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Chapter 13

Energy production in anaerobic membrane bioreactors: Opportunities and challenges

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Abstract

Anaerobic Membrane Bioreactors (AnMBRs) have been favored over their aerobic counterparts because the former have the potential to recover energy from different types of wastewater streams. Currently, the majority of these AnMBR operations involve big improvements in methane production. Technical studies have been undertaken showing that biohydrogen and Volatile Fatty Acid (VFA) can also be a potential source of energy recovered from the AnMBR. Recent developments in AnMBR design have made possible the production of methane and biohydrogen or VFA simultaneously in various stages of the bioreactor. Controlling process inhibition and improving the energy density through post-treatment can be challenging for sustainable energy recovery from this system. There are challenges in designing a safe and reliable storage system for

28 biohydrogen. Economically, VFA has not yet been considered a viable option due to the cost-
29 intensive separation and purification process. Nonetheless, overcoming these challenges can lead
30 to a potential solution as a way to maximize energy recovery from AnMBRs.

31 **Keywords:** Anaerobic, fouling, methane, biohydrogen, energy

32 **1. Introduction**

33

34 Anaerobic Membrane Bioreactors (AnMBRs) can recover energy from different wastewater
35 streams through the degradation of organic waste. In waste management, the anaerobic process
36 has been favored over the aerobic process as it offers an energy recovery option through the
37 production of methane-containing biogas. Furthermore, any full-scale operations of the anaerobic
38 process are not yet possible in the waste management industry due to a low energy density, poor
39 cost effectiveness and technical issues in the process operations as well [1].

40

41 Over the past few years, energy recovery has been mainly confined to generating methane which
42 is the final product of anaerobic digestion. Anaerobic digestion is a combination of four major
43 biochemical steps: bacterial hydrolysis, acidogenesis, acetogenesis, and methanogenesis.
44 Methanogenesis has been identified as the most critical step as it is the slowest among all other
45 stages in anaerobic digestion (AD). It is also dependent under strict operating conditions. As a
46 result, improving methane production using the AD process was extensively studied in order to
47 improve its energy efficiency [2].

48

49 The opportunities available in energy recovery from the AnMBR can be divided into two major
50 streams. Firstly, the operating conditions of AnMBR can be optimized for final product recovery

51 without a change in the AnMBR design. This approach also involves integrating pre- and post-
52 treatment processes of wastewater streams to improve product yields. Secondly, the product
53 spectrum can be controlled for an AnMBR to produce Volatile Fatty Acid (VFA), and biohydrogen
54 instead of methane. The second approach includes design modification, optimizing the process
55 parameters, coupled with the inhibition of the methanogenesis process [3, 4].

56

57 With the aim of producing methane, AnMBR technology is now at a more mature level of
58 development. Studies have shown that the growth rate for methanogenic microorganisms is higher
59 in thermophilic conditions (50–70 °C) compared to the rate in mesophilic or psychrophilic
60 conditions. A pH range of 6.8-7.4 has been identified as ideal for the production of methane using
61 the anaerobic process. Unlike temperature and pH, the optimum value of Hydraulic Retention
62 Time (HRT) and Solid Retention Time (SRT) cannot be defined universally as both depend on the
63 design of the bioreactor, as well as the composition of feed material, including the additional
64 operating conditions like temperature and pH [5]. Apart from the process parameters, chemical
65 additives like nanoparticles containing Co, Ni, Fe, Fe₃O₄, biochar, ozone, etc., and treatment
66 processes like high pressure, ammonia soaking, alkaline pre-treatment have also been applied to
67 improve the production of methane [5-7]. Despite these improvements, methane production has
68 still not resulted in a net overall revenue earned from using the AnMBR. Hence, additional
69 challenges lie in the percentage of methane actually produced from biogas in the AnMBR. Pipeline
70 quality bio-methane production, and CO₂ removal from produced biogas are considered the major
71 challenges of energy recovery from the AnMBR.

72

73 VFAs have been identified as the potential raw materials of Polyhydroxyalkanoates (PHA), and
74 these include aldehydes, ketones, alcohols, and biogas. As a result, these are a potential resource
75 of energy recovery from the AnMBR. Economically, the production of VFA can be beneficial
76 compared to the revenue earned from the production of methane through anaerobic digestion.
77 Kleerebezem et al. (2015) compared the revenue earned from cardboard wastewater. The
78 comparison showed that the daily revenues earned from methane and PHA were 3.6 and 20.2 k€
79 respectively [8]. At the same time recovering VFA helps to avoid the problem of VFA
80 accumulation in the AnMBR. This helps to maintain a stable level of pH inside the reactor [9].
81 Therefore, producing VFA from an anaerobic process can be beneficial from both technical and
82 economic viewpoints. Challenges still lie ahead for the separation and purification technologies
83 involved in VFA recovery. For an anaerobic VFA production process, the costs associated with
84 extracting VFA are a major challenge for sustainable VFA production using the AnMBR.

85

86 Production of biohydrogen using the anaerobic process is favored for methane production due to
87 a number of reasons. For example, the common fuel properties such as energy density, wide
88 flammability limit, and environment-friendly combustion have made biohydrogen a better energy
89 source over methane. Whilst AnMBRs are designed to produce biohydrogen instead of methane
90 this does not have the negative environmental impact caused by the dissolved methane.
91 Simultaneously, production of hydrogen and methane can improve the overall product revenue of
92 the AnMBR. However, the biggest challenge in biohydrogen production is in designing a safe
93 storage and transportation system for biohydrogen. Low storage density, hydrogen loss due to the
94 boiling-off phenomenon, and methane embrittlement due to hydrogen penetration are the major
95 issues in biohydrogen storage and transportation [4].

96

97 This chapter includes the most recent opportunities that AnMBR technology can offer in terms of
98 energy recovery. Although the different designs and multiple product recovery solutions do offer
99 an improved energy recovery from the AnMBR. The current technical and economic challenges
100 must be overcome to replicate the research successes in industrial practical applications.

101

102 **2. Current energy production scenario**

103

104 The current status of energy production in an AnMBR is mainly dependent on the production rate
105 and yield of methane. Although VFA and biohydrogen are considered to be useful resources, they
106 have been recovered with methane as a by-product. The amount of energy recovered from an
107 anaerobic process depends on feed composition, bioreactor design and arrangement, type of pre-
108 and post-treatment processes and above all on the microbial activity. Table 1 lists some examples
109 of anaerobic membrane bioreactors, and their energy production in terms of methane, biohydrogen,
110 and VFA production.

