRT varied from 0.75 to 60.00 days. The optimum HRT was suggested to be in the range of 16 to 60 days [162–167]. In order to prevent washouts of microorganisms required for the process, HRT should not be less than 10 to 25 days [166]. Kaosol and Sohgrathok [163] used seafood wastewater as anaerobic co-digestion material at different HRTs (10, 20, and 30). The maximum methane production was observed with the implementation of HRT of 20 days. HRT has fluctuated between 7.9 to 37.3 days during the study conducted by Krakat and coauthors [168], using 5.7 L lab-scale reactors. Decreasing the HRT leads to an increase in the number of species in the reactor and a slight increase in the CH_4 content. Schmidt and coauthors [166] studied the reduction of HRT from 6.0 to 1.5 days at three different reactor systems. The fastest inhibition was observed in the anaerobic sequencing batch reactor at an HRT of 3.0 days, and it was followed by a continuously stirred tank with HRT of 2.0 days. The experiment conducted using a fixed bed reactor was stable until the end of the experiment. Nevertheless, decreasing HRT resulted in a decrease in the specific biogas production.

3.6. Nutrients

The nutrients, which supply stability of microorganisms taking part in the anaerobic digestion process, can be classified under two categories: Micronutrients and macronutrients. Macronutrient ratio, carbon to nitrogen to phosphorus to sulfur ratio (C:N:P:S) = 600:15:5:1, is suitable to obtain a sustainable process [26]. The processes, where macronutrients are consumed, can be listed as follows:

- Carbon: For building cells' structure.
- Nitrogen: For protein biosynthesis.
- Sulfur: For the growth of methanogens and component of amino acids.
- Phosphate: To create energy carriers in the metabolism [169,170].

In addition to macronutrients, micronutrients such as iron, nickel, cobalt, selenium, molybdenum, and tungsten are needed in the process for microbial growth and should be added as supplemental nutrients to the process, in case the feedstock has a deficiency in such nutrients [26,171]. Conversely, the excess amount of trace elements can lead to inhibition of the process [171,172].

3.7. Process Inhibitors

According to Chen and coauthors [173], the main inhibitors of the anaerobic digestion process are the ammonia, sulfide, organics, and light and heavy metals.

3.7.1. Ammonia

The optimum concentration of the ammonia (as well the ammonium ion) inside the digesters has a critical role in the stability of the anaerobic digestion process. The optimal ammonia concentration increases the stability process through ensuring adequate buffer capacity of the methanogenic medium. It is worth mentioning that the ammonia is considered to be an end product of the biological degradation of the nitrogenous part of the substrates, such as the proteins and the urea [173,174]. The microorganisms need the ammonia as a nutrient for their metabolisms [175].

Nonetheless, high ammonia concentration is considered to be an inhibitor to the anaerobic digestion process and to the microbial activity inside the digesters [173–175]. Researchers have been trying to find the optimum total ammonia-nitrogen concentration (TAN) in the anaerobic digestion process, and their inhibitory levels. Chen and coauthors [173] summarized the results of other research mentioning that concentrations lower than 200 mg L^{-1} are beneficial for the anaerobic digestion. However, the TAN concentrations 1.7 to 14.0 mg L^{-1} can cause a drop in the methane formation. The decrease in efficiency can reach up to 50%, depending on the substrates, inoculum, and environmental conditions.

3.7.2. Sulfide

Sulfide is considered as one of the inorganic inhibitors of the anaerobic digestion process [176]. The sulfide is typically an output of the sulfate-producing bacterial (SRB) activities. These bacteria are responsible for: (I) sulfides generation, which may cause inhibition of SRB or methane-producing bacteria, (II) alkalinity sources, causing a change in the pH value, (III) accelerating the oxidation of the organics, (IV) reducing the efficiency of the methanogenesis process, and (V) decreasing the methane formation [177].

