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Municipal wastewater treatment with anaerobic membrane Bioreactors for non-potable reuse: A review

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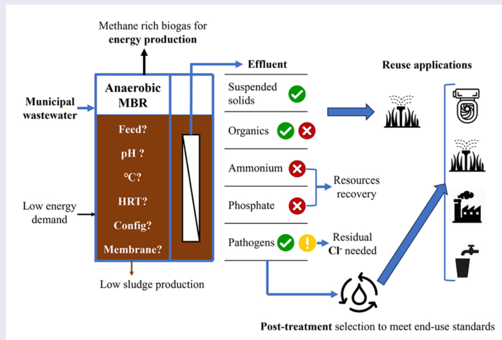
ABSTRACT

Anaerobic membrane bioreactors (AnMBRs) are seen as a promising technology for application in water reuse schemes. However, the evidence base for their potential and efficacy in this regard is fragmented. We draw together this disparate knowledge base to offer a state of the art review of municipal wastewater treatment with AnMBRs and evaluate the technology's potential application for water reuse. Water quality regulations and standards from different regions of the world are used as performance metrics to compare and contrast the treatment performance of pilot and laboratory scale AnMBR systems reported in the literature (*n* = 50). Findings indicate that under stable operation, AnMBRs have the potential to produce water for agricultural reuse. However, without post-treatment, AnMBRs are incapable of delivering water that meets other non-potable reuse standards across a range of important parameters such as COD, BOD_5, NH_3-N and TP. Analysis of key operational parameters determine the operation of AnMBR for non-potable reuse purpose cover influent water matrix, pH, temperature, hydraulic retention time, system and membrane configuration. An assessment of candidate post-treatment technologies suggests a tradeoff between the cost and effluent quality based on the reuse application requirement. We conclude by discussing a number of challenges and limitations to the use of AnMBRs for reuse applications in order to outline a pathway to maturity for effective treatment trains.



KEYWORDS Anaerobic; membrane bioreactor; post-treatment; standards; water reuse

HANDLING EDITORS Eakalak Khan and Lena Q. Ma

Introduction

Water stress is an increasingly urgent and widespread global challenge with water shortages highlighting the need for more sustainable water management strategies (Song et al., 2018). Water reuse is a useful foil to such water scarcity, also offering opportunities to recover nutrients and energy, helping to offset the cost of wastewater treatment (Winpenny et al., 2010), and leading to a transformation of conventional linear water treatment approaches into circular economy solutions with enhanced economic value (Smol et al., 2020; Voulvoulis, 2012). Progressive regulations and policies are needed to ensure the success of water reuse implementation (Sgroi et al., 2018) and recent years have seen major advances in the provision of supportive regulatory frameworks at national and supra-national levels (CNEPA, 2021; The European Commission,

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2015; USEPA, 2012). These regulatory interventions are typically focused on forms of reuse that show particular promise or opportunity within a national or regional context and set quantitative limits for water quality parameters such as organics, solids, nutrients and pathogenic indicators (CNEPA, 2021; EUPC, 2020; USEPA, 2012).

Conventional water and wastewater treatment trains customarily comprise three stages: primary, secondary, and tertiary (Shareefdeen et al., 2015), which remove settleable solids, suspended solids, biodegradable organic matter, nutrients, and pathogens. However, these processes in isolation often cannot produce effluents that meet non-potable standards and therefore advanced treatment is needed to deliver a final effluent of sufficient quality for reuse. Advanced treatment technologies including physical (absorption and membrane), biological (algae, wetland, and anaerobic reactor) and chemical (ion exchange and advanced oxidation) are reported to produce effluents of sufficient qualities for different reuse purposes (de Aquim et al., 2019). Among these options, membrane processes, and in particular Membrane Bioreactors (MBRs) have spurred the most interest as they offer easy operation and a high quality effluent with a high degree of selectivity (Sgroi et al., 2018).

MBRs can be operated under both aerobic and anaerobic conditions depending on the presence or absence of oxygen in the biological reactor (Huang & Lee, 2015). Historically, AnMBRs have been typically deployed to deal with high strength wastewaters (Futselaar et al., 2013), with multiple studies arguing anaerobic treatment offers a number of advantages over aerobic comparators. For example, the process leads to lower levels of biosolids to dispose of due to the low growth yield of the anaerobic biomass (Giménez et al., 2011). This significantly reduces the footprint of wastewater facility, also the carbon footprint from the sludge management for aerobic systems (Seib et al., 2016). Degradation of organic matter and its conversion to methane-rich biogas provides a renewable source of energy to offset the energy demand for wastewater treatment (Chen et al., 2016). Since anaerobic treatment converts nutrients to chemically available forms such as ammonia and phosphate, AnMBRs facilitate nutrient recovery *via* subsequent precipitation (Shin & Bae, 2018), as well as offer apotential option of reusing the produced effluent for agricultural irrigation (Augsburger et al., 2021). By integrating membrane separation processes such as microfiltration (MF) or ultrafiltration (UF) with anaerobic reactors, the hydraulic retention time (HRT) can be decoupled from the sludge retention time (SRT) (Pileggi & Parker, 2017), allowing the slow growth of anaerobic bacteria and also maintaining a higher biomass concentration to raise treatment capacity (Berkessa et al., 2018). Thereby, precise control of organic loading rates and short HRTs can be achieved, driving efficient conversion of organic compounds to biogas due to increased active biomass densities in the bioreactor (Tassew et al., 2019). This provides a cost effective solution to the need of dosing extra carbon source when treating low strength municipal wastewater for aerobic systems hence reduces the operational expenditure (Xu et al., 2020), while suggesting AnMBRs are capable for deploying into a wide range of process scales. Additionally, as a membrane system, AnMBRs eliminate total suspended solid (TSS) and turbidity concerns and have been shown to be effective in the removal of both bacteria (MF) and viruses (UF) (Mai et al., 2018b). To summarize, extensive evidence has proven the benefits of AnMBRs when applied to municipal wastewater (Shin & Bae, 2018; Song et al., 2018; Wang et al., 2018), and demonstrating that their use can reduce asset footprint, energy consumption and HRT (Shareefdeen et al., 2015), as well as a solution toward sustainable water management.