111

insert Table 1

112

113 Table 1 shows a minimum of 86% and a maximum of 99% COD removal for different wastewater
114 streams. Landfill leachate treated in the cross-flow ultrafiltration AnMBR indicated the highest
115 methane production of 460 L/kg COD. The potential of AnMBR in energy production can be
116 evaluated through COD mass balance, and biogas production in terms of methane. The COD fed
117 into the system is usually divided considering COD present in the bioreactor. For example, Gianico
118 et al. (2013) have identified a consumption amount of 1.42 g COD for 1 g of biomass, and the total

119 amount is converted into 0.35 L of methane under standard temperatures and pressure. Therefore,
120 for a given anaerobic process the potential energy production in the form of methane can be
121 calculated through the amount of COD consumed by the system [22, 23].

122

123 However, energy recovery from the AnMBR through the production of methane needs to address
124 the technical, economic and environmental issues. Since the final stage of anaerobic methane
125 production is the slowest (AD stage), the production of methane containing biogas is, in fact, a
126 very slow process. Different pre- and post-treatment processes integrated with the AnMBR
127 technology have been effective to accelerate the initial hydrolysis or acidogenesis process, but it
128 cannot necessarily increase the speed of methane production to a great extent [1]. Currently, the
129 percentage of methane in the produced biogas has become a higher concern. For different
130 AnMBRs, the composition of produced biogas depends on the bacterial community, substrate, feed
131 composition, and operating conditions [3, 24, 25]. For industrial application, it is a challenge to
132 maintain the same feed composition at long-term AnMBR operations. Consequently, the methane
133 composition in the produced biogas cannot be maintained at a fixed value.

134

135 Energy recovery from the AnMBR through methane is also largely affected by the possible
136 inhibition of methanogenesis due to the chemicals produced in the intermediate stages of anaerobic
137 digestion. AnMBR operating in a high Organic Loading Rate (OLR) or short Hydraulic Retention
138 Time (HRT) experiences a fast hydrolysis process that eventually leads to a higher rate of VFA
139 production. The produced fatty acids can accumulate inside the reactor as they are consumed at a
140 slower rate by the methanogens. The accumulated fatty acids can be responsible to cause a sharp
141 decrease in the reactor pH and make the operation unstable.

142

143 Production of methane involves environmental outcomes like aquatic eco-toxicity, human toxicity,
144 abiotic depletion and above all global warming [26-28]. The combustion product of methane
145 includes CO₂ and CO based on the oxygen supply. Both these combustion products are potentially
146 responsible for increasing the effects of global warming from using the AnMBR. At room
147 temperature, about 22.7 mg of methane can be present in each litre of bioreactor effluent as
148 dissolved methane. The dissolved methane in the AnMBR effluent is directly responsible for
149 causing adverse impacts on the environment, such as freshwater eco-toxicity and human toxicity.
150 Furthermore, the net energy production from the AnMBR depends on the amount of energy
151 required in AnMBR operations. The current mode of biogas production requires biogas scouring
152 but this consumes most of the energy that an AnMBR requires for its operation. Khan et al. (2016)
153 in their study reported that the gas scouring in a AnMBRs treated a volume of 20,000 m³ municipal
154 wastewater. This required 46.7% of the total energy cost. Their study also noted that 73.5% of the
155 total energy was consumed by a biogas recycle blower [recycling blower?] in an AnMBR treating
156 (3.2 ± 0.7 m³/day) sulphate-rich urban wastewater [9].

157

158 The concept of recovering biohydrogen and VFA from AnMBR is relatively new. Only a few
159 studies have so far been published on producing biohydrogen and VFA from AnMBRs. Table 2
160 lists some commonly used AnMBR configurations along with the production rates, and yields of
161 biohydrogen for each system.

162

163

insert Table 2

164

165 From Table 2, it is evident that only a few research studies have been done on producing
166 biohydrogen from AnMBR. This suggests there is not enough data in these research studies that
167 actually compares the expected revenues and operating costs. Therefore, it is difficult to
168 demonstrate the feasibility of biohydrogen production from an economic viewpoint. Apart from
169 biogas and biohydrogen production, extracting VFA from AnMBR has been a major challenge as
170 this actually limits the economic feasibility of VFA production. Production of VFA from AnMBR
171 has not been widely accepted for many reasons. One of the primary concerns is associated with
172 the cost involved in separation, and post-treatment of VFA. The production of VFA can be
173 maximized at low HRT and high OLR. Both these operating conditions are responsible for causing
174 severe membrane fouling. The fouling layer can eventually retain VFA inside the anaerobic
175 bioreactor, and make the separation and purification processes even more challenging [38, 39]. On
176 this issue, Khan et al. (2019) carried out an experiment to produce VFA from low strength synthetic
177 wastewater using a single stage AnMBR [3]. Their results showed the highest VFA yield of
178 $48.20 \pm 1.21\%$ (mg VFA/mg COD_{feed}) at HRT lasting 8 hrs. The corresponding membrane fouling
179 rate was higher compared to the rates observed at HRT lasting 48, 24, 18, and 12 hrs. The same
180 study revealed an overall reduction in the VFA yield due to COD removal efficiency being at
181 35.39% when the OLR rose from 68.75 to 89.38 mg COD/L.h.

182

183 The present scenario of energy recovery from the AnMBR demonstrates not enough research has
184 been undertaken to extract VFA and biohydrogen. The issues involved in bioreactor operation
185 along with the costs involved in product recovery have for this reason made AnMBR a less
186 attractive option in energy recovery.

187

188 **3. Energy production opportunities**

189 **3.1 Production of biohydrogen**

190 Biohydrogen is produced from the volatile fatty acids during acidogenesis, and acetogenesis stages
191 of anaerobic digestion [4]. Compared to methane, hydrogen has potential advantages, for instance,
192 higher energy density and clean combustion production. Additional fuel properties of hydrogen
193 have been compared with methane and these are summarized in Table 3 below.

194

195

insert Table 3

196

197 From Table 3 it is evident that, besides energy density, hydrogen has significantly higher specific
198 heat constant, wider flammability limit in air (%), higher flame temperature (K) and greater
199 explosion limit. As a result, biohydrogen can be considered a better alternative than methane when
200 fuel properties are taken into consideration. During the acidogenic phase, production of
201 biohydrogen can be divided into three different types. H₂ and CO₂ are produced with acetic and
202 butyric acid during butyrate-type fermentation. Propionate-type fermentation does not contribute
203 significantly to biohydrogen and CO₂ production. Acetic, propionic and valeric acids are the major
204 products derived from this type of fermentation. Ethanol-type fermentation involves the
205 production of ethanol, and acetic acid with biohydrogen and CO₂. VFA produced during this stage
206 goes through the third anaerobic stage called acetogenesis. During this stage, the produced volatile
207 fatty acid components are again converted to acetates and biohydrogen. The amount of
208 biohydrogen produced throughout the third acetogenic stage is significantly larger compared to
209 the amounts generated during the second stage. The resulting biohydrogen from the second and
210 third anaerobic stages is directly consumed in the final stage of anaerobic digestion. At this point,

211 hydrogenotrophic methanogens consume the available biohydrogen to produced methane and
212 carbon dioxide. Biohydrogen acts as a proton donor at this stage. Consequently, it is important to
213 inhibit the activities of methanogens for the production of biohydrogen [4].

214

215 Type of substrates plays a very important role in improving the yield of biohydrogen produced
216 from the anaerobic process. Although only very few research studies have been done on generating
217 biohydrogen from the AnMBR, different anaerobic digestion processes have demonstrated
218 promising results. Table 4 shows the highest biohydrogen yield achieved from a range of different
219 substrates and bioreactor configurations. Findings from these studies can be applied to AnMBRs,
220 and it can eventually contribute to improving the amount of energy recovered from it.

221 **# insert Table 4 ##**

222

223 Table 4 shows that a fluidized bed reactor produces the highest biohydrogen yield (4.26 mol
224 H₂/mol sucrose). It is significantly larger than the other biohydrogen production processes.
225 Continuous stirred-tank and fluidized bed reactors have proved to be efficient in biohydrogen
226 production. Modified designs can be applied to existing AnMBR technology to improve
227 biohydrogen production. Hexose and glucose are two major carbon sources that have shown a high
228 conversion rate to biohydrogen. Some research studies have set out to optimize the production of
229 biohydrogen. Temperature, pH, Hydraulic Retention Time (HRT), Solid Retention Time (SRT)
230 and Organic Loading Rate (OLR) have been further refined for different processes involved in
231 generating biohydrogen (both HRT and SRT), organic loading rate and specific chemical additives
232 that enhance biohydrogen production.

233

234 Temperature has a positive effect on the production of biohydrogen through the anaerobic process.
235 Since hydrogen is produced at the second and third anaerobic stages, a high rate of initial
236 hydrolysis and biomass acclimatization can increase the rate of biohydrogen being produced. In
237 general, high temperature favors the biomass acclimatization and the rate of initial hydrolysis. For
238 example, Zhong et al. (2015) revealed that the biohydrogen production rate increased from 116.5
239 to 131.5 ml/ g-COD when the temperature rose from 40 to 60 °C [55]. High temperatures can also
240 be effective in inhibiting the microbial activity of the methanogens. According to the findings
241 documented in Jariyaboon et al. (2015), anaerobic sludge treated at 100 °C for 30 minutes can
242 inhibit the activity of the methanogens. Unfortunately, the findings from this research are still
243 confined to laboratory scale applications [56]. For industrial processes, the feasibility of using high
244 temperature can be assessed based on the expected higher revenue generated from the
245 biohydrogen.

246

247 pH is the second operating condition that can be optimized so that the ability to produce
248 biohydrogen is maximized. Biohydrogen is favored within a pH range between 5.5-6.8, whereas a
249 pH level below 4.5 is said to be inhibitory. Most of the research findings have identified pH 5.5 to
250 be the optimum value for the production of biohydrogen [4].

251

252 HRT, SRT and OLR are the operating conditions depending on the design and arrangement of the
253 bioreactor, including the type and composition of the substrate. Hence, it is important to understand
254 these changes in biohydrogen production when the parameters change for different anaerobic
255 hydrogen production processes, as a change in HRT or SRT actually changes the optimum OLR
256 in an anaerobic process. Technically, the HRT of a bioreactor is designed to inhibit the activity of

257 hydrogen consuming hydrogenotrophic methanogens whilst simultaneously preventing the
258 washout of hydrogen produced bacteria. In general, a smaller HRT can increase the production
259 rate of biohydrogen [5]. Angeriz-Campoy et al. (2015) demonstrated that HRT values between 3 to
260 6 hrs can maximize the biohydrogen production rate (25.9 L H₂/L-d) from granular hydrogen
261 producing mixed cultures [57]. An experiment by Kumar et al. (2014) reveals that the highest
262 biohydrogen production rate (4.49 L/L/d) was attained at a HRT range between 6-18 hrs [58].

263

264 The OLR and HRT share a unique relationship to maximize the production of biohydrogen in an
265 anaerobic process. For AnMBRs, it is particularly challenging as a high organic loading rate can
266 be responsible for severe membrane fouling and could make the operation unstable through having
267 a high production rate of VFA. Therefore, it is rather practical to ascertain the optimum pair of
268 HRT and OLR rather than optimizing them individually. For example, for a given anaerobic
269 process, a particular HRT might involve an OLR high enough to make the operation of AnMBR
270 unstable.

271

272 Several research studies have been conducted to carry out the influence of HRTs and OLRs on
273 biohydrogen production. According to Zhang et al. (2013) the production of hydrogen in an
274 anaerobic CSTR rose when the operating conditions were adjusted to 60 g-glucose/L-reactor/day
275 of 6 hrs HRT using 20 g-glucose/L/day, and 12 hrs of HRT [59]. This was then followed by another
276 experiment to optimize the HRT, and OLR simultaneously. Four different OLRs (10, 15, 20 and
277 40 g/L/day) were applied at 6, 12 and 24 hours of HRT. These results determined that a
278 combination of 40 g/L/day and HRT of 12 hrs provides the maximum yield of hydrogen [60].

279

280 The opportunities in energy recovery through the production of biohydrogen still require extensive
281 research and new initiatives to produce feasible results from both a technical and economic
282 perspective. Different types of substrates, design modifications, and ensuring process optimization
283 are evident approaches to increase the production of biohydrogen using AnMBRs.

284

285 **3.2 VFA Recovery**

286 The products of VFA include biogas and alcohol which are deemed to be a useful source of energy.
287 This recovery of VFA could then contribute to the improvement of the energy recovery from the
288 AnMBR. During anaerobic digestion, the production of VFA can occur in two different ways.
289 Initially, the complex organic compounds present in the feed are converted to soluble
290 carbohydrates, amino acids and fatty acids through the process of hydrolysis. VFA is also produced
291 at the second anaerobic stage when the products in the initial stage are converted again to produce
292 VFA. As VFA is consumed to produce methane at the final anaerobic stage, a very low rate in
293 VFA production can result in a low production rate of biogas. In contrast, an excessive production
294 of VFA can have adverse effects on the total production of (final) biogas product as the rate of
295 consumption of VFA is slower compared to the initial anaerobic stages of VFA production. In fact,
296 a major problem in the AnMBR is the accumulation of VFAs inside the reactor. The accumulation
297 triggers a sharp pH drop, and this disrupts the stability of AnMBR operations [3, 61].

298

299 Recovering VFA can actually improve product revenues that eventually improve the overall
300 income earned from the AnMBR, and this in turn improves the energy efficiency of the system.
301 Although different organic components like alcohols, aldehydes, ketones, and organic acids can
302 be synthesized from VFA, it has also been used a potential precursor of biodegradable polymers

303 and biogas. From a technical perspective recovering VFA helps to maintain a stable pH in the
304 AnMBR especially at high organic loading rates and lower HRTs. Consequently, the capacity of
305 a given AnMBR can be increased when it is designed for VFA and methane recovery. Hence, VFA
306 can be a favorable AnMBR economically as compared to the traditional methane. AnMBRs
307 designed to produce VFA need to apply the selective inhibition of methanogens which are the
308 major VFA consumers during anaerobic digestion. Heat shock and load shock are two common
309 methods that can inhibit the activity of the VFA-consuming microbes. Besides selective microbial
310 inhibition, the common process conditions can be optimized to maximize the production of VFA.

311

312 Generally, an increase in temperature has a positive impact on VFA production. Yuan et al. (2011)
313 carried out an experiment to observe the effect of temperature on VFA production. In this
314 observation three different temperatures (24.6, 14 and 4 °C) were applied to obtain the effects on
315 VFA production from waste activated sludge, and this revealed that the highest temperature
316 resulted in maximum VFA production (2154 mg L⁻¹) [62]. Several other studies have reported an
317 increase in temperature within the psychrophilic (4–20 °C) and mesophilic (20–50 °C) range
318 increases VFA production. This increment is associated with the fact that the rate of hydrolysis in
319 an anaerobic process generally increases at high temperature which results in a higher production
320 rate of VFA [62, 63].

321

322 Besides temperature, pH affects the overall VFA production in a more complex way. The
323 components present in the overall VFA mixture requires different optimum pH values. For
324 simplicity, the current section will focus on the overall VFA yield, and production rate only.

325 Research studies have shown that between pH 5.0 and 6.0, the highest overall VFA concentration
326 is observed regardless of the type of which inoculum was used while producing VFA from food
327 waste [64]. However, Khan et al. (2019) reported that the highest VFA yield from low-strength
328 synthetic wastewater recorded 48.74 ± 1.5 mg VFA/ 100 mg COD_{feed} at pH 7.0, whereas Jie et al.
329 (2014) documented at pH 10.0 the accumulation of VFA reached the maximum limit during
330 anaerobic digestion of excess sludge (ES) [61, 65]. As different types of microbial species are
331 present in different inoculums, their optimum growth rates vary at different pH levels. Therefore,
332 it is more practical to analyze the microbial species first rather than generalizing an optimum pH
333 level for VFA production. It is evident that operational parameters like HRT and OLR rely on the
334 design of the bioreactor. Between these two, optimum HRT can be generalized for VFA production
335 from an anaerobic process. A general decrease in HRT of an anaerobic process results in increased
336 VFA production [66]. Khan et al. (2019) demonstrated that for an AnMBR treating low-strength
337 synthetic wastewater, 8 hrs of HRT provide the highest VFA production rate and yield [3].
338 However, it is also important to consider the membrane fouling, nutrients, and removal efficiency
339 of COD in the AnMBR at low HRTs [9, 24].

340

341 ***3.3 Two-stage AnMBRs for multiple AnMBR product recovery***

342 Two-stage AnMBRs have an interesting design that separates the initial stage of acidogenesis and
343 final stage of methanogenesis [67, 68]. The produced VFA accumulated inside an AnMBR can
344 inhibit methane production by sharply decreasing the level of pH. As a result, two-stage AnMBR
345 design offers the advantage of producing VFA, biohydrogen and methane simultaneously. In
346 addition to this, extracting multiple AnMBR products simultaneously can improve product
347 revenues earned from an AnMBR, and improve energy efficiency. However, the two-stage design

348 has not yet been popular due to the high cost in initial installation and the high energy requirements
349 in the process operation [38, 68-70]. Two-stage AnMBR designs have been particularly favorable
350 for extracting multiple products from the AnMBR. However, much research needs to be
351 undertaken to compare the increase in product revenues, added costs in installation and operations
352 for the two-stage design. Table 5 summarizes the features of some two-stage anaerobic bioreactors
353 that have been employed for multiple product recovery.

354 **# insert Table 5 ##**

355

356 The information provided in Table 5 when analyzed provides two different viewpoints. Firstly,
357 there is the lack of research done on how to produce VFA and methane simultaneously from the
358 anaerobic process. Recovering VFA can actually improve the production of methane at the final
359 stage of an anaerobic process. At the same time, it reduces potential hazards of process inhibition
360 due to a sudden drop in pH [55]. Secondly, the potential of the two-stage AnMBRs has not been
361 completely discovered for multiple product recovery. The reasons are mainly associated with
362 severe membrane fouling at low HRT, and high OLR, a high initial cost of installation and high
363 energy requirements in the bioreactor operation.

364

365 **4. Challenges**

366

367 Various challenges lie ahead to improve energy recovery from the AnMBR. They mainly include
368 controlling process inhibition, storage and transportation of biohydrogen, recovery of dissolved

369 methane, VFA extraction and purification, and finally the need to reduce costs when operating the
370 AnMBR.

371

372 ***4.1 Controlling process inhibition***

373 Recovering energy from the AnMBR can be particularly challenging because of potential process
374 inhibitions due to the compounds produced at different stages of anaerobic digestion. The major
375 inhibitors of the anaerobic process include five major categories: ammonia; VFA; organic
376 toxicants; heavy metals; and sulphides. The following sub-section describes the challenge involved
377 in controlling the concentration of inhibitory components during anaerobic digestion.

378

379 **4.1.1 Ammonia**

380 Ammonia is one of the most common process inhibitors in anaerobic digestion. AnMBRs treating
381 wastewater and wastewater streams with a high amount of nitrogen can release ammonia nitrogen
382 in the form of NH_4^+ . Ammonia can also be present in the AnMBR in the form of free ammonia
383 (NH_3) which is responsible for inhibiting methane production.

384

385 Different studies have shown a reduction of 50% in methanogenic activity in upflow anaerobic
386 sludge bed (UASB), and expanded granular sludge bed (EGSB) reactors at 2.48 and 2.89 g/L
387 concentrations of ammonia nitrogen, respectively. Free [Free radicals derived from this?] ammonia
388 ammonia can rapidly diffuse into the cell membrane and cause proton imbalance whereas
389 ammonium ions can directly inhibit the methane synthesizing enzyme [81].

390

391 Controlling ammonia inhibition can be challenging, current approaches include increasing the
392 SRT, dilution, and reducing the bioreactor pH. Few studies have proven that the addition of zeolite
393 along with humic acid can reduce ammonia inhibition in the anaerobic process. Although certain
394 experimental initiatives have proven to be effective, controlling ammonia inhibition still remains
395 a challenge for large-scale operations.

396

397

398 **4.1.2 VFA**

399 Controlling the accumulation of VFA can be a challenge for single stage AnMBRs. VFAs can be
400 accumulated inside a reactor for many reasons: high OLR, low HRT, and severely fouled
401 membrane layers. High organic loading rate or low HRT can increase the rate of initial hydrolysis
402 in an anaerobic process whereas fouled layer on a membrane can reject the produced VFA inside
403 an AnMBR. Of the major VFA components, acetic and butyric acid can be easily consumed by
404 the methanogen. About 60% of the biogas is produced through the conversion of acetic and butyric
405 acid. The conversion of another major VFA component (propanoic acid) is thermodynamically not
406 favorable. Therefore, propanoic acid is mainly responsible for reducing the level of pH in an
407 AnMBR [3, 4].

408

409 VFAs can be equally damaging for biohydrogen production. They can be responsible for possible
410 deviation of the metabolic pathway from acidogenesis to solventogenesis. In this process, organic
411 solvents such as alcohols and acetone are produced by VFA. The accumulated VFA penetrates the
412 cell membrane, dissociates and increases the H⁺ ion concentration. A pH imbalance caused by high

413 H⁺ concentration can cause cell death and suppression. A combination of these events can inhibit
414 biohydrogen production [4].

415

416 **4.1.3 Organic toxicants**

417 The feedstock used in anaerobic digestion sometimes goes through different pre-treatment
418 processes, i.e. heat treatment, alkaline or acidic pre-treatment and these can speed up the hydrolysis
419 process. The pre-treatment processes can produce organic compounds that are toxic to the
420 anaerobic process [82]. Organic toxicants such as chlorophenol and halogenated open-chain
421 hydrocarbons can inhibit the overall anaerobic process. Chlorophenols directly disrupt the proton
422 gradient through the membrane and negatively affect the cellular energy transduction. This
423 outcome can in turn can cause process inhibition through a reduction in cell growth. Additionally,
424 open chain halogenated hydrocarbons like chloroform, trichloroethylene, and perchloroethylene
425 can also wield an inhibitory effect on methanogenesis. Furan, phenol derivatives such as Furfural,
426 Phenol, and Vanillin also exert an inhibitory effect on the production of biohydrogen [4, 81].

427

428 **4.1.4 Sulphides**

429 Different industrial effluents, such as those produced by tanneries, pharmaceuticals, and coal-
430 based power plants can produce wastewater streams that are rich in sulfide. The activities of
431 Sulphate Reducing Bacteria (SRB) and methane-producing bacteria are significantly affected by
432 the high sulfide concentration present in the bioreactor feed. In this case, a general decrease in
433 methane production was observed as it competed for the available carbon and hydrogen. Studies
434 have identified that H₂S concentrations of 160 and 220 mg/L can completely inhibit the microbial
435 activity of acetotrophic and hydrogenotrophic methanogens. A possible solution for solving this

436 problem is to incorporate a sulfide removal stage within the AnMBR design. For membrane
437 bioreactors, the biomass is retained inside the reactors for a longer period of time. In this case, the
438 adaptation of methane-producing bacteria to free H₂S can improve the methanogens' tolerance to
439 sulfides [81].

440

441 **4.1.5 Metal ions**

442 Light and heavy metal ions contribute to increase enzymic activity, cell metabolism and finally
443 promote bacterial growth. For instance, iron supports bacterial growth, stimulates enzymic
444 activities, and helps to eliminate sulfide inhibition during biohydrogen production. Yet, an iron
445 concentration above 100 mg/L can have an inhibitory effect on hydrogen production. The
446 inhibitory effect of Mg²⁺ ions has been observed above 20.0 mg/L although it works as a cellular
447 protein builder at smaller concentrations. Two other micronutrients, Na⁺ and Ca²⁺ show an
448 inhibitory effect above 2000 mg/L and 100 mg/L, respectively. Similarly, 1600, 15, 3 and 0 mg/L
449 are the threshold limits for Ni, Cr, Cu and Zn ions, respectively. Precipitation, coagulation and
450 sorption methods can be applied to remove or reduce the concentration of different metal ions
451 during anaerobic digestion [4].

452

453 **4.2 Dissolved Methane recovery**

454 Methane is a greenhouse gas and the global warming potential is 34 times greater compared to
455 CO₂ over a 100-year period. Nearly 2.8% of the total GHG emissions is related to anaerobic waste
456 and wastewater treatment processes that occur worldwide. Dissolved methane in the AnMBR
457 effluent is one of the main causes of destruction to the environment. At the same time, it reduces

458 the amount of recoverable energy from AnMBR. At atmospheric pressure [what specific pressure
459 amount are you referring to?] and a temperature of 25 ° C, 21.6 mg methane can be present in each
460 litre of water. The solubility of methane increases when the temperature is decreased. Anaerobic
461 processes operated at low temperatures can lead to 60% of the total methane being dissolved in
462 the bioreactor effluent whereas the percentage varies between 20 to 60% for sewage treatment.
463 Therefore, recovery of dissolved methane not only improves the energy recovery, but it also
464 reduces the negative environmental impacts of the AnMBR [83].

465

466 One common strategy for methane recovery is to integrate a post-treatment process for an
467 anaerobic bioreactor effluent. Aeration, air stripping, catalytic methane oxidation and membrane-
468 based separation have been used to remove dissolved methane. Membrane-based removal of
469 dissolved methane from liquid streams is the most effective and commonly used technology of
470 dissolved methane removal. Table 6 lists the common methane removal technologies for dissolved
471 methane removal from municipal wastewater.

472

473 **# insert Table 6 ##**

474

475 The issues that are involved in dissolved methane recovery are primarily technical and economical.
476 At the same time, dissolved methane can be responsible for creating an explosive atmosphere when
477 the concentration exceeds 0.14 g/L in a closed conduit. Typically, the energy demand for an
478 AnMBR process compared to other competitive anaerobic bioreactors is high. During municipal
479 wastewater treatment, a typical AnMBR can have an energy demand ranging between 0.03–16.52

480 kWh/m³ compared to 0.133–0.227 kWh/m³ of an AFBR- AFMBR system. The reasons for this are
481 linked to biogas sparging and the degree of supersaturation.

482

483 A novel process was designed using a down-flow hanging sponge in anaerobic domestic
484 wastewater treatment. Methane Oxidizing Bacteria (MOB) was used in this process to remove
485 dissolved methane from the effluent through oxidation. The highest methane removal rate was
486 2.2 kg-COD m⁻³ day⁻¹ but the study did not include the effect on sulfide and organic
487 carbon oxidation. A follow up study showed that above 90% removal rate for COD, sulfide,
488 methane, and ammonium can be achieved by integrating down-flow hanging sponge unit installed
489 in a UASB reactor. Although the findings show the technical feasibility of methane removal, it
490 does not provide any estimation of energy requirement in full-scale application [95].

491

492 Recovery of methane-using membranes involves different technical issues like the efficiency of
493 recovery, limitation in mass transfer and above all the energy required for the recovery process.
494 At the same time, controlling membrane fouling can also be a technical issue. Membrane modules
495 operated at a lower temperature can encounter higher resistance if and when the liquid viscosity
496 increases and diffusivity decreases. The energy efficiency of this recovery process becomes more
497 complex for AnMBRs operated below mesophilic and thermophilic conditions. At low
498 temperature, the solubility of methane in water increases and this in turn increases the energy
499 requirement for methane recovery. Therefore, from the perspective of improving energy
500 efficiency, methane recovery is not a feasible option at low temperatures. Optimization of process
501 conditions is another area for future research to improve the overall energy requirement in a
502 methane recovery process.

503

504 **4.3 Storage and transportation of biohydrogen**

505 The challenges involved in biohydrogen storage directly affect the initiatives for energy recovery
506 from AnMBR and made the energy recovery through hydrogen production less feasible for
507 industrial application. Storage of biohydrogen poses a greater challenge as it has wider
508 flammability (4 -75%) and explosion limit in air (13.0–59.0%) compared to methane. Although
509 different types of hydrogen storage systems are currently in operation in the industry, the type of
510 storage depends largely on the type of use. For automobile applications, gravimetric density is the
511 main design consideration for hydrogen storage. However, for hydrogen transportation, process
512 safety is the primary area of concern along with the density of hydrogen. The currently used
513 hydrogen storage system suffers from different technical and safety issues. They include: low
514 gravimetric density, evaporative loss, boiling-off phenomenon, hydrogen embrittlement, etc. The
515 following sub-section details the challenges involved in different hydrogen storage systems.

516

517

518 **4.3.1 Challenges in physical storage**

519 The physical storage of biohydrogen mainly includes storage in two forms, compressed gas and
520 cryogenic liquid hydrogen. Recently developed technologies in physical storage also include
521 adsorption on solid materials such as carbon nanostructure, Borophene, etc., and solid storage. The
522 most common physical storage involves pressurization up to 700 bars. Low storage density is a
523 major problem of this method. At 350 and 700 bars the density can be only up to 5.5 and 4.6%
524 (w/v) which is very low considering automobile applications. Recently developed storage material

525 based on carbon fiber can store 6–10 wt% H₂ at 350–700 bars but the energy needed for
526 compression and volume reduction still remains a burning issue for this process [4, 96].

527

528 Storing hydrogen as cryogenic liquid at low pressure eliminates the issue of low gravimetric
529 density; the density can be up to 20% wt at 1 bar and -253°C during this process. At the same time,
530 storing hydrogen as liquid introduces a new problem – evaporative loss. Reducing the cost
531 involved in the liquefaction process is also a major challenge in this process.

532

533 Different porous solid materials can accommodate molecular hydrogen in molecular state.

534 Clathrate compounds such as hydrates, fullerenes, graphene, etc., have served for the physical
535 storage of hydrogen. The storage capacity of each component depends on the porous structure,
536 available surface area and stability. Metal-organic frameworks (MOFs), CMPs (conjugated
537 microporous polymers), and HCPs (hyper-cross-linked polymers) have been extensively studied
538 in this process. Subsequently, the results have shown that the applicability of each type is limited
539 at a specific temperature. Research studies need to be conducted at different temperatures to
540 improve the application range of different adsorption components.

541

542 **4.3.2 Challenges in chemical storage**

543 The most recent studies have shown that metal hydrides can offer high storage capacity of
544 hydrogen and can release it at different temperatures and pressures. AB type alloys show high
545 absorption/desorption capacity usually containing high hydride equilibrium pressure. For example,
546 TiFe alloys have high hydride equilibrium pressure and low gravimetric storage capacity. To

547 resolve this issue, hydrides of sodium and lithium have been employed but using sodium and
548 lithium still remains expensive and thermodynamically unstable.

549

550 Metal borohydrides can be a possible solution in this case where both stability and high storage
551 capacity could be problematic. For example, LiBH_4 shows a hydrogen storage capacity of
552 18.5 wt% when the temperature for decomposition is 673K. When a catalyst (SiO_2) was added to
553 reduce the decomposition temperature, the overall storage capacity was reduced to 13.5 wt%.
554 Consequently, it is particularly challenging to design a borohydride alloy that offers both high
555 storage capacity and low temperature for decomposition.

556

557 Organic compounds such as Liquid Organic Heterocycles (LOH), hydrazines, organic acids, and
558 alcohols have been employed for hydrogen storage due to not much energy being required for
559 hydrogenation. To improve hydrogen storage capacity, solid catalysts have been used in this case.
560 Silver nanoparticles with pd coating have been used to decompose the stored hydrogen in formic
561 acid. Ionic liquids such as methyl-guanidinium borohydride can contribute to increasing hydrogen
562 release when added with chemical hydrides. However, they have also demonstrated synergistic
563 effects [96].

564

565 Hydrogen can be stored electrochemically where it is adsorbed on substances in aqueous solution.
566 The effectiveness of a particular material in this process depends on the discharge rate of hydrogen
567 and the storage capacity. In some cases, life cycle behavior is important because the material loses
568 the adsorption capacity after a certain number of adsorption/desorption cycles. In this scenario, the

569 properties of TiNi have been studied and the results showed storage capacity of 230 mAhg^{-1} but
570 the rate of hydrogen discharge was very slow. AB_3 type alloys such as LaNi_3 , CaNi_3 , etc., have
571 been investigated to increase the storage capacity of hydrogen through the electrochemical process.
572 However, improving the capacity again triggers a drop in the recyclability of this storage system.
573 Much more research needs to be done on discovering the intermetallic properties of these alloys.

574

575 The challenges involved in chemical and electrochemical storage of biohydrogen are many. The
576 catalysts synthesized for hydrogen storage in formic acid show improved performance at a certain
577 temperature and pressure. New research initiatives are needed to synthesize new catalysts for
578 biohydrogen storage in organic liquids. Improved rates of hydrogenation and dehydrogenation at
579 different temperatures and pressures are another concern in LOHCs. Most importantly, the
580 economic aspects of hydrogen storage through different chemical and electrochemical processes
581 have been neglected. This is potentially a serious issue when the storage system is subjected to
582 full-scale industrial application.

583

584 ***4.4 Additional challenges***

585 Separation and purification of VFA from different anaerobic processes have not yet been assessed
586 for their economic feasibility. Although currently available research shows the recovery of VFA
587 can be technically feasible, the cost involved in full-scale operation has not been addressed.
588 Currently extracting VFA using organic solvents is the most common separation process for lab-
589 scale operations. Reducing the cost of organic solvents for VFA recovery can be very challenging
590 in the VFA recovery process. Reduction in operating and maintenance costs is one of the most

591 widely researched areas in AnMBR technology. A typical AnMBR requires a lot of energy for gas
592 sparging, sludge feeder, stirring, permeate pump and membrane tank feeding pump. Additionally,
593 membrane fouling control, membrane cleaning and membrane replacement costs are essential
594 maintenance aspects of AnMBR operations.

595

596 Over the past few years, there have been significant improvements in membrane fouling control
597 and membrane fabrication processes. The costs involved in membrane fabrication have been
598 reduced and different physical and chemical processes for membrane fouling control have been
599 applied. However, only a few studies have characterized the problem of membrane fouling when
600 AnMBR is being operated to produce alternative AnMBR products like VFA and biohydrogen.
601 Recently developed membrane modules have a higher surface area, low energy requirement and
602 are more resistant to membrane fouling. For instance, a recently developed membrane module by
603 Pentair has 40% more surface area and requires 35% less energy during cross-flow operating mode
604 [97]. AnMBR systems that integrates Microbial Fuel Cells (MFCs) and Microbial Electrolysis
605 Cells (MECs) have shown that the voltage generated can be effective in controlling the fouling
606 through a reduction in foulants' deposition. However, the lab-scale successes have to be applied
607 in pilot/full-scale operations so that we know what the challenges are when attempting industrial
608 applications.

609

610 Pretel et al. (2014) [98] investigated the energy requirement of an AnMBR treating sulphate-rich
611 urban wastewater. According to their study, biogas sparging, membrane tank sludge feeding pump,
612 feeding and permeate pumps are the additional energy consumers in AnMBR operation. The
613 minimum energy requirement was 0.07 kW h/m³. A follow-up study [99] on this topic calculated

614 the minimum energy requirement for a system treating 50,000m³/d. The results showed the
615 minimum energy was in fact 0.04 kWh/m³ which is lower compared to their previous study. The
616 cost reduction opportunities still need to be explored for AnMBR treating different wastewater
617 streams. Challenges lie ahead to assess the energy consumption when product type, scale of
618 operation, and operating conditions are changed in an AnMBR.

619

620 **5. Conclusions and Perspectives**

621

622 The energy recovery options from AnMBR have not yet been completely discovered. Although
623 the currently available options mainly focus on methane, recovering VFA and biohydrogen from
624 AnMBR can actually improve the energy efficiency of this system. Challenges like controlling
625 process inhibition, recovering dissolved methane, storage and transportation of biohydrogen, and
626 a reduction in operating and maintenance cost have to be resolved before the full-scale application
627 of AnMBR.

628

629

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635

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948 Table 1: Current Status of energy production in AnMBR [10, 11]

Feed wastewater	Bioreactor configuration, membrane type	COD removal rate (%)	Energy Production (Methane) (L/kg COD)	Methane Conversion rate (%)	Reference
Municipal Wastewater	UASB, HFM PVDF	91	160.5 ± 5.6	45.3	[12]
Synthetic Municipal wastewater	CSTR, PVDF	90-96	338	96.5	[13]
Kraft evaporator condensate	UASB, submerged MF	97–99	290–310	-	[14]
Landfill leachate	Cross-flow MBR	UF 90	460	-	[15]
Real municipal	CSTR, ceramic membranes (Al ₂ O ₃)	86–88	300	-	[16]
Meat packing wastewater	AnMBR, hollow-fibre UF	88–98	130–180	-	[17]
Synthetic wastewater	CSTR, FSM PVDF	94.3–95.5	326	93%	[18]
Domestic and food waste-recycling wastewater	AnCMBR, N/A	97.9–99.3	200–220	-	[19]
Synthetic wastewater	Semi-continuous SAnMBR, flat sheet PVDF	>98	290	-	[20]
Synthetic wastewater	Granular AnMBR, PVDF HFM	93.7 ± 1.7%	156.3 ± 5.8	-	[21]

949 UASB - Upflow Anaerobic Sludge Blanket; HFM – Hollow Fibre Membrane; PVDF - Polyvinylidene
 950 Difluoride; MF – Microfiltration; UF - Ultrafiltration; CSTR - Continuous Stirred Tank Reactor; AnCMBR
 951 - Anaerobic Ceramic Membrane Bioreactor; SAnMBR – Submerged anaerobic Membrane Bioreactor.
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953 Table 2: Production of biohydrogen from AnMBR

Substrate	AnMBR type, membrane, surface area	Operating Condition(s)	Highest biohydrogen yield	Maximum production rate	Reference
Tofu processing waste	CSTR, hollow fibre, 0.025 m ²	HRT 2–8 h pH 5.5 ± 0.1 T 60 °C ± 0.1	42.4 L H ₂ /mol hexose	19.8 L H ₂ /L-d	[29]
Glucose	H ₂ producing AnMBR, hollow-fibre, 0.047 m ²	23.0 ± 0.1 °C pH 5.5 ± 0.1 HRT - 8 h SRT – 24 d	-	4.4 L H ₂ /L-d	[30]
Glucose	SAnMBR, Plate-flame type, 0.1 m ²	35 ± 0.5 °C HRT - 9 h SRT – 2–90 d	27 L H ₂ /mol glucose	5.8 L H ₂ /L-d	[31]
Glucose	H ₂ producing AnMBR, hollow-fibre	HRT 8h SRT- -24h 23 ± 1 °C 5.5 ± 0.1	40.2 L H ₂ /mol glucose	4.5 L H ₂ /L-d	[32]
Glucose	SAnMBR, plate flame (flat sheet) type, 0.1 m ²	SRT 90 d 35 ± 0.5 °C 5.5 ± 0.05	19.5 L H ₂ /mol glucose	2.5 L H ₂ /L-d	[33]
Glucose	AnMBR with magnetic stirring, microfiltration, 0.1 m ²	SRT 12.5 h HRT 9h 35 ± 0.5 °C pH 5.5 ± 0.1	35.4 L H ₂ /mol glucose	5.9 L H ₂ /L-d	[34]
Glucose	UASB, tubular ultrafiltration, 0.04 m ²	35 ± 1 °C 4.5 ± 0.1 HRT of 4 h	-	475 mL H ₂ L ⁻¹ h ⁻¹	[35]
Glucose	External dynamic MBR	37 °C. HRT 12,6,3, and 2 h pH 7.0	2.98 mol H ₂ /mol glucose	51.38 L H ₂ /L-d	[36]
Cheese whey	Ceramic-alumina membrane, 55 cm ²	SRT 50 days 20 °C	3087.57 mL/g bacteria (<i>R. aquatilis</i>)	-	[37]

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955 Table 3: Comparison of different fuel properties between methane and hydrogen [40, 41]

Property	Methane	Hydrogen
Energy Density (MJ Kg ⁻¹)	143	55.6
Specific heat capacity (Jkg ⁻¹ K ⁻¹)	2.22	14.89
Flammable limit (% v/v in air)	5.3 – 15.0	4.0–75.0
Density (Kg/m ³)	0.65	0.08
Stoichiometric air/fuel ratio (kg/kg)	17.1	34.2
Temperature of flame (K)	2148	2318
Explosion limit (% v/v in air)	6.3–14.0	13.0–59.0

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957 Table 4: Different anaerobic process for production of biohydrogen

Bioreactor	Substrate	Operating conditions	Highest biohydrogen yield	Reference
Continuous Stirred-tank Reactor	Starch	37 °C pH - 5.5	2.3 mol H ₂ / mol hexose	[42]
Stirred-tank Reactor	Food waste	35± 1 °C pH - 6.0	1.73 mol H ₂ / molhexose	[43]
Batch Fermenter	Distillery wastewater	37 °C pH -5.5	1000 ml H ₂ /L medium	[44]
Continuous Stirred-tank Reactor	Anaerobic sludge	70 °C pH – (7.0-8.0)	1.11 mol H ₂ /mol-hexose	[45]
Batch Fermenter	Activated sludge	55 °C pH - 7.0	1.25 mol H ₂ /mol glucose	[46]
Upflow anaerobic sludge blanket	Glucose	37 °C pH - 6.5	1.44 ± 0.1 mol H ₂ /mol-hexose	[47]
Fluidized bed reactor	Municipal sewage	40 °C	4.26 mol H ₂ /mol sucrose	[48]
Upflow anaerobic sludge blanket digestion	Activated sludge	35± 1 °C	1.7 mol H ₂ /mol-hexose	[49]
Batch Fermenter	Corn stalk	60 °C	89.3 mL H ₂ / g dry biomass	[50]
Continuous Stirred-tank Reactor	Glucose	37 °C pH - 5	1.3 mol H ₂ /mol glucose	[51]
Continuous Stirred-tank Reactor	Tofu-processing waste	60 °C pH - 5.5	2.3 mol H ₂ /mol glucose	[52]
Continuous Stirred-tank Reactor	Cow dung compost	33.5 °C pH - 5	2.15 mol H ₂ /mol glucose	[53]
Trickle Bed Sequenced Batch Reactor	Municipal wastes	pH – (4.65–5.87)	1.67 mol H ₂ /mol glucose	[54]

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959 Table 5: Two-stage anaerobic bioreactors for multiple product recovery

Bioreactor type, design	Feedstock	Operating conditions	Hydrogen/ VFA yield	Methane yield	Reference
Two-stage thermophilic anaerobic bioreactor	Palm oil mill effluent	55 °C HRT: H ₂ - 2 days; CH ₄ -10 days	H ₂ : 73 L/Kg-VS	342 L/Kg- VS	[71]
Two-stage anaerobic digester	landfill leachate	pH: VFA- 5.5 , 11 CH ₄ – N/A T: 37 ± 2 °C	VFA: 48 g/L leachate	6 g/L leachate	[72]
Two-stage anaerobic CSTR (H ₂) + AFBR (CH ₄)	Food waste	H ₂ -55 ± 2 °C; CH ₄ -37 ± 2 °C HRT: H ₂ - 3.5 days; CH ₄ - 1.5 days	115.2 ± 5.3 L/Kg-VS	334.7 ± 18.6 L/Kg-VS	[73]
Two-stage induced bed reactors (IBR)	Dairy processing waste	H ₂ - 60 °C; CH ₄ – 40 °C HRT: H ₂ – 3 days; CH ₄ - 15 days	160.7 ml/g- COD	168.8– 178.1 ml CH ₄ ml/g- COD	[55]
Two-stage anaerobic CSTR	Ethanol stillage, cake and glycerol waste	35 °C HRT: H ₂ -3 days; CH ₄ -12 days	48 L/Kg-VS	344 L/Kg- VS	[74]
Two-phase thermophilic CSTR	Bio-waste	T - 55°C HRT - 32 days	51 L/Kg-VS	780 L/Kg- VS	[75]
Two-stage anaerobic batch process	Wheat bran	37 ± 1°C HRT: H ₂ - 4 days; CH ₄ - 40 days	18.9 L/Kg- VS	243.5 L/Kg- VS	[76]
Two-stage anaerobic leach bed + UASB	Corn silage and cattail	37 °C HRT - 60 days	59.4 ± 4.1 L/Kg-VS	328.8 ± 16.8 L/Kg-VS	[77]
Two-stage anaerobic batch process	Grass silage	H ₂ – 35 °C; CH ₄ - 55 °C HRT: H ₂ - 6 h; CH ₄ - 6 days	6.46 L/Kg- VS	467 L/Kg- VS	[78]
Two-stage pilot scale CSTR	Sargassum sp.	55 °C HRT: H ₂ - 3.3 days; CH ₄ - 12.6 days	66.7 L/Kg- VS	720 L/Kg- VS	[79]
Two-stage anaerobic digestion	Vinasse	HRT: H ₂ - 2 d H ₂ ; CH ₄ - 15 days	14.8 l/kg VS substrate	274 ml/g VS substrate	[80]

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962 Table 6. Estimation of dissolved methane from different anaerobic bioreactors treating municipal
 963 wastewater

Bioreactor type	Operating Temperature (°C)	Scale	CH ₄ lost in effluent (%)	CH ₄ recovery process, (%) CH ₄ recovered	Reference
EGSB	16	Pilot	45	Sweep gas desorption, 72%	[84]
UASB	35	Bench	12	Degassing membrane 89% - 97%	[85]
UASB	25	Pilot	41	-	[86]
UASB	21–28	Pilot	70	Down-flow hanging sponge 76.8%	[87]
UASB	25	Bench	45	Desorption by membrane contactor 98.9%	[88]
AFBR- AFMBR	25	Bench	63	N/A	[89]
AnMBR	15	Bench	40–50	N/A	[90]
AnMBR	22	Pilot	19	N/A	[91]
SAnMBR	33	Pilot	43	Biogas assisted Stripping 57.4%	[92]
AnMBR	25	Bench	88	Desorption by membrane contactor 98.9%	[88]
EGSB	25	Bench	N/A	polypropylene membrane contactor 98%	[93]
Anaerobic digester	39.4	Bench	N/A	Adsorption by zeolite 56.82 ± 3.09	[94]

964 EGSB - Expanded Granular Sludge Bed; AFBR - Anaerobic Fluidized Bed *Reactor*; AFMBR - Anaerobic Fluidized
 965 Membrane Bioreactor

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