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Review

Biogas Production in AnMBRs via Treatment of Municipal and Domestic Wastewater: Opportunities and Fouling Mitigation Strategies

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Abstract: In recent years, significant progress has been achieved in developing the potential of anaerobic membrane bioreactors (AnMBRs). The present paper presents a comprehensive review of studies focused on biogas production via the treatment of municipal and domestic wastewater with the use of such technology. The main aim of the current work was to evaluate the impact of operating parameters on the biogas production yield. Moreover, the possibilities of applying various fouling mitigation strategies have been discussed in detail. Analyses have been performed and reported in the literature, which were conducted with the use of submerged and external AnMBRs equipped with both polymeric and ceramic membranes. It has been shown that, so far, the impact of the hydraulic retention time (HRT) on biogas yield is ambiguous. This finding indicates that future studies on this issue are required. In addition, it was demonstrated that temperature has a positive impact on process performance. However, as presented in the literature, investigations have been carried out mainly under psychrophilic and mesophilic conditions. Hence, performing further experimental studies at temperatures above 40 °C is highly recommended. Moreover, it has been shown that in order to restore the initial permeate flux, a combination of several membrane cleaning methods is often required. The findings presented in the current study may be particularly important for the determination of operating conditions and suitable fouling mitigation strategies for laboratory-scale and pilot-scale AnMBRs used for biogas production via the treatment of municipal and domestic conditions.

Keywords: anaerobic digestion; anaerobic membrane bioreactor; biogas; energy carrier; fouling; membrane cleaning; methane; wastewater treatment

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1. Introduction

Nowadays, special research focus is being placed on the concept of the environmental protection and sustainability development. In this context, the increasing interest in biogas is related to the fact that it is an alternative to fossil fuels. In particular, biogas technology may contribute to reducing both the waste generation and emission of greenhouse gases. Therefore, in recent years, a continuous increase in biogas production has been noted all over the world. Moreover, since in the energy sector of many countries biogas production is a significant option, it is envisioned that its worldwide market size will increase from USD 55.84 billion in 2022 to USD 78.8 billion by 2030 [1] (Figure 1).

Biogas primarily consists of methane (CH_4, 50–75% by volume), carbon dioxide (CO_2, 25–50% by volume), and minor amounts of other gases, such as nitrogen (N_2), oxygen (O_2), hydrogen (H_2), hydrogen sulfide (H_2S) as well as water vapor $(H_2O)_{(g)}$ [2–4]. It is a green energy carrier characterized by a calorific value between 20 and 32 MJ/m^3 [5] depending on the CH_4 content. However, it is important to note that to find various applications, the methane concentration in biogas should exceed 90% [4]. After upgrading and cleaning with the use of commercially available technologies [6–9], biogas may be used for power and heat generation, transportation, as well as thermal energy generation for industrial applications. Moreover, methane-rich biogas can be used as a feedstock in material and chemical production [10]. The final biogas applications depend not only on its composition but also on the factors such as the upgrading process and national frameworks [11]. Worthy of note, the largest share of biogas is produced in Europe [12] (Figure 2), where it is mainly used for the generation of heat and electricity [6,13]. The biogas perspectives in Europe were thoroughly discussed in the review paper [14].

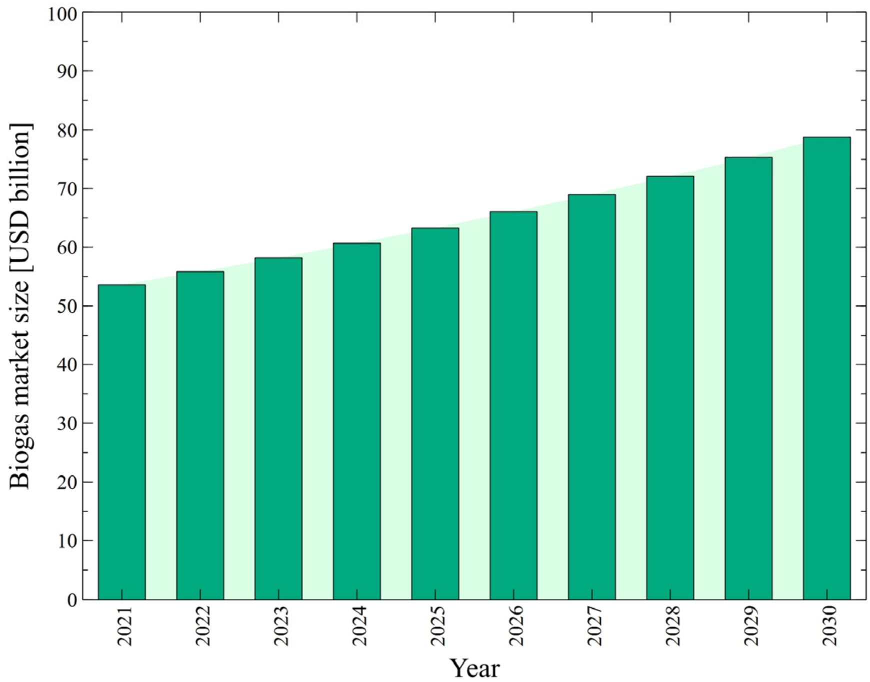

Figure 1. Biogas market size from 2021 to 2030. Based on [1].

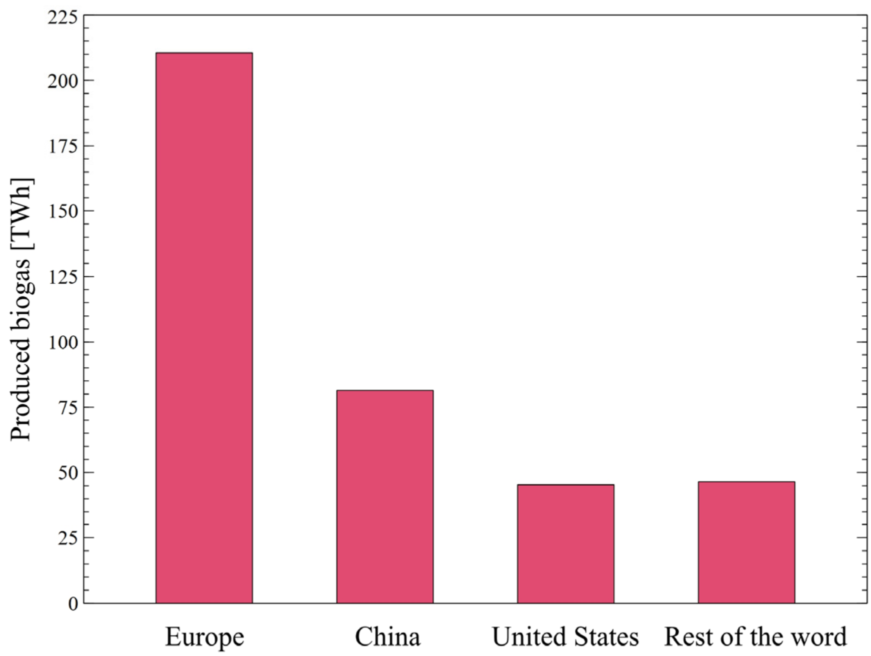

Figure 2. Biogas production in 2018. Based on [12].