3.7.3. Light and Heavy Metals

The primary light metals influencing the anaerobic digestion process are sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), and aluminum (Al) [173]. These metals are required in the process for the microbial growth, enhancement of the bacterial cell immobilization (Ca), and formation of adenosine phosphate (Na^+) [178–181]. However, the concentrations of these light metals should be controlled where: Mg^{2+} is responsible for limiting the production of double cells [178], K^+ is in charge of neutralizing the cell membrane potential [173], Na^+ can inhibit the acetoclastic methanogens [178], Ca^{2+} is accountable for the destabilization of the buffering system through precipitation of phosphates and carbonates [180], and finally, Al^{3+} is considered as an inhibitor of the anaerobic process—it can also compete with the adsorption of other metals [182].

The heavy metals affecting the anaerobic digestion are mainly iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), cobalt (Co), molybdenum (Mo), chromium (Cr), cadmium (Cd), lead (Pb), and mercury (Hg) [173,178]. Metals with inhibitory effects on the anaerobic digestion process are summarized in Table 4 together with their inhibitory concentrations. Generally, the inhibitory and optimum metals concentrations can vary for different temperature conditions of the digesters.

Table 4. Metal concentration in the feedstock. Adapted from References [183–187].

Metal	Inhibitory Concentration in mg L^{-1}	Positive Concentration in mg L^{-1}	Reference
Aluminum	1000–2500		[188]
Cadmium	36–3400	0.1–0.3	[189–193]
Calcium	300–8000	100–1035	[173,188,194–196]
Chromium	27–2500	0.1–15	[191–193,197]
Cobalt	35–950	0.03–19	[197–202]
Copper	12.5–1000	0–10	[190,191,193,197,201,203]
Iron		0.3–4000	[189,202]
Lead	67.2–8000	0.2	[191,196,204]
Magnesium	750–4000	0–720	[183,188]
Mercury	125		
Molybdenum	1000	0–0.1	[202,205]
Nickel	35–1600	0.03–27	[191,193,198–201]
Potassium	400–28,934	0–400	[188,196,206]
Sodium	3000–16,000	100–350	[188,206,207]
Zinc	5–1500	0–5	[189,191,193,198,201,202]

3.7.4. Organics

The anaerobic digestion process can be inhibited by the poorly soluble organic compounds, or by the organic compounds that can be adsorbed to the surface of the biodegradable feedstock [173]. The following organic compounds are already listed to be toxic to the anaerobic digestion process [173,208]: alkylbenzenes, halogenated benzenes, nitro benzenes, phenol, alkylphenols, nitrophenols, halogenated phenols, alcohols, halogenated alcohols, alkanes, halogenated aliphatics, aldehydes, ethers, ketones, acrylates, carboxylic acids, amines, nitriles, amides, pyridine and its derivatives, as well as long-chain fatty acids [209–234].

3.7.5. Secondary Metabolites

Anaerobic digestion can be considered as a suitable treatment of food waste for biogas production, due to their high moisture and organic content. Plants contain components, such as flavor substances, which may affect the digestion process [235]. The plants' secondary metabolites are classified into carotenoids, terpenes, phenolics, alkaloids, and glucosinolates. Terpenes are one of the largest groups, with more than 30,000 compounds synthesized in a myriad of plants [236]. In a study done by Wikandari and coauthors [228], fruit flavor compounds including hexanal, α-Pinene, Car-3-ene, Nonanal, E-2-hexenal, myrcene, and octanol were found to be inhibiting the methane production. The results of this work stress that all the tested terpenoids are inhibiting the anaerobic bacteria. Generally, the type of inhibition is depending on the concentration of inhibitory substances entering the biogas digester [236].

4. Monitoring of the Operational Conditions in Biogas Plants

As mentioned before, the anaerobic digestion process includes four stages that come in sequence, where different kinds of microorganisms take part at each stage. In order to obtain a stable and efficient process, process monitoring is necessary [4,62,237]. Monitoring enables early detection of problems and disturbances and indicates the required adjustments to the operational parameters (to be within acceptable ranges).