Useful reviews reporting AnMBR fundamentals, system configuration and performance for wastewater treatment can be found in Skouteris et al. (2012), Shin and Bae (2018), and Song et al. (2018), with recent publications largely focusing on the biogas production (Hu et al., 2020), micropollutants removal (Lim et al., 2020), membrane fouling mechanism (Wang et al., 2022), and anti-fouling strategies (De Vela, 2021; Sohn et al., 2021). However, and of significance to this contribution, the exploitation of AnMBRs in the context of water reuse has attracted little attention from researchers and technologists. Nevertheless, there remain several significant challenges in the development of AnMBRs for clean water and resource recovery from wastewater, particularly municipal wastewater. These include lack of focus on low organic and nutrient loads in municipal wastewater, operational strategy on process stability and effluent water quality, as well as poor understanding of additional treatment requirements to meet higher quality non-potable reuse standards (Evans et al., 2019; Mai et al., 2018b; Shin & Bae, 2018; Song et al., 2018).

Given the promise of AnMBRs as a facilitating technology for sustainable water management and the need to premise future research on a thorough understanding of a fragmented and poorly focused literature base, the following sections critically review the performance of AnMBRs in the context of water reuse. We respond to two queries: What evidence is there that AnMBRs have potential for non-potable water reuse applications? and Where should future research be focused to further develop the opportunities for AnMBR deployment in reuse applications? Regulations and standards published in several jurisdictions are used to understand water quality targets and the potential of AnMBR technology to produce effluent meeting existing standards for reuse applications. Key operational parameters that determine the successful operation of AnMBR for water reuse are analyzed in-depth. We also discuss potential post-treatment processes that might be adopted to meet stricter consents. Finally, remaining gaps in understanding that could further unlock the potential application of AnMBRs for water reuse are identified.

Non-potable water quality standards

In order to provide quantitative pollutant removal benchmarks for assessing the performance of AnMBRs we have collected and collated data from water reuse regulations issued by a number of national and regional bodies (Table S1). Our intention here is not to generate a comprehensive global listing of non-potable reuse regulations but rather to provide a sample of frequently referenced metrics from parts of the world where water reuse is widespread. These water quality standards provide maximum allowable pollutant levels for water delivered for different uses. Standards generally reflect the principle that those uses with higher likelihood of human contact are subject to more stringent control. In our sample, indicator bacteria levels are prescribed in all standards not involving aquifer recharge, with fecal coliforms being the most common parameter. Additional protection against microbial risk is often secured through the presence of a chlorine residual in the delivered water typically with a required concentration above 1 mg/L. However, there is significant variation in other parameter values across standards (e.g. BOD_5, TSS, and nutrients). Emerging organic contaminants such as pharmaceutical residues, endocrine disruptors, and personal care product residues are poorly covered in the standards with only the Australian national guidelines for the augmentation of drinking water supplies referencing them (NRMMC, 2008).

Organic consents referencing both biological oxygen demand (BOD_5) and chemical oxygen demand (COD) are universally listed in reuse standards. Allowable BOD_5 levels for different end uses provide a useful example of how problematic the comparison of standards is across jurisdictions when only using headline water use descriptors. For non-potable reuses, the BOD_5 limit in our selected standards ranges from 6 to 30 mg/L (Table S2), driven by minor differences in the end use application (e.g. toilet flushing has a lower limit compared with urban grounds irrigation). It also is worth mentioning the dissimilar characteristics of municipal wastewater in different regions. Due to a lower storm water infiltration from mature rain and sewage diversion system, the organic and nutrients loading is usually higher in developed countries compared to those in developing countries (Qadir et al., 2020). Other differences are also reported in the comparison of domestic wastewater strength between Asia and Europe/America, as the low dairy Asian diet tends to produce lower concentrations in BOD and COD (Sun et al., 2016). All of these will influence the treatment needs and hence, the application of the technology to meet the consents for reuse.