Biogas is produced via anaerobic digestion (AD) process including instantaneous and continuous complex phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Table 1) as a result of organic matter decomposition by various groups of synergistically acting facultative or obligatory anaerobic microbial species [15–22]. The detailed characteristics of the subsequent steps in AD have been presented in many previously published studies [3,10,15,20,23–28]. Roughly speaking, in the first phase, organic matters, mainly proteins, polysaccharides, and lipids, are hydrolyzed into simple components, such as glucose ($C_6H_{12}O_6$), amino, and fatty acids. This phase is relatively slow and is considered a rate-limiting step in the AD process due to the complex floc structure of the sewage sludge. Key bacteria involved in the hydrolytic phase include, for instance, *Bacteriocides*, *Clostridia*, *Bifidobacteria*, *Streptococci*, and *Enterobacteria*. In the following stage, known as the fermentation phase, amino acids, lipids, and glucose are degraded into methanogenic compounds, such as hydrogen (H_2), alcohols, carbon dioxide (CO_2), carbon acids, and ammonia. It should be pointed out that when pH is higher than 5, the production of volatile fatty acid is favored. On the other hand, for pH lower than 5, ethanol production (CH_3CH_2OH) is enhanced. During this phase, bacteria such as *Streptococcus*, *Staphylococcus*, *Escherichia*, *Bacillus*, *Sarcina*, and *Desulfovibrio* are active. During the acetogenesis, volatile fatty acids are converted into CO_2, H_2, and acetate. Importantly, it determines the biogas production efficiency since the acetate ion reduction forms about 70% of CH_4. Among the involved bacteria are mainly *Desulfovibrio*, *Syntrophobacter wolinii*, and *Syntrophomonas*. Finally, during methanogenesis, acetic acid is converted into methane and CO_2. In addition, more CH_4 is produced via the reaction of CO_2 with hydrogen gas and ethanol decarboxylation. Importantly, the CH_4 production rate depends on both availability of substrate and methane formers. At this stage, there are mainly the following bacteria: *Methanosarcina* and *Methanosaeta* (acetophilic methanogenic) and *Methanospirilum*, *Methanobacterium formicicum*, *Methanoplanus*, and *Methanobrevi bacterium* (hydrogenophilic methanogenic).

In recent years, there is a growing recognition that for biogas production, many types of widely available wastewater can be used as feedstock. This is particularly important since approximately 400 billion m^3 of wastewater is generated worldwide every year [29–31]. Currently, the greatest attention is focused on municipal and domestic wastes which are recognized as a considerable environmental, economic, and social problem around the world [32–34]. Importantly, a comprehensive evaluation of the scientific literature allows us to indicate that the process performance is strongly dependent on several other factors, such as the reactor design, feed pretreatment process, concentration of volatile fatty acids, carbon-to-nitrogen ratio (C/N), and pH as well as operating conditions: (i) temperature, (ii) hydraulic retention time (HRT), (iii) solid retention time (SRT), and (iv) organic loading rate (OLR) [16,18,20,23,24,35–40].

Biogas production from sludge in wastewater treatment plants (WWTPs) has been implemented for many years [35]. Traditionally, it is realized by coupling the cattle manure treatment and sewage sludge from WWTPs. Although, for this purpose, various types of reactors can be used [25,37,40–42]; according to [13], the up-flow anaerobic sludge blanket (UASB) reactor is the most popular system. In fact, the benefits of the AD process have been frequently presented in the literature [10,13,20,43,44]. Briefly, there is general agreement that it is an environmentally friendly technology that allows conserving natural resources. However, conventional anaerobic technologies are characterized by several disadvantages including process sensitivity, long start-up period, odor problems, and requirements of post-treatment processes [45,46].

Table 1. Subsequent steps in the anaerobic digestion process. Based on [3,10,15,20,23–28].

Process	Description	Stoichiometric Equation	Equation
hydrolysis	- complex organic matters are broken into simple molecules, such as sugars i.e., glucose ($C_6H_{12}O_6$), amino acids, and fatty acids - reaction catalyzed by acids - phase relatively slow considered a rate-limiting step in the anaerobic digestion - exemplary microorganisms: *Bacteriocides*, *Clostridia*, *Bifidobacteria*, *Streptococci*, *Enterobacteria*	$nC_6H_{10}O_5 + nH_2O \rightarrow nC_6H_{12}O_6$	(1)
acidogenesis	- known as the fermentation stage - compounds formed during the hydrolysis are degraded into hydrogen (H_2), alcohols, carbon dioxide (CO_2), carbon acids, and ammonia - for pH > 5 volatile fatty acid production is favored, meanwhile for pH < 5 ethanol (CH_3CH_2OH) production is enhanced - produced acetic acid (CH_3COOH) and butyric acid ($CH_3CH_2CH_2COOH$) are the preferred precursors for CH_4 production - exemplary microorganisms: *Streptococcus*, *Staphylococcus*, *Escherichia*, *Bacillus*, *Sarcina*, *Desulfovibrio*	$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow 3CH_3COOH$	(2) (3) (4)
acetogenesis	- conversion of acidogenesis products into CO_2, H_2, and CH_3COOH - phase reflecting the biogas production efficiency - exemplary microorganisms: *Desulfovibrio*, *Syntrophobacter wolinii*, *Syntrophomonas*	$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+HCO_3^- + 3H_2$ $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$ $CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+$	(5) (6) (7)
methanogenesis	- the most crucial stage in biogas production, - production of CH_4 from acetate by methanogens (nearly 70%) and via reaction of CO_2 and H_2 - formation of CH_4 by decarboxylation of ethanol - the CH_4 production rate depends on both the availability of substrate and methane formers - exemplary microorganisms: *Methanobacterium formicicum*, *Methanobrevi bacterium*	$CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$	(8) (9) (10)

Recent advances in chemical engineering have opened up the possibility of overcoming the above-mentioned limitations by application of anaerobic membrane bioreactor (AnMBR) technology. AnMBRs combine conventional anaerobic digestion with a membrane separation unit that retains high molecular-mass substances and prevents the washout of methane-forming microorganisms. For this purpose, mainly the low-pressure membrane processes: microfiltration (MF) and ultrafiltration (UF) are applied. Consequently, as was indicated in [47], the amount of biogas produced in AnMBRs is more significant than that obtained via conventional processes of the wastewater treatment. The undeniable advantages of AnMBRs technology have been presented in a significant number of review papers [26,38,48–55]. According to the above-mentioned studies, the most important benefits of the AnMBRs application are high biomass concentration and enhanced biogas yield, effluent with excellent quality without suspended solids, small footprint, low sludge production, and high treatment capacity. It should be pointed out that in our recently published review article [48], it was demonstrated that the AnMBRs are energy-efficient technology. Indeed, through detailed studies, it was concluded that the net energy demand of submerged AnMBRs used for the treatment of sulfate-rich municipal wastewater is significantly lower than that noted for WWTPs. Furthermore, results obtained in the above-mentioned work indicated that the AnMBRs technology used for the treatment of low-sulfate municipal wastewater has the potential to be a net energy producer. Due to the above-presented advantages, the AnMBRs technology is a highly appreciated opportunity for biogas production via municipal and domestic treatment.

The application of AnMBR technology for biogas production is frequently investigated in scientific research. Indeed, ScienceDirect contains 5946 records related to the presented subject which have been published between 2003 and 2022. Moreover, the performed analysis demonstrated that the number of articles focused on biogas and AnMBRs increased significantly, especially in the last decade (Figure 3). Undoubtedly, this finding confirms the importance of the research topic presented in the current study.