In general, monitoring parameters of the biogas plants can be classified under three categories: parameters characterizing the process (feedstock type and quantity, biogas production amount and its quality, reactor temperature, dry matter concentration, ammonia concentration, and pH), parameters supplying early detection of instability (VFA, alkalinity, hydrogen concentration, redox potential, and other complex monitoring parameters), and variable process parameters defined by plant operators (OLR and HRT) [62].

The monitoring of the biogas plant's operational parameters can be achieved by on-line, at-line, and off-line analyzers. There is an increased interest in the on-line monitoring applications, due to the fast and automated process control. There are several parameters that can be monitored at the biogas plant on a real-time basis. The frequently on-line-monitored parameters in biogas plants are summarized in Table 5.

Table 5. Studies conducted on biogas plants' operational parameters and their monitoring methods.

Parameter	Measurement Method	Reference
Cobalt concentration in the high presence of iron concentrations	Total reflection X-ray fluorescence spectroscopy	[238]
VOCs (volatile organic compounds) emitted from different units of food waste anaerobic digestion plant	Portable GC-MS (gas chromatography–mass spectroscopy)	[239]
CH_4 emissions from pressure relief valves of an agricultural biogas plant	Flow velocity and temperature sensors	[240]
Ammonia in biogas	Impedance measurement of biogas condensate in the gas room above the digester	[241]
Dissolved active trace elements in biogas	Total reflection X-ray fluorescence spectroscopy in dried digester slurry	[238]
H_2S in biogas	Gas responsive nano-switch (copper oxide composite)	[242]
Microbial communities depend on the substrate combinations	Sequencing of the 16S rRNA, biodegradable feedstock samples from eight different biogas plants	[243]
Controlling gas pressure in the digester	Programmable logic controller (PCL)	[244]
Ammonia in biomethane	Luminescent ammonia sensor based on an imidazole-containing Ru(II) polypyridyl complex immobilized on silica microspheres	[183]
pH, temperature, oxidation-reduction potential (ORP)	via electrodes, on-line monitoring with PCL	[245]
CO_2, CH_4, H_2O	On-line monitoring with a Supercontinuum laser-based off-resonant broadband photoacoustic spectroscopy	[246]
Different volatile fatty acids	On-line monitoring with total-reflectance Fourier-transformed infrared spectroscopy (ATR-MIR-FTIR)	[2]

The currently available technologies do not enable the monitoring of all operational parameters of the biogas plant. Therefore, samples have to be collected from the biogas plant and analyzed in individual facilities (off-line monitoring) [142]. Off-line monitoring takes place in the laboratory, where samples should be taken for the defined test. Unlike the off-line monitoring, on-line monitoring can provide real-time data on the plant's operation without any time loss for sampling, transfer, and analysis. A study about the on-line monitoring system was done in 2013 in Germany, and it showed that the majority of the biogas plants are equipped with on-line systems to monitor the electricity generation. Additionally, on-line systems were used to determine produced heat, input solid feedstock, biogas temperature, parasitic electricity demand, biogas volume, biogas composition and input liquid feedstock [62].

To improve monitoring systems of the biogas reactors, near infrared spectroscopy (NIR) and mid-infrared spectroscopy (MIR) are seen as promising technologies [9]. In order to obtain operation flexibility at biogas plants (e.g., changing operational parameters and feedstock type and amount), improvements to the biogas plants' monitoring technologies and applications are necessary [2,9,247].

5. Conclusions

Anaerobic digestion is an established technology, used to treat a wide variety of organic wastes. It is one of several biological processes that deliver economic and environmental benefits (i.e., producing bioenergy and/or biochemical while treating the organic fraction of waste). The anaerobic digestion process is complex—it includes various physical and biochemical reactions. The stability of the anaerobic digestion process is affected by many factors (e.g., the conditions inside and surrounding the reactor, the reactor's design, the operational parameters, etc.). In order to maintain a stable, efficient, and sustainable biogas production, the operational parameters should be determined and controlled.