Methodology

Early success at bench scale (Skouteris et al., 2012; Smith et al., 2012), prompted additional research on AnMBRs at pilot-scale (Shin & Bae, 2018). Most reported AnMBR studies have utilized commercial membrane modules and used real domestic wastewaters to reflect diurnal and seasonal changes in the feed. However, to the authors' knowledge there are only three publications to date specifically focusing on the implementation of AnMBRs for water reuse; two of which have explored the performance of a gas sparging AnMBR (Martinez-Sosa et al., 2011) and an AnMBR followed by RO and IEX (Gu et al., 2019). The third, lab scale, project assessed the use of an AnMBR to treat cheese whey with the treated effluent being recovered and used for site cleaning purposes (Ribera-Pi et al., 2020). However, AnMBR performance in treating municipal wastewater (outside the context of reuse) has been extensively explored and can be used in combination with the few studies noted above to provide a more detailed picture of the technology's potential application to water reuse.

Our evidence acquisition strategy involved (i) identifying suitable research paper repositories, (ii) application of selected search terms (in several stages) and rationalization of the database records to remove duplicates, quality control entries, and ensure comparability of sources, and (iii) structuring of the resulting studies to facilitate data analysis. Scientific publication databases Scopus, Mendeley and Google Scholar and citation tracing were used to source literature initially using the keywords "anaerobic" + "membrane bioreactor" + "wastewater." A second search used the keywords "AnMBR" + "municipal wastewater" and a third search the keywords "AnMBR" + "water reuse." Retrieved papers were filtered to identify studies which reported performance data at either pilot or full scale. The operational data from these studies were extracted to populate a database and a subset of studies was identified ($n = 50$) which allowed a comparative analysis of performance to be conducted. Table S3 provides a listing of systems evaluated in this review with each system having a unique marker to efficiently compare and contrast. The marker indicates the specific information of system configuration, anti-fouling strategy, membrane, and operational strategy. For example, GS-F1 indicates this AnMBR was operated with gas sparging for anti-fouling control and flat sheet membrane module, as PFPS-H1 consisted of a plug flow partially stirred bioreactor and a hollow fiber membrane. Additional technologies and operational parameters are listed in Table S4. As stated above, water reuse regulations typically target BOD_5 as the organic content indicator. However, most studies focusing on wastewater treatment for discharge use COD and only 16 out of the 50 studies have recorded the effluent BOD_5 concentration whereas 37 out of 50 studies have COD data. For the purpose of the evaluation, considering the municipal wastewater effluent as a stable compensated wastewater, BOD_5 values were estimated from the respective COD values reported and the calculated average effluent BOD/COD ratio of 0.3 (±0.1) obtained from the 16 studies where both COD and BOD_5 measures were available.

Anaerobic membrane bioreactor performance

The 50 systems captured in our review demonstrate significant variability in the ranges of pollutant removal efficacy across parameters (Figure 1). A consistent range of measured parameters is not available across all the 50 reviewed systems.

Total suspended solids

As AnMBRs possess an integrated membrane unit, there should be no TSS concern in the effluent water, which may explain the lack of data on this parameter in the reported studies. However, two studies reported relatively high effluent TSS concentrations of 16 (NGS-T1) and 15 mg/L (GS-T1). These unusual values, which would prevent the effluent being used for a number of purposes, were reported to be due to biofilm growth on the permeate pipe walls. Other systems are able to meet the TSS concentration limit for every reuse purpose in the sample standards with five of them reporting none detected and GS-H9 and GS-H13 reporting 5.33 and 2 mg/L, respectively.

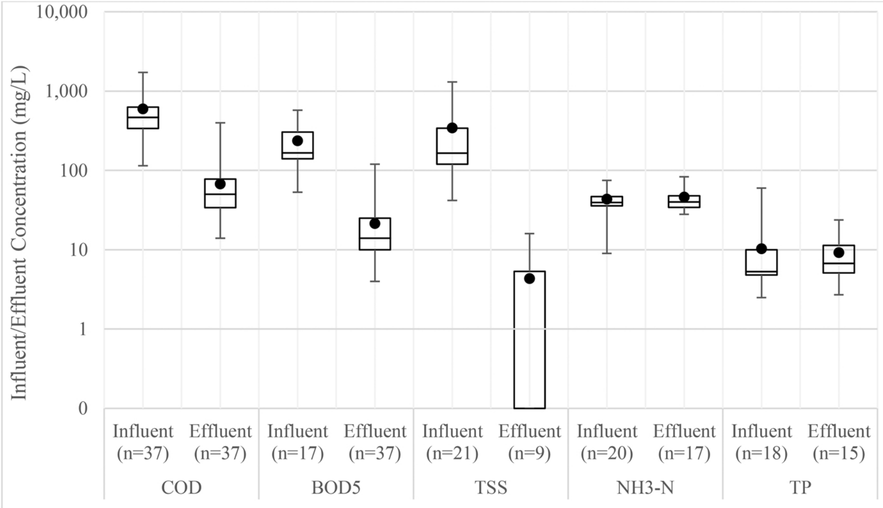

Figure 1. Influent/Effluent Concentration of AnMBR treating municipal wastewater. *n* represents the number of data sets available for each parameter. The black spot stands for the mean value for each parameter. The box represents the distribution of the concentration for the first quartile (bottom), median (middle) and third quartile (top) of the data and the error bar represent the maximum and minimum concentrations.