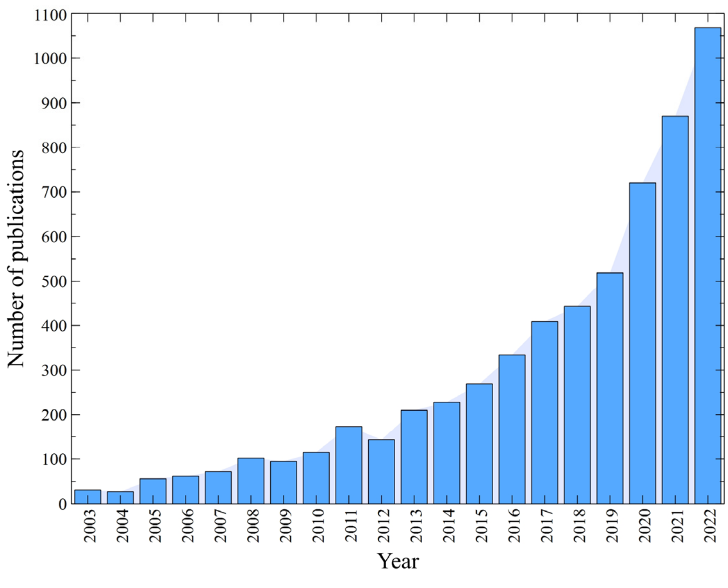

Figure 3. The number of articles focused on biogas production in membrane bioreactors according to ScienceDirect. Keywords: 'anaerobic membrane bioreactor + biogas'. Data retrieved: 29 March 2023.

It is recognized that the large-scale implementation of AnMBR technology is a great challenge mainly due to the fouling which is caused by the matter attached to the membrane surface or trapped inside its pores. This issue is of critical importance since it leads to a reduction in the system performance and thus, an increase in the operation cost. In terms of the treatment of municipal and domestic wastewater, fouling is a very complex phenomenon. It is due to the fact that the above-mentioned types of wastewater contain a huge number of various compounds, such as organic matters, nutrients, heavy metals, and organic micropollutants [56–58]. Moreover, the wastewater composition may vary with the seasons and location [59–61] which additionally hinders the estimation of the process performance and efficiency. Worthy of note, anaerobic sludge may produce granules leading to more severe membrane contamination [50]. A more detailed overview on the membranes fouling in the AnMBRs can be found for example in [54,62–66].

It has been recognized that the successful long-term performance of AnMBRs depends on the effectiveness of membrane cleaning. Indeed, it is a key procedure that aims to maintain the membrane performance and separation properties as well as to prevent contamination of the installation with microorganisms. In AnMBRs technology, the fouling mitigation strategy is of crucial importance since it accounts for more than 70% of the energy consumption [67]. In brief, the methods of membrane cleaning are categorized into three groups: chemical, physical, and physio-chemical. It should be emphasized that physical cleaning is adopted to remove reversible fouling while chemical cleaning to remove irreversible fouling [26,68,69].

To the best of the authors' knowledge, the review articles focused on biogas performance in AnMBRs applied for the treatment of municipal and domestic wastewater are very limited. Consequently, the impact of the process parameters on biogas yield has been poorly described so far. The present paper is a continuation and complement of our recently published study [48] wherein it was clearly documented that the AnMBRs are an energy-efficient technology. Accordingly, the current work aimed at comprehensively evaluating and discussing the impact of the process parameters, such as temperature and hydraulic retention time, on biogas production yield in AnMBRs via the treatment of municipal and domestic wastewater. Analysis reported so far in the literature have been conducted with the use of submerged and external AnMBRs equipped with both polymeric and ceramic membranes. Moreover, the possibilities of applying various fouling mitigation strategies have been discussed in detail.

2. Biogas Production in AnMBRs

2.1. AnMBR Configurations and Operating Conditions

Our systematic literature review indicated that investigations on biogas production in AnMBRs have been carried out at the pilot [70–82], semi-industrial/semi-pilot [83,84], and laboratory (bench) scales [77,85–103] (Table 1).

Two AnMBRs configurations were used: external (side-stream) and submerged (Figure 4). In the case of the external system, the membrane filtration unit was separated from a biological reactor, while in the submerged installation, the membrane was submerged inside the reactor (or inside an external tank). Most of the above-mentioned works have been performed with the use of submerged AnMBRs. Undoubtedly, this is related to the fact that this configuration has a significantly lower energy requirement [104–106], which is crucial for industrial implementations of the technology.

Moreover, an analysis of the collected data showed that polymeric membranes, such as polyvinylidene fluoride (PVDF), polyethersulfone (PES), polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET), were the most commonly used. Only a few papers [87,89,92,102,103] have investigated the suitability of ceramic membranes. This can be attributed to the fact that the application of ceramic membranes leads to an increase in the cost of AnMBR technology. Indeed, although a decrease in the cost of ceramic membranes over the last 20 years has been noted [107], their fabrication is complex and they are more expensive than polymeric ones [108–111]. However, ceramic membranes have several significant advantages, including high porosity and hydrophilicity, excellent separation properties, and high thermal, mechanical, and chemical stability [112–118]. Hence, additional experimental investigations are needed to determine the process performance in AnMBRs equipped with ceramic membranes.

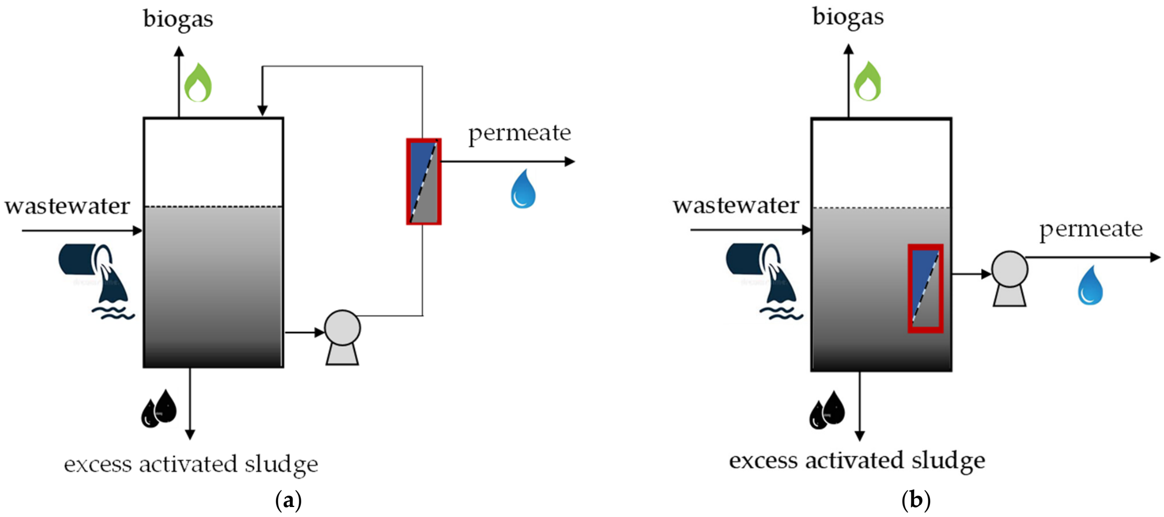

Figure 4. Schematic diagrams of the AnMBR configurations used for biogas production: (**a**) external; and (**b**) submerged.

Generally, the digestion process can be performed at psychrophilic (<25 °C), mesophilic (30–40 °C), or thermophilic (50–60 °C) conditions. The studies performed in the literature have been carried out under temperatures in the range from 10 °C [76] to 37 °C [81,84]; nevertheless, mesophilic temperatures are the most frequently applied.

Worthy of note, in the analyzed studies, wide ranges of HRT and SRT were used. Indeed, the values of HRT, defined as a ratio of the reactor volume to the influent flow rate in time, ranged from 2.2 h [71] to 47 days [84]. In turn, SRT, which indicates the average time of the activated-sludge solids in the AnMBR, was between 20 days [72,80] and 1000 days [99].

The optimum pH for the methanogenesis process is between 6.8 and 7.4 [119–122]. In most of the investigations, the feed pH was kept in the above-mentioned range. For this purpose, feed neutralization with the use of chemicals such as sodium bicarbonate ($NaHCO_3$) [77,86,102,103] and sodium hydroxide (NaOH) [98] solutions was carried out.

The process performance is described by the biogas (methane) yield, which is defined as the ratio of the total volume of biogas (methane) produced (V_{gas}) to the chemical oxygen demand (COD) removed (difference between the COD fed (COD_f) from the reactor and the COD of the permeate (COD_p)) according to the following equation:

$$\text{biogas (methane) yield} = \frac{V_{gas}}{COD_f - COD_p} \tag{11}$$

The theoretical biogas and methane yields at standard temperature and pressure conditions are equal to 0.5 L/g COD and 0.35 L/g COD, respectively [123].

2.2. Process Yield

2.2.1. Impact of HRT

The key factor affecting the process of biogas production is HRT. It is a well-accepted fact that microorganisms occurring in the feed that convert organic substrates into biogas require sufficient retention time. In addition, performing wastewater treatment in AnMBRs under a short HRT may significantly affect the microbial community, which is important for the performance of the anaerobic process [97,124]. Importantly, HRT should also be selected according to the expected quality of the effluent and the costs of reactor maintenance [77]. Roughly speaking, a small-volume bioreactor is related to a short HRT and, consequently, to lower capital costs [125].

The literature reports related to the impact of the HRT on the biogas yield in the AnMBRs used for the treatment of municipal and domestic wastewater are ambiguous in terms of results. In studies [70,79,85,91,96,99] it has been demonstrated that biogas production increased with the decrease in HRT. More specifically, Chen et al. [91] investigated biogas production in a laboratory-scale submerged AnMBR inoculated with anaerobically digested sludge from the WWTP. The above-mentioned authors noted the average values of the biogas production rate as equal to 0.14 L/L/day; 0.28 L/L/day; 0.42 L/L/day; 0.56 L/L/day; and 0.89 L/L/day at HRT equal to 48 h; 24 h; 16 h; 12 h; and 8 h, respectively. Moreover, it has been demonstrated that the CH_4 content in biogas increased from 70% to about 80% with HRT decreasing from 48 h to 12–8 h. Huang et al. [85] studied the effect of HRT and SRT on the treatment performance and membrane fouling in a submerged AnMBR used for the treatment of low-strength wastewater. In the above-mentioned study, the authors applied the HRT in the range from 8 h to 12 h. The highest value of the CH_4 yield equal to 0.25 ± 0.041 L/g COD was obtained for an HRT of 8 h. On the other hand, the lowest value, equal to 0.138 ± 0.031 L/g COD, was noted for an HRT of 12 h. The authors pointed out that this finding can be attributed to the fact that at shorter HRT, the biomass concentration in AnMBR is higher, which resulted in a higher methane production. These results are in good agreement with the results of [79], wherein a large pilot-scale submerged AnMBR was used. The system was firstly operated under an HRT equal to 48 h and, subsequently, HRT was gradually decreased to 24 h; 12 h; 8 h; and 6 h. For an HRT of 24 h, the biogas yield was equal to 0.16 L/g COD, while for HRT between 12 h and 6 h, it was equal to 0.25 L/g COD. In turn, investigations performed with the use of the external AnMBR were presented by Wei et al. [99]. Wastewater treatment was studied for the HRT of 6 h and 12 h. For an HRT of 6 h, the CH_4 yield was in the range from 0.175 ± 0.006 L/g COD to 0.386 ± 0.035 L/g COD; meanwhile, for the HRT of 12 h, values between 0.129 ± 0.004 L/g COD to 0.359 ± 0.010 L/g COD were noted. Overall, the above-presented results indicate that in the initial period of the wastewater treatment process, the bioconversion rate and CH_4 yield are higher. Subsequently, due to substrate loss and increases in metabolite concentrations, the process efficiency decreases and more by-products are formed. As a result, the average value of gas production expressed as [L/g COD] decreases with an increase in the retention time.

Interestingly, the study presented by Ji et al. [70] does not support the above-discussed findings. The above-mentioned authors investigated the treatment of municipal wastewater in pilot-scale submerged AnMBRs at a low temperature (15 °C). It was shown that extending the HRT had a positive effect on the biogas yield. Indeed, at an HRT of 24 h, the biogas yield was equal to 0.28 L/g COD, while at an HRT of 16 h and 12 h, it was equal to 0.26 L/g COD, and 0.17 L/g COD, respectively.

On the other hand, the above-discussed results are not in line with those presented in [77,96,100] wherein it was found that HRT does not have an impact on the biogas production in AnMBRs. Ho and Sung [100] used a laboratory-scale AnMBR equipped with a tubular polytetrafluoroethylene (PTFE) microfiltration membrane. They demonstrated that the obtained methane yield was equal to 0.21–0.22 L/g COD, regardless of the applied values of HRT (12–6 h). In turn, in [96], two AnMBRs with MF and UF membranes for the treatment of municipal wastewater were used. The process was conducted under a wide range of HRT values, from 24 h to 12 h. It was demonstrated that in an AnMBR equipped with the MF membrane, under the HRT of 24 h; 12 h; 14.4 h; and 12 h, the methane yield was equal to 0.15 ± 0.02 L/g COD; 0.15 ± 0.02 L/g COD; 0.18 ± 0.03 L/g COD; and 0.19 ± 0.02 L/g COD, respectively. In turn, with regards to the AnMBR system with a UF membrane, under the HRT of 24 h; 14.4 h; and 12 h, the methane yield was 0.16 ± 0.04, 0.20 ± 0.03 L/g COD; and 0.18 ± 0.02 L/g COD, respectively.

As demonstrated above, defining the impact of HRT on the biogas production in AnMBRs applied for municipal and domestic wastewater is not straightforward. Therefore, in the current study, we performed an analysis data collected from the literature [70–75,77,78,83–85,87,89,90,92,95,96] (Figure 5). It can be seen that, generally, the highest methane yield values have been obtained for the shortest HRT. However, the most suitable value of HRT in AnMBRs technology applied for biogas production depends on other operational factors, including temperature. Based on the literature review and findings presented above, it can be concluded that further experimental studies on the impact of HRT on the biogas yield in AnMBRs are highly warranted.

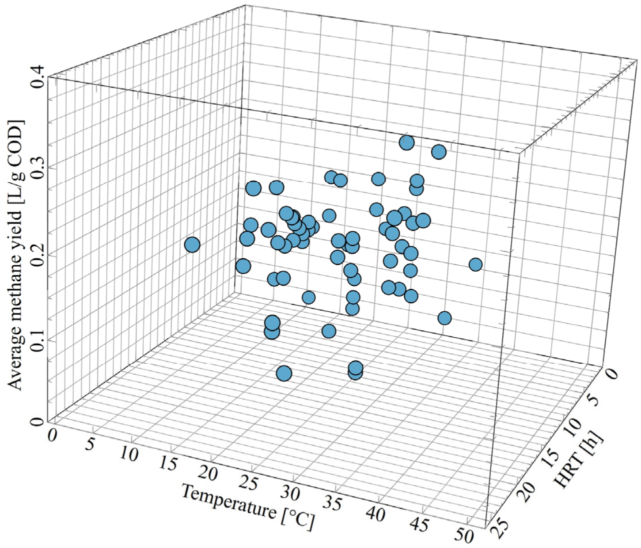

Figure 5. Impact of temperature HRT of the average methane yield in submerged AnMBRs used for the treatment of municipal and domestic wastewater. Data from [70–75,77,78,83–85,87,89,90,92,95,96].

It is important to point out that HRT may also have a significant impact on the membrane fouling mechanism. For instance, in [91], it was documented that performing wastewater treatment in a laboratory-scale AnMBR under HRT for longer than 12 h leads to membrane pore blocking. On the other hand, for HRT less than 8 h, the main reason for the decline of permeate flux was the formation of a cake layer on the membrane surface. These findings can be explained by the fact that, generally, shortened HRT results in an enhanced accumulation of particulates and colloidal matter in a feed.

2.2.2. Impact of Temperature

It is apparent that temperature plays a key role in biogas production in AnMBR technology. Indeed, it mainly affects the structure and composition of the microbial community, the hermodynamic equilibrium of biochemical conversion, and the stoichiometry of the final products [126,127]. More precisely, the process temperature allows the thermodynamically feasible reactions and microorganisms able to grow [128]. In general, municipal wastewater has a temperature below 20 °C, which limits the hydrolysis process and the dissolution of complex organic constituents (Table 1) [125]. It should be pointed out that the microbial community is sensitive to temperature fluctuations, which may lead to changes in the rate of maximum specific growth and substrate utilization [129]. Moreover, the decreasing temperature may result in a decrease in both the production rate of volatile fatty acids and ammonia concentration [40]. Furthermore, the temperature has a significant impact on the hydrogen partial pressure in a rector; hence, it affects the kinetics of the syntrophic metabolism [130].

Due to the aforementioned reasons, it is of crucial importance to investigate the impact of temperature on the biogas yield in AnMBR technology. From a technological point of view, the important fact is that temperature may have an impact on methane distribution between the gas and liquid phases. Indeed, a decrease in temperature leads to an increase in the fraction of methane dissolved in a permeate [131,132]. Surprisingly, according to the data presented in Table 2, it can be indicated that although many attempts have been made to examine the biogas production in AnMBRs, the influence of temperature on the process performance has only been reported in a limited number of studies for both laboratory-scale [95] and pilot-scale [74,76,80] installations.

Table 2. Studies on the biogas production in AnMBRs applied for the treatment of municipal and domestic wastewater: Literature review.

Scale	AnMBR Configuration	Volume (L)	Membrane Characteristics					Process Conditions				*Biogas* or Methane Production Yield [L/g COD]	Ref.
			Type	Pore size (μm)	Material	Configuration	Area (m^2)	Temperature (°C)	HRT (h) or (d)	SRT (d)	pH		
pilot	submerged	20	MF	0.4	PVDF	hollow fiber	NI	15	6–24 h	20.7–515.7 d	NI	*0.17–0.28*; 0.12–0.23	[70]
pilot	submerged	25	MF	0.2	NI	hollow fiber	5.4	35	2.2 h	NI	NI	0.12	[71]
pilot	submerged	160	UF	0.045	NI	hollow fiber	0.93	18 ± 2	7.0–17.1 h	20 d	NI	0.18; 0.23	[72]
pilot	submerged	326	UF	0.045	NI	hollow fiber	0.93	18	9.8–20.3 h	NI	NI	0.14 ± 0.01–0.26 ± 0.01	[73]
pilot	submerged	350	UF	0.038	PES	flat sheet	3.5	20–35	0.8 d	NI	NI	0.23; 0.27	[74]
pilot	submerged	350	UF	0.038	PES	flat sheet	3.5	20 ± 1	0.74–1.10 d	NI	NI	0.29	[75]
pilot	submerged	496	UF	0.045	NI	hollow fiber	1.86	10–28	8–10 h	NI	8.2 ± 0.3	*0.09–0.14*	[76]
pilot	submerged	550	UF	0.04	PVDF	hollow fiber	5.4	23 ± 1	8.5 h	40–100 d	6.7–6.8	0.115 ± 0.021–0.072 ± 14	[77]
pilot	submerged	1300	UF	0.05	NI	hollow fiber	30	33.3 ± 0.2	6–21 h	70 d	6.72 ± 0.08	0.069 ± 0.022	[78]
pilot	submerged	5000	MF	0.4	PVDF	hollow fiber	72	25.3 ± 0.9–26.5 ± 0.8	6–48 h	29.0–123.5 d	6.69 ± 0.11–6.80 ± 0.26	*0.16–0.27*	[79]
pilot	submerged	5000	MF	0.4	PVDF	hollow fiber	72	15–25	8 h	20–100 d	NI	0.205–0.244	[80]
pilot	external	50	UF	NI [1]	NI	cross-flow	1	37	7 d	NI	7.31–8.37	*0.46*	[81]
pilot	external	2100	UF	0.03	NI	hollow fiber	31.999	27 ± 1	24.4 ± 0.4 h	140 ± 3 d	NI	0.108 ± 0.018	[82]
semi-industrial	submerged	2100	UF	0.05	NI	hollow fiber	30	33	15 h	70 d	NI	0.333	[83]
semi-pilot	submerged	94	MF	0.4	PVDF	flat sheet	0.14	37 ± 1	47 d	NI	NI	0.28; 0.29	[84]
bench	submerged	5	MF	0.45	PES	plate and frame	0.118	25–30	8–12 h	30 d; 60 d and infinite	7.0 ± 0.5	0.124 ± 0.012–0.219 ± 0.027	[85]
bench	submerged	5	MF	0.45	PES	plate and frame	0.118	25–30	10 h	30–90 d	7.0 ± 0.5	NI [2]	[86]
bench	submerged	8	UF	0.04	PVDF	hollow fiber	0.07	23 ± 1	12.5 h	40 d	6.7–6.8	0.072 ± 13	[77]
bench	submerged	24	UF	0.1	ceramic	NI	0.2	30–35	12 h	NI	NI	0.185 ± 0.08; 0.222 ± 0.12	[87]
laboratory	submerged	3	MF	40	NI	rectangular	0.0108	35 ± 1	14 h	NI	NI	0.24	[88]
laboratory	submerged	3.6	MF and UF	0.08–0.30	ceramic	NI	NI	25–30	7.5 h	60 d	NI	0.1 ± 0.02	[89]
laboratory	submerged	4	MF	0.2	PP	hollow fiber	0.06	35 ± 1	12–48 h	NI	NI	0.15–0.35	[90]
laboratory	submerged	6	MF	0.2	PE	flat sheet	0.116	25 ± 1	8–48 h	infinite	6.8–7.5	NI [3]	[91]
laboratory	submerged	6	MF	0.1	ceramic	flat sheet	0.045	30 ± 3	17 h	30 d	7.80 ± 0.21; 7.84 ± 0.11	0.064 ± 0.02; 0.070 ± 0.03	[92]
laboratory	submerged	6	MF	0.2	PET	flat sheet	0.116	25 ± 1	12 and 24 h	NI	6.9–7.3	NI [4]	[93]
laboratory	submerged	6	MF	0.2	PET	flat sheet	0.116	25 ± 1	12 h	NI	NI	NI [5]	[94]
laboratory	submerged	20	MF	0.4	PVDF	hollow fiber	NI	15–25	6 h	20.7–93.9 d	7.0–7.3	0.06 ± 0.01–0.17 ± 0.01; *0.09 ± 0.02–0.22 ± 0.02*	[95]
laboratory	submerged	20	MF	0.4	NI	NI	0.146	25	12–24 h	infinite	6.9 ± 0.1	0.15 ± 0.02–0.19 ± 0.02; *0.20 ± 0.03–0.24 ± 0.02;*	[96]
laboratory	submerged	20	MF	0.05	NI	NI	0.27	25	12–24 h	infinite	6.9 ± 0.1	0.16 ± 0.04–0.20 ± 0.03; *0.21 ± 0.05–0.26 ± 0.04*	[96]
laboratory	submerged	20	MF	0.4	NI	NI	NI	25.0 ± 0.2	4–24 h	NI	NI	NI [6]	[97]
laboratory	submerged	20	UF	0.05	NI	NI	NI	25.0 ± 0.2	10–24 h	NI	NI	NI [7]	[97]
laboratory	submerged	80	UF	NI [1]	PVDF	flat sheet	0.6	30 ± 3	10 h	NI	7.0 ± 0.2	0.24	[98]
laboratory	external	2	UF	0.03	PVDF	hollow fiber	0.031	35 ± 1	6 h; 12 h	1000 d	7.0 ± 0.1	0.129 ± 0.004–0.396 ± 0.033	[99]
laboratory	external	4	MF	1	PTFE	tubular	0.090– 0.012	25 ± 1	6–12 h	NI	7.3–7.9	0.21–0.22	[100]
laboratory	external	5.5	UF	0.05	PVDF	flat sheet	0.02	NI	2.4 ± 0.6–3.6 ± 1.1 d	NI	7.6 ± 0.3–8.4 ± 0.2	0.214 ± 0.079–0.322 ± 0.060	[101]
laboratory	external	30	MF	0.1	ceramic	NI	0.09	35 ± 1	5 d	140 d	7.0	*0.4–0.6*	[102]
laboratory	external	30	MF	0.1	ceramic	NI	0.09	35 ± 1	4 d	180 d	7	0.2	[103]

[1] 100 kDa cut-off, [2] methane yield: 0.19 ± 0.05–0.50 ± 0.16 L/d, [3] biogas production rate: 0.14–0.89 L/L/d, [4] biogas production rate: 1.13–2.55 L/d, [5] biogas production rate: 2.25–4.25 L/d, [6] biogas production rate: 0.06–0.1 L/L, [7] biogas production rate: 0.076–0.093 L/L, NI—no information, PE—polyethylene, PES—polyethersulfone, PET—polyethylene terephthalate, PVDF—polyvinylidene fluoride, PP—polypropylene, PTFE—polytetrafluoroethylene, HRT—hydraulic retention time, SRT—sludge retention time.

Ji et al. [95] investigated the application of a laboratory-scale submerged anaerobic membrane bioreactor for the treatment of municipal wastewater under constant HRT equal to 6 h and temperatures of 15 °C; 20 °C; and 25 °C. For this purpose, a PVDF microfiltration membrane was used. In the above-mentioned study, it was demonstrated that temperature has a remarkable effect on biogas production. Indeed, for 20 °C and 25 °C, the obtained biogas yield was equal to 0.18 L/g COD and 0.22 L/g COD, respectively. In turn, for a temperature of 15 °C, the value of 0.09 ± 0.02 L/g COD was obtained. These results demonstrated that at low operation temperatures, the activity of anaerobic microorganisms is significantly lower. The same range of temperature values was applied by Rong et al. [80] wherein a pilot-scale AnMBR system equipped with a PVDF microfiltration membrane was used. Likewise, it was shown that temperature is a key factor affecting methane production. More specifically, for temperatures of 25 °C; 20 °C; and 15 °C the recorded values of the methane yield were equal to 0.244 L/g COD, 0.234 L/g COD and 0.205 L/g COD, respectively. In turn, Peña et al. [76] have demonstrated that in a pilot-scale submerged AnMBR used for municipal wastewater treatment, decreasing the temperature below 15 °C resulted in negligible biogas production. What becomes apparent from the discussed studies is that, generally, increasing temperature leads to an increase in the biogas and methane yield.

Analysis of data collected from the literature (Figure 5) shows the slight impact of the temperature on the average methane yield. It can be observed that the highest process performance (methane yield: 0.312 L/g COD and 0.333 L/g COD) was obtained under the highest values of temperature (33 °C and 35 °C) applied. This finding can be attributed to the fact that increasing temperature allows for an increase in the reactivity and kinetics of the biological and chemical processes of biogas production. On the other hand, it has to be emphasized that since heating the reactors requires energy, it leads to an increase in the AnMBRs technology cost.

Based on the findings presented above, it can be indicated that there is a lack of feasibility studies on biogas production in AnMBRs via the treatment of municipal and domestic wastewater under thermophilic conditions. Although mesophilic conditions are more stable, thermophilic ones demonstrate several benefits, such as earlier organic material degradation and thus shorter hydraulic retention times and greater efficiency [16,39]. Hence, it would be meaningful to investigate biogas production in AnMBRs under thermophilic conditions.

3. Fouling Mitigation Strategies

It is a well-accepted fact that the membrane fouling phenomenon can be controlled by various methods. Table 3 shows literature reports on fouling mitigation strategies in submerged and external AnMBRs applied for biogas production via the treatment of municipal and domestic wastewater. Overall, the strategies can be categorized into the following methods: (i) physical cleaning, such as biogas sparging, manual cleaning, relaxation, and ultrasonication as well as (ii) physio-chemical cleaning, including chemically enhanced backwashing, and (iii) chemical cleaning. It is fundamental to note that in most of the studies, a combination of several methods of membrane cleaning has been applied. This can be explained by the fact that some compounds of wastewater form irreversible fouling, the removal of which requires various cleaning methods, including chemical cleaning.

Table 3. Fouling mitigation strategies in AnMBRs technology applied for the treatment of municipal and domestic wastewater: Literature review.

AnMBR		Membrane Characteristics			Fouling Mitigation Strategy							
Scale	Configuration	Type	Material	Configuration	Biogas Sparging	Manual Cleaning	Relaxation	Ultrasonic	(Chemically Enhanced) Backwashing	Chemical Cleaning/ Soaking	Used Agents	Ref.
pilot	submerged	UF	NI	hollow fiber	+	–	+	–	+	+	NaClO	[72]
pilot	submerged	UF	NI	hollow fiber	+	–	+	–	+	–	-	[73]
pilot	submerged	UF	PES	flat sheet	+	–	+	–	+	–	-	[74]
pilot	submerged	UF	PES	flat sheet	–	–	+	–	+	–	-	[75]
pilot	submerged	UF	NI	hollow fiber	–	–	–	–	+	+	NaClO	[76]
pilot	submerged	UF	NI	hollow fiber	+	–	+	–	–	–	-	[78]
pilot	submerged	MF	PVDF	hollow fiber	+	–	+	–	+	–	NaClO and citric acid	[79]
pilot	submerged	MF	PVDF	hollow fiber	+	–	–	–	+	+	NaClO and citric acid	[80]
pilot	external	UF	NI [1]	cross-flow	–	–	–	–	–	+	NaOH, $NaHSO_4$, citric acid, EDTA	[81]
pilot	external	UF	NI	hollow fiber	–	–	+	–	+	–	-	[82]
semi-pilot	submerged	MF	PVDF	flat sheet	–	–	–	–	+	–	-	[84]
bench	submerged	MF	PES	plate and frame	–	–	–	–	–	+	NaClO	[85]
bench	submerged	UF	ceramic	NI	+	–	+	–	+	–	-	[87]
laboratory	submerged	MF	NI	rectangular	+	–	–	+	–	–	-	[88]
laboratory	submerged	MF, UF	ceramic	NI	–	+	–	–	+	–	-	[89]
laboratory	submerged	MF	PP	hollow fiber	–	+	–	–	–	+	NaOH and HNO_3	[90]
laboratory	submerged	MF	PE	flat sheet	–	–	–	–	–	+	NaClO and citric acid	[91]
laboratory	submerged	MF	ceramic	flat sheet	–	+	–	–	–	+	NaClO and citric acid	[92]
laboratory	submerged	MF	PVDF	hollow fiber	–	–	–	–	+	–	NaClO	[95]
laboratory	submerged	MF	NI	NI	–	+	–	–	+	+	NaClO and citric acid	[96]
laboratory	external	MF	PTFE	tubular	–	–	–	–	–	+	NaClO	[100]
laboratory	external	UF	PVDF	flat sheet	–	+	–	–	–	+	NaClO	[101]
laboratory	external	MF	ceramic	NI	–	–	–	–	–	+	NaOH	[102]

[1] 100 kDa cut-off, EDTA—ethylene diamine tetraacetic acid, NI—no information, PE—polyethylene, PES—polyethersulfone, PVDF—polyvinylidene fluoride, PP—polypropylene, PTFE—polytetrafluoroethylene.

3.1. Physical Cleaning

In AnMBRtechnology used for biogas production, the physical cleaning of membranes is carried out via biogas sparging, manual membrane cleaning (sponge sweeping), relaxation, and ultrasound. Biogas sparging has been used to control the membrane fouling in submerged AnMBRs [21,72–74,78–80,87,88]. Gas bubbles may affect the properties of the cake layer formed on a membrane surface. Finally, this strategy may result in the detachment of the cake layer and reduce its thickness and compactness [29], leading to back transport of foulants to the feed. In the literature, a wide range of gas velocities have been applied (Table 4). For instance, Gouveia et al. [73] applied continuous biogas sparging with a superficial velocity between 8 m/h and 16 m/h at the bottom of hollow-fiber UF membranes mounted in a pilot-scale AnMBR. In turn, Martinez-Sosa et al. [74] employed gas sparging to minimize particle deposition on the surface of a polyethersulfone (PES) ultrafiltration membrane during the whole operation of a pilot-scale AnMBR. For this purpose, the gas velocity of 62 m/h was applied. In a subsequent paper, Gimenez et al. [78] applied a constant biogas sparging intensity of 0.23 Nm^3/m^2h to ensure suitable shear conditions over the surface of an industrial hollow-fiber UF membrane. It should be pointed out that this strategy is energy-consuming [80]; however, it facilitates the mass transfer of CH_4 to a reactor headspace, which may ensure a reduction of its losses in the liquid phase [133].

Table 4. Biogas velocity applied in AnMBR technology.

AnMBR		Membrane Characteristics			Biogas velocity (m/h) or (L/min)	Ref.
Scale	Configuration	Type	Material	Configuration		
pilot	submerged	UF	NI	hollow fiber	40–60 m/h	[72]
pilot	submerged	UF	NI	hollow fiber	9–16 m/h	[73]
pilot	submerged	UF	NI	hollow fiber	62 m/h	[74]
pilot	submerged	UF	NI	hollow fiber	NI [1]	[78]
pilot	submerged	MF	PVDF	hollow fiber	0.75 m/h	[79]
laboratory	submerged	MF	NI	rectangular	1 L/min	[88]

[1] biogas sparging intensity: 0.23 Nm^3/m^2h, NI—no information, PVDF—polyvinylidene.

Manual cleaning is a well-known method of recovering membrane permeability, usually performed ex situ [68]. Several studies [89,90,92,96,101] have employed this strategy for the fouling control in AnMBRs used for biogas production. An interesting protocol for MF membrane cleaning was proposed by Ji et al. [96]. In the above-mentioned study, the membrane was gently scrubbed with a sponge before backwashing and soaking. Likewise, in another study [92], before soaking the ceramic MF membrane in chemical agents, it was manually cleaned by a sponge. In turn, in [101], before submerging the polyvinylidene difluoride (PVDF) ultrafiltration membrane in a solution of NaClO, it was manually flushed with distilled water.

Relaxation, known as the intermittent cessation of filtration [134–136], is a method of membrane cleaning based on diffusive back foulant transport from a membrane surface caused by a concentration gradient [68,137]. It has been used as an intermediate step among other membrane cleaning methods in several studies [73–75,78,79,82,87]. Our literature review indicated that in pilot-scale AnMBRs, the relaxation time is generally conducted for 5 s [72] to 60 s [79] (Table 5). For instance, in [74,75], in the operation mode of the AnMBs, a 30 s pause was applied to relax the polyethersulfone (PES) ultrafiltration membranes. In turn, Kong et al. [79] proposed 1 min for relaxing PVDF microfiltration membranes. On the other hand, in [87], wherein a bench-scale AnMBR was used, the membrane relaxation time was significantly longer (12 h). This can be explained by the fact that long-duration membrane relaxation leads to a break in the operation of AnMBRs, leading to a reduction in the economic viability of the technology.

Finally, although the use of ultrasound to restore membrane performance is a relatively new strategy [138], it has already been applied in AnMBRs used for biogas production. This method aims to dissolve and displace soluble and insoluble particles [139]. Hence, it is an effective method to eliminate the concentration polarization and cake layer formed on the membrane [68]. Li et al. [88] found that ultrasonic effectively removed the cake layer from fouled MF membranes used in a laboratory-scale submerged AnMBR. Importantly, this method did not lead to membrane damage. It is worth mentioning that the most important factors affecting the efficiency of this strategy are ultrasonic frequency, duration, and power density [68].

Table 5. Membrane relaxation time applied in AnMBRs technology as a fouling mitigation strategy.

AnMBR		Membrane Characteristics			Time	Ref.
Scale	**Configuration**	**Type**	**Material**	**Configuration**	**(s) or (h)**	
pilot	submerged	UF	NI	hollow fiber	5 s	[72]
pilot	submerged	UF	NI	hollow fiber	10 s	[73]
pilot	submerged	UF	PES	flat sheet	30 s	[74]
pilot	submerged	UF	PES	flat sheet	30 s	[75]
pilot	submerged	UF	NI	hollow fiber	50 s	[78]
pilot	submerged	MF	PVDF	hollow fiber	60 s	[79]
pilot	external	UF	NI	hollow fiber	50 s	[82]
bench	submerged	UF	ceramic	NI	12 h	[87]

NI-no information, PES-polyethersulfone, PVDF-polyvinylidene.

3.2. Physio-Chemical and Chemical Cleaning

Chemically enhanced backwashing is an essential process for the effective mitigation of the fouling phenomenon in AnMBRs. This strategy has been performed in several studies [21,74–76,79,80,82,84,87,89,95,96] wherein both submerged and external AnMBRs have been applied. During backwashing, liquid flows from the permeate side to the feed side, leading to the removal of the matter loosely attached to the membrane surface and deposition inside its pores [140,141]. In most of the analyzed studies, the applied backwashing was enhanced with the use of sodium hypochlorite (NaClO) and citric acid ($C_6H_8O_7$). Worthy of note, in industrial installations, backwashing is performed fully automatically [137].

Chemical membrane cleaning, including soaking, has been successfully used as a fouling mitigation strategy in numerous studies [29,72,76,80,81,85,90–92,100–102]. Our literature review indicated that among the most commonly used chemical agents are alkalis (sodium hydroxide, NaOH), oxidants (NaClO), chelates (ethylene diamine tetraacetic acid, EDTA), as well as acids (citric acid and nitric acid, HNO_3) (Figure 6). As mentioned by Puspitasari et al. [142], the efficiency of the above-mentioned agents depends mainly on the following factors: agent chemical properties, membrane characteristics, and cleaning operating conditions. Furthermore, the choice of proper cleaning products requires knowledge of the feed nature [143]. Importantly, in membrane technology, a blend of various cleaning agents is often used.

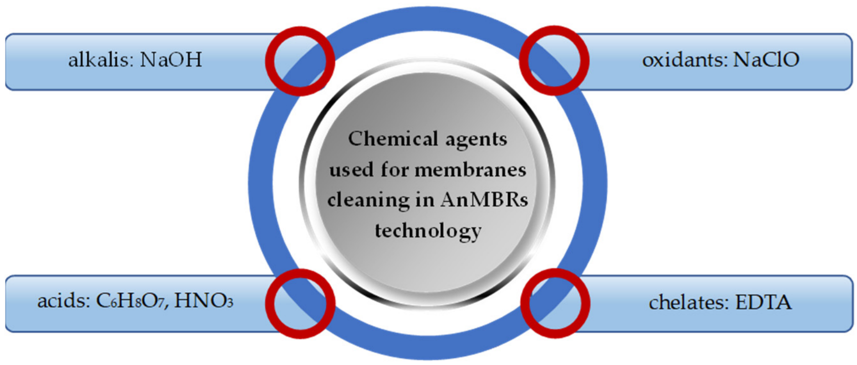

Figure 6. Chemical agents used for membrane cleaning in AnMBRs technology applied for the treatment of municipal and domestic wastewater.

For instance, Huang et al. [85] applied the soaking of PES microfiltration membrane in a NaClO solution overnight followed by thorough flushing with deionized water. NaClO is the most used oxidant employed for membrane cleaning. It allows for the removal of organic and biological foulants via oxidation and disinfection processes [68,69]. It may degrade functional groups of natural organic matter (NOM) into ketonic, carbonyl, and aldehyde groups, leading to their hydrolysis at high pH levels [144]. Moreover, NaClO enhances the detachment of organic molecules from the membrane surface by increasing their hydrophilicity [138]. In another study [101], a PVDF ultrafiltration membrane was physically and chemically cleaned. The chemical cleaning included submerging the membrane into the NaClO solution for 2 h. Regarding ceramic membranes, Song et al. [102] demonstrated that the permeate flux can be successfully restored by the use of NaOH. Worthy of note, in the above-mentioned study, the chemical cleaning was conducted under a temperature of 70 ± 1 °C. Clearly, NaOH is a well-known chemical cleaning agent which acts by both disintegrating large organic particles (e.g., colloids) into fine particles and hydrolyzing organic matters into small molecules [145]. In addition, NaOH reacts with fats and oils to form water-soluble soap micelles (saponification process) [139] and can be successfully used to remove silicates and inorganic colloids [146]. In [147], it was indicated that the combination of oxidants and alkaline agents removes organic foulants with greater efficiency than oxidant agents alone. However, it should be pointed out that chemical cleaning with the use of NaOH and NaClO solutions may lead to a loss of the polymeric membranes' integrity the shortening of their lifespan [110,148–150]. Hence, in order to prevent membrane damage, chemical cleaning should be carried out at a suitable frequency [151] with the use of suitable agents of an acceptable concentration.

It is well known that improving the membrane cleaning efficiency may be achieved by sequentially combining alkaline or oxidant reagents with acids, such as citric and nitric acids. This can be explained by the fact that acids are effective agents for the dissolution of scale compounds and metal oxides via solubilization and chelating processes [138]. Moreover, HNO_3 may also be used to clean organic and biological foulants by nitration [137]. This strategy of chemical cleaning has been well adopted in studies focused on the applications of AnMBRs for biogas production [79,80,90–92,96]. For instance, in [91], in order to restore the MF performance, a chlorinated polyethylene (PE) membrane was first cleaned with tap water and then was soaked in solutions of citric acid and NaClO solutions. Importantly, the above-mentioned agents are commonly used to neutralize residual alkalinity after alkaline cleaning and to remove mineral deposits that have been formed during the cleaning procedure [152].

4. Conclusions

The current study provides a comprehensive review of the performance of biogas production in submerged and external AnMBRs equipped with polymeric and ceramic membranes. Special attention has been paid to the impact of temperature and hydraulic retention time on the biogas yield. Moreover, possible fouling mitigation strategies were described in detail.

It was demonstrated that in recent years, significant progress has been made in research focused on the AnMBR applications for biogas production. Indeed, the reliability and stability of this technology have been qualified by investigations carried out with the use of laboratory- and pilot-scale installations. The evidence from this study confirmed that AnMBR technology can be successfully used for biogas production via municipal and domestic wastewater treatment.

Importantly, the performed literature review indicated that it is not very straightforward to define the impact of HRT on biogas production in AnMBRs. Indeed, there has been some disagreement concerning the effect of this parameter on the process performance. However, data analysis presented in the current study demonstrated that, generally, the highest values of the methane yield are obtained for the shortest hydraulic retention time. In addition, increasing the temperature has a positive impact on the methane yield.

In addition, the fouling mitigation strategies commonly applied in AnMBR technology were presented and discussed. It was pointed out that, so far, a large number of protocols for membrane cleaning have been presented in the literature. Furthermore, it has been shown that in order to restore the initial permeate flux, a combination of several cleaning methods is often required. This can be explained by the fact that some wastewater compounds form irreversible fouling on the membrane surface and inside its pores, removing of which requires specific conditions.

Finally, the findings presented in the current study may be particularly important for the determination of operating conditions as well as suitable fouling mitigation strategies for laboratory- and pilot-scale AnMBRs used for biogas production via the treatment of municipal and domestic conditions. It should be pointed out that the present study highlights further research efforts which are essentially required.

5. Challenges and Perspectives

Our thorough literature review allowed showed that future studies on biogas production in AnMBRs via the treatment of municipal and domestic wastewater are required. More precisely, so far, the vast majority of experimental studies have been carried out with the use of polymeric membranes. Hence, due to the many unique advantages of ceramic membranes, their application in AnMBR technology is a vital issue for future research. Most importantly, the impact of operating conditions on biogas yield requires further efforts and must be analyzed in more detail. The effect of hydraulic retention time on the biogas production yield has not been thoroughly defined. In addition, as reported in the literature, studies have been performed mainly under psychrophilic and mesophilic conditions. Hence, an important issue to resolve for future studies is to determine the biogas production yield in AnMBRs under thermophilic conditions.

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