The aim of this paper was to review and evaluate recent studies in the field to determine the critical parameters and their impacts on the anaerobic digestion process, and consequently, on the biogas production. This paper presented a summary to the design parameters of the biogas plant, the significant environmental conditions in the reactor, and the available monitoring and controlling technologies of the anaerobic digestion process (Figure 4).

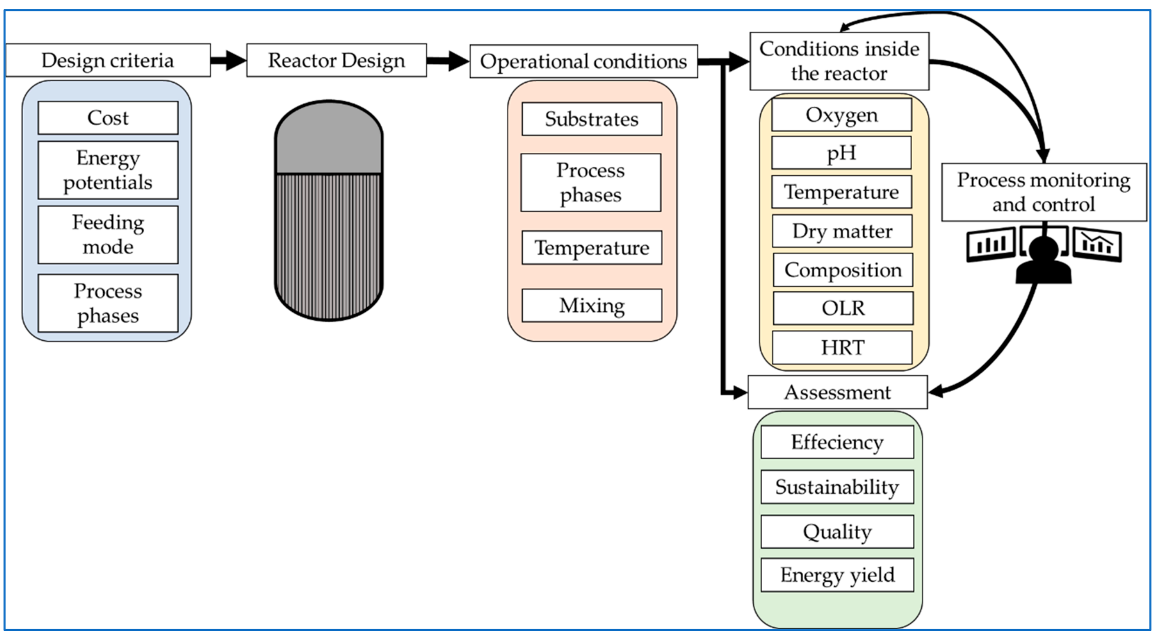

Figure 4. A summary of the paper's discussed aspect.

This review concludes that decisions regarding biogas plants' design, operation, and monitoring conditions depend on many factors (e.g., feedstock, temperature, pH, OLR, HRT, nutrients, inhibitors, biogas quality, etc.). However, the optimal range of the operational parameters varies from one biogas plant to another. Therefore, an inclusive monitoring system is required to enhance the performance of the anaerobic digestion process. Based on this review, it is recommended to improve and expand the available monitoring methods of the process in order to obtain an efficient, sustainable, and flexible operation of the biogas plants. To achieve that, further research needs to focus on the development of on-line, at-line, and off-line monitoring analyzers in the biogas plants.

Author Contributions: Conceptualization, A.N. and S.O.C.; methodology, A.N. and S.O.C.; validation, A.N., S.O.C., A.A., H.A.Q. and K.K.; writing—original draft preparation, A.N., S.O.C. and A.A.; writing—review and editing, A.N., S.O.C., A.A., H.A.Q. and K.K.; visualization, A.N., S.O.C. and A.A.; supervision, H.A.Q. and K.K.; funding acquisition, K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Publishing fees were supported by Funding Programme *Open Access Publishing* of Hamburg University of Technology. Thanks to the German Academic Exchange Service for their scholarship to the researcher (SOC).

Conflicts of Interest: The authors declare no conflict of interest.

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