Pathogen

Pathogen concentrations constitute one of the most important criteria for reused water quality (Asano et al., 2007; ISO, 2018; Lazarova, 2015). Pathogen requirements for non-potable water are evaluated using the concentration of three indicator coliform measures: fecal, Escherichia (E.) and total coliforms. Every standard has a numerical limit for different indicator bacteria with fecal coliforms being the most commonly adopted parameter. Despite this, indicator bacteria are rarely recorded in any of the reviewed studies. This can partially be explained by the presence of the membrane in an AnMBR which removes a significant fraction of bacteria. Interestingly, GS-F7 reported a higher MS-2 phage (often used to model the behavior of pathogenic human viruses) removal rate (3 LRV) compared with aerobic MBRs (1.2 LRV) using similar membranes which may be due to the action of certain anaerobic solutes which could be further studied (Fox & Stuckey, 2015). Studies GS-F1 and GS-H12 monitored indicator bacteria with the effluent fecal coliforms concentrations reported as 49 and 42 ± 48 CFU/100 mL respectively. Both these effluents could meet the 200 CFU/100 mL limit quoted for many agricultural uses (except the non-detectable limit for the irrigation of raw consumed food crops) and industrial reuse but would need a disinfection process to meet the stricter consents (typically non-detectable) required by applications such as toilet flushing or street maintenance and fire-fighting. The requirement in many standards for a chlorine residual concentration of between 0.5 and 1.0 mg/L means that a further disinfection process is compulsory for many water reuse applications.

Nutrients

It is also important to note that, as demonstrated by many previous studies (e.g. Song et al., 2018), AnMBRs do not remove nutrients. Reported effluent NH_3-N concentrations range from 28 to 83.2 mg/L as the effluent TP concentrations varies from 2.7 to 23.8 mg/L. None of the AnMBR systems could directly produce an effluent satisfying the NH_3-N and TP consents in our sample standards. To illustrate, the NH_3-N concentrations have a limit ranging from 5 to 20 mg/L for various uses in the Chinese reuse standard but none of the AnMBRs could meet this consent and no system could meet the highest TP limit of 1 mg/L.

As negligible nutrient is removed from the influent, apart from impact of the operational variables and system configuration, this argues the purpose of agriculture and landscape irrigation can be more preferable and attractive as the food crops or plants can directly extract the nutrients from the AnMBR effluent (Xu et al., 2020). However, for other reuse purposes such as recreational and landscape irrigation, meeting consents would require post-treatment process to remove nutrients down to sufficient level. This offers an insight of multistep removal and recovery of resources through the conversion of the organics into energy and recovery of the nutrients as fertilizer. Indeed, having the nutrients in relatively clean and solids free effluent facilitate their recovery (Guida et al., 2021a, 2021b).

Organics

The performance of AnMBRs on organic removal is shown in Figure 2 together with the BOD_5 limits taken from our benchmark standards. Compared with the BOD_5 limit of non-potable water reuse standards in Table S1, there are 32, 31, and 30 of the 37 systems which could respectively meet the BOD_5 limit of 35, 30, and 25 mg/L with no further treatment required.

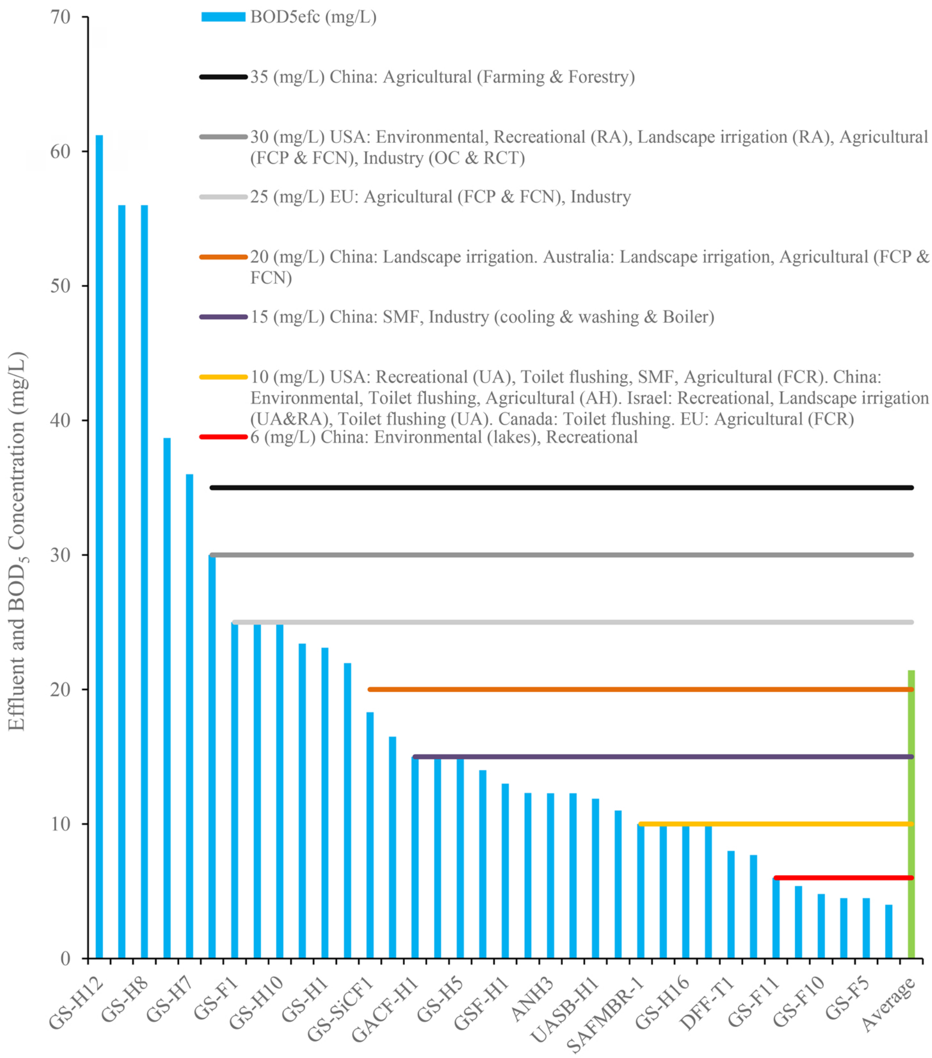

Figure 2. Effluent BOD_5 concentration of AnMBR systems against non-potable water reuse standards.

Consents of 20 and 15 mg/L, where most standards for agricultural irrigation lie, can be met by 24 and 22 systems, respectively, and 12 systems meet the consent of 10 mg/L, which includes direct human contact reuse applications. Finally, six systems meet the strictest BOD_5 limit of 6 mg/L for non-potable reuse purposes in all standards.

Only the EU and Chinese standards have a COD consent. Agricultural reuse has the most wide-ranging limit for different purposes and 33 systems satisfy the EU's COD limit of 125 mg/L for agricultural irrigation (except where raw consumed food crops are involved), There are 30 and 13 AnMBRs that can respectively satisfy the COD limit set by the Chinese agricultural reuse standards for farming and forestry of 90 mg/L and animal husbandry of 40 mg/L (Table S1). Overall these results show that, although there is a wide variability in effluent quality reported in the different studies evaluated, AnMBRs can be operated in such a way that they will ultimately meet the organics limit for any non-potable reuse standard.

Impact of operational variables and system configuration on performance

The variations in AnMBR performance reported above invite us to explore how other factors influence the operational sweet spot of AnMBRs as well as investigate how their configuration and design might be finessed specifically for water reuse. Such considerations can be extended to assess the role that AnMBRs might play in wider circular economy solutions, supporting recovery of nutrients and energy for example. The profile of COD removal rate versus occupied anti-fouling strategy (Figure S1) and installed membrane configuration (Figure S2) of reviewed AnMBRs respectively argues for their insignificant role on the organic removal performance. However, statistical analyses including a principal component analysis (Figure S3) and a multivariate correlation

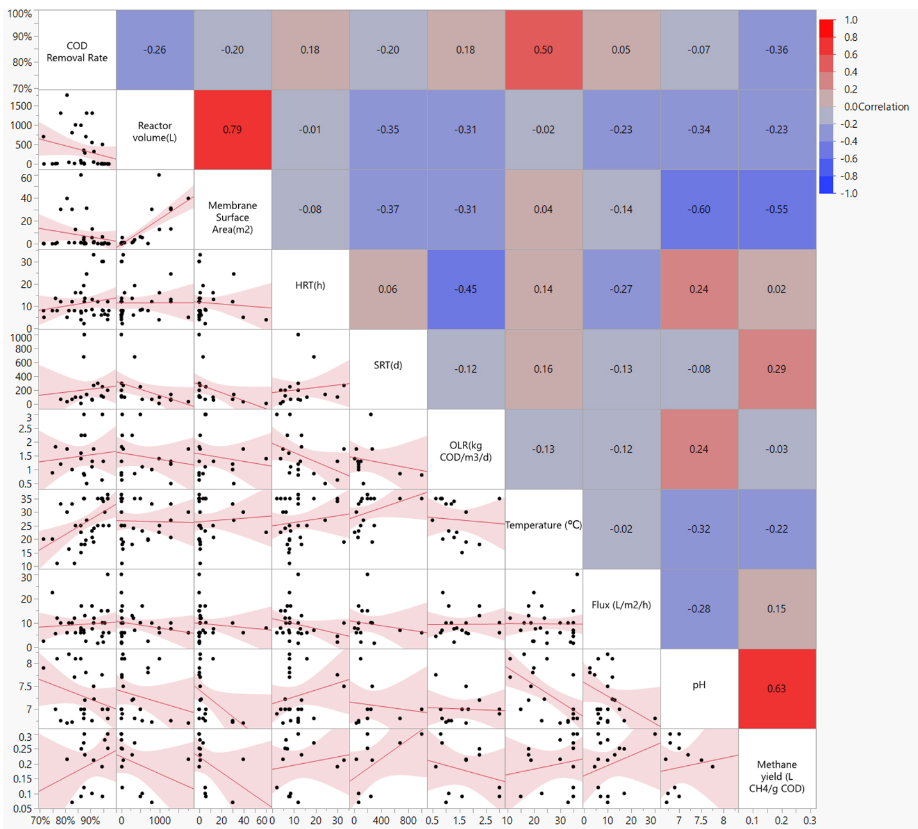

Figure 3. Multivariate correlations scatterplot matrix of operational parameters.

analysis (Figure 3) suggested further explore the influence of feed water matrix, pH and salinity, temperature, hydraulic retention time, as well as system and membrane configuration on AnMBR performance in the context of meeting water quality criteria for non-potable applications.

Influent water matrix

Reviewed literature shows a general trend of increasing organic removal performance from (in order) concentrated synthetic wastewater, raw wastewater, mixed raw wastewater, settled wastewater, synthetic wastewater, and synthetic primary effluent (Figure S4). Indeed, the six AnMBRs reporting the lowest COD effluent concentrations were treating synthetic wastewater. This indicates that the difference in influent wastewater type may have an impact on AnMBR performance, which could be explained by the more complex matrix of compounds in real wastes and possibly the more biodegradable organics available in synthetic wastewater as demonstrated by the higher BOD_5/COD ratio of synthetic wastewater (0.5–0.7) compared to real wastewater (0.3–0.5). Moreover, those AnMBRs with an organic removal rate higher than 95% were also using synthetic wastewater as feed, and no commensurable removal rate was reported for those treating actual wastewater. Therefore, selecting authentic wastewater for future study will give a more accurate understanding on the process fundamental specifically for reuse application.

pH and salinity

When comparing the effluent pH value of the reviewed AnMBR systems with water reuse standards (5.5–9), it is clear that they can all meet the pH limit. However, influent wastewater pH may have a negative impact on AnMBR operation but insignificant influence on effluent quality. To illustrate, a higher membrane fouling rate was observed in GS-H11 (Khan et al., 2019), in both acidic and alkaline pH conditions, with the lowest fouling rate observed at pH 7.0. The effect of pH shock has been studied in GS-F5 (Kunacheva et al., 2017) by changing the feed water pH from 7 to 5 and 11 for 4 h and 24 h, respectively. The 4-h pH shock did not have a negative effect on the AnMBR performance but there is a significant effect when the pH shock was for 24 h. For the pH 5 shock, the system took 24 h to recover due to high concentrations of carbohydrates being present. For the pH 11 shock, the system only took 8 h to recover with large molecular weight (MW – 1500 kDa-0.2 pm) protein-like compounds being observed. As larger colloids related to protein-like compounds cause more fouling on the membrane, the biofouling layer is an important factor in the removal of neutral and negatively charged low MW compounds, which effectively increases COD removal in submerged AnMBRs. Additionally, the pH shock reduced the ability of the process to remove these compounds therefore having a negative impact on AnMBR performance. However, under the pH shocks GS-F5 could still stably produce an effluent with 15 mg/L COD which satisfies the organic consent in all non-potable reuse standards. There is a wide range of pH values listed in water quality for reuse standards and consequently little concern that AnMBRs would not be able to adequately perform. However, significant variation in pH within that range may affect operation (fouling) and possibly treatment performance (organics); hence close monitoring of pH is essential. Salinity is also a factor that demands attention as high salinity results in lower biological performance and poor COD removal. A significant increase of soluble microbial products (SMPs) was associated with the increase of salinity in GS-F11 although the effluent COD concentration stayed under 20 mg/L which satisfies all the reference set organic consent levels.

Temperature

AnMBRs are more commonly operated under either thermophilic (50–60 °C) or mesophilic (30–40 °C) conditions (Galib et al., 2016). The statistical analysis carried out here did demonstrate a clear correlation between the temperature and COD removal (Figures 3 and S3). However, psychrophilic conditions (<20 °C) have also been shown to be associated with good treatment of municipal wastewater (Robles et al., 2013). The benefit of operating at lower temperatures is that there is no need to heat the reactor, especially in temperate climates, which reduces energy consumption and can potentially deliver energy-neutral operation (Martin et al., 2011). However, a number of studies report that operating AnMBRs at low temperature can result in several limitations, including slow contaminant biodegradation, aggravated membrane fouling, low CH_4 production and high CH_4 solubility in the effluent (Dolejs et al., 2017; Martin et al., 2013; Smith et al., 2012; Yoo et al., 2014). In the context of satisfying water reuse standards, slow contaminant biodegradation directly influencing effluent quality leads to longer HRT or a requirement for additional treatment. Furthermore, higher membrane fouling decreases the permeate production efficiency and leads to more frequent membrane backwash/cleaning which ultimately increases operational expenditure. Another concern of operating AnMBR at low temperatures is a lower energy recovery potential compared to those operating under higher temperatures. Hydrolysis of particulate matter into dissolved molecules is limited at low temperature, leading to the accumulation of suspended solids in the reactor and a decrease in methanogenic activity (Chen et al., 2016). Decreased CH_4 production could also be attributed to its increased solubility in the effluent when the temperature is 20 °C or below. In addition, the mixed liquor viscosity also increases as temperature decreases, thus requiring more energy for mixing and pumping which results in a slightly lower organic and nutrients removal performance and generates faster membrane fouling rates (Ding et al., 2019). Low temperature tolerance of AnMBR has also been reported at both lab-scale and pilot-scale (Smith et al., 2015; Yoo et al., 2014). Although seasonal changes in temperature will result in lower hydrolysis-rates and higher methane dissolution rates in the effluent, COD removal remains similar during both summer and winter (Giménez et al., 2014). For GS-F1, an increase in the total suspended solids content and soluble COD in the bioreactor was observed when the temperature of the AnMBR was reduced from 35 to 20 °C. However, the organic removal stayed constant with an effluent COD and BOD_5 no higher than 80 mg/L and 25 mg/L, respectively.

The effect of psychrophilic temperature shocks was studied on a gas-lift AnMBR (GL-T1) as the temperature was decreased from 35 to 15 °C. The effluent BOD_5 concentration remained at a low level (16.5 mg/L) as more than 80% of the influent COD accumulated in the reactor which is 41% higher than in mesophilic conditions, leading to lower biogas production. Additionally, the membrane function had a positive effect on the rejection of the COD inside the reactor with only a slightly higher filtration resistance increase observed due to the decreased viscosity of the permeate.

Those AnMBRs operating at around 35 °C generally exhibited better organic removal performance than those running at lower temperatures (especially systems under 25 °C). Effluent COD concentrations of 15 and 14 mg/L, satisfying all non-potable reuse standards, were achieved under temperatures of 25 °C and 35 °C with the GS-F5 and FBR-CT1 systems respectively. Additionally, GS-F5 and FBR-CT1 achieved COD removal rates of 96.8% and 97.2%, respectively. It should however be noted that GS-F5 was treating synthetic wastewater and FBR-CT1 was treating synthetic primary effluent which, as stated before, are shown to be more easily degraded than real wastewaters. Systems operated under 25 °C showed significant variation in organic removal performance. Representatively, the systems operated at 11 °C (GSF-H1 and GSG-H1) achieved a lower COD removal rate of 83.7% and 76.8% when compared to others operated under higher temperatures. However, GSF-H1 and GSG-H1 could produce an effluent with COD concentrations of 34 and 39 mg/L, respectively, which equivalently (assuming a BOD_5/COD ratio of 0.3) satisfies the 15 mg/L BOD_5 standard consents for applications such as agricultural and landscape irrigation.

These results indicate that good organic removal can be achieved under a psychrophilic temperature range and that operating under higher temperatures should be considered when wishing to meet strict reuse standards such as those for recreational purposes (BOD_5 10 mg/L). In terms of operation, the GS-H3 study reported that higher membrane fouling propensities were observed under mesophilic than under psychrophilic conditions due to higher SMP production. As highlighted above, for long-term operation there will be a tradeoff between energy use (heating of reactor, membrane operation) and effluent quality. However, by effectively managing solids concentration and biogas sparging, evidence shows that AnMBRs could be stably operated at psychrophilic temperatures for treating municipal wastewater for non-potable reuse.

Hydraulic retention time

Significant variation in organic removal rates are observed for AnMBRs reviewed in this contribution (Figure 3). Most systems operated in an HRT range between 4 and 12 h, with the average being around 8 h. Effluent COD (COD removal rate) of 16 (96.7%), 15 (96.7%), 15 (96.8%) and 14 mg/L (97.2%) were achieved respectively with HRTs of 4 (GS-F10), 12 (GS-F3), 6 (GS-F5) and 8 h (FBR-CT1), while other studies also reported COD removals as low as 70-75% for similar HRTs. Higher HRT delivers more predictable performance with all systems operating with an HRT longer than 15 h achieving a removal rate of 84% or higher. Interestingly, the PCA analyses (Figure S3) highlighted a clear link between HRT and methane yield. These results show that it is possible to achieve high effluent quality with short HRTs but also highlights that other factors are influencing treatment performance.

System GS-H2 was operated with a short hydraulic retention time (2.2 h) and a flux of 6 LMH for 340 days without any membrane cleaning but unfortunately no organic removal rates were recorded in this study. The lowest COD removal rate (71.4%) was reported in NGS-T1 operated under an HRT of 8 h, a result mainly due the lack of gas sparging which resulted in higher membrane fouling and also decreased the mixing in the upper part of the UASB reactor. In another study (GS-F6) a concentrated synthetic wastewater which had an influent COD concentration of 1410 mg/L was treated under a 5 h HRT with complete organic biodegradation not being achieved. In those studies reporting long-term treatment of municipal wastewater, AnMBRs were capable of operating at low HRTs with a tolerance to hydraulic shock loads but reduced organic removal performance. GS-F4 reported an effluent COD concentration of 16 mg/L when operating under a 4 h HRT. However, VFAs began to accumulate when the HRT was reduced to 2 h or further down to 1 h, accounting for 69% and 89% of the effluent COD, respectively. Studies ANH3 and ANH4 also argued that under a stable HRT, an AnMBR operating at psychrophilic temperatures had a slightly lower organic removal performance and a faster membrane fouling rate (Ding et al., 2019) which had a negative impact on effluent quality. This led to the effluent quality failing to satisfy most non-potable reuse standards.

Overall these results show that it is possible to operate AnMBRs with a very short HRT (5-10 h), hence reducing the footprint of the system, and still achieve very good organics removal (>90%). Ultimately, it is difficult to conclude on the impact of one specific parameter because the overall performance of these AnMBRs would have been affected by many parameters and all the reviewed systems are different. For instance, GS-H12 has both the highest effluent COD and BOD_{5efc} concentrations of 150 and 61.2 mg/L, respectively, but this can be attributed to the fact that the influent wastewater had the highest COD concentration of 1729 mg/L. However, ANH2 achieved a lower effluent COD concentration (86 mg/L) had similar influent COD concentration of 1720 mg/L. The later was operated under 34 °C and 30 h HRT while GS-H12 operated under 24 °C and 6 h for temperature and HRT. This confirms that the operating temperature and HRT can be expected to have a positive influence on treatment performance and can be adapted to tailor the organic removal to the effluent quality requirement associated with specific standards for reuse.

System and membrane configuration

Produced water quality can be enhanced through the modification of system configuration and the application of advanced membrane technology. The reviewed AnMBR systems (Table S3) typically consisted of a biological reactor and an immersed or side-streamed membrane unit, with upflow anaerobic sludge blanket (UASB) being the most common. Membrane configurations included hollow fiber, spiral-wound, flat sheet and tubular membrane, with hollow fiber being the most common.

GSDM-F1 was configured with a 75 µm pore size nylon mesh dynamic membrane module which successfully operated under high flux (22.5 L/(m^2h)) and 8 h HRT at psychrophilic temperature. When treating municipal wastewater, this system produced an effluent satisfying the 25 mg/L BOD_5 reuse standard consents. The fluidized-bed reactor using a ceramic tube membrane and downflow floating media filter using a PVDF tube membrane produced high quality effluents with COD concentrations of 14 mg/L and 25 mg/L and BOD_5 concentrations of 5 mg/L and 8 mg/L, respectively. The fixed-film reactors enhanced the biodegradation of organic compounds and the 0.018 µm pore-sized ceramic tube membrane increased the rejection performance. However, this configuration consumed 65–75% more energy than the conventional AnMBRs with energy neutral operation (Seib et al., 2016). These results again highlight the tradeoff between energy use and operation and treatment performances, especially when strict standards are to be met.

Recent progress to advance AnMBRs has resulted in the emergence of high retention systems. The combination of NF, RO, or FO membranes with anaerobic reactors is often aimed at producing water that can be reused while enhancing the nutrients removal or offering an opportunity for nutrient recovery. These include anaerobic membrane distillation bioreactors (AnMDBRs) and anaerobic osmotic membrane bioreactors (AnOMBRs) (Shin & Bae, 2018).

MD is a thermally driven separation process, in which the thermal gradient between a feed solution and distillate drives the transportation of water vapor through a hydrophobic, microporous membrane. The competitive advantages of anaerobic processes can be readily utilized when they are combined with MD because thermophilic operation can reduce the extra heat requirements for MD operation (Kim et al., 2015). GS-C1 integrated an MD process with AnMBR, resulting in high levels of organic matter and nutrient removal with an effluent COD concentration of 101.5 mg/L, satisfying the COD consent in the EU's agriculture reuse standard. The high retention capacity of the MD membrane resulted in significant phosphate accumulation in the feed solution, thereby producing an opportunity for phosphorus recovery from the AnMBR effluent. Similar results were reported by Jacob et al. (2015) with 90% removal of COD and ammonium nitrogen from AnMBR effluent by a direct contact MD process. Further research is necessary to address the issue of MD membrane fouling when coupled with an anaerobic reactor. It is noteworthy that a reduction in NH_4^+ removal was observed in Jacob's due to its transportation through the MD membrane *via* ammonia evaporation. This issue can be addressed by using a FO and MD hybrid system, where the FO membrane can reject $NH4^+$ while MD can be used to regenerate the draw solution and produce clean water for reuse, while simultaneously providing a recovery potential of both nitrogen and phosphorus.

FO involves the transport of water across a semi-permeable membrane similar to natural osmosis. Systems that have coupled FO membranes with an anaerobic bioreactor provided a higher quality effluent compared to a conventional AnMBR, especially in terms of nitrogen and phosphorus removal (Chen et al., 2016; Ding et al., 2014). FO has also been reported to reject particles, pathogens and emerging contaminants in wastewater (Lutchmiah et al., 2014). Additionally, FO could be both considered as a pretreatment for AnMBR as FO-AnMBR or replacement for the membrane unit as AnOMBR. During AnOMBR operation, a desalination process, such as nanofiltration (NF) or reverse osmosis (RO), can be used to regenerate the draw solution and produce clean water. Compared to conventional MF and UF membranes, FO has higher selectivity, lower membrane fouling propensity and better membrane fouling reversibility (Xie et al., 2015). However, FO has a much lower flux and the permeate requires further separation to produce a useable water (Ansari et al., 2017), to regenerate the draw solution driving the osmosis process, increasing process complexity and cost (Ding et al., 2014). CSTR-H1 (treating synthetic municipal wastewater) was configured with a forward osmosis unit and heat pump to evaluate the feasibility of energy neutrality. The FO unit was set up as a pretreatment unit together with the heat pump to achieve a mesophilic temperature in AnMBR and the effluent quality of 15 mg/L BOD_5 was sufficient for many non-potable standards. The ANH2 study also looked at the feasibility of the FO + AnMBR configuration and reported similar results. Here the FO unit concentrated the wastewater for an AnMBR and at 15 °C a lower organic loading rate (OLR) was applied to maintain stable operation when compared to higher temperature. Under the optimum conditions, the effluent water from FO could meet the 25 mg/L BOD_5 reuse consent=. However, the high salinity stream from the FO unit could have a negative impact on methane production, reducing the energy recovery potential (Yin Tang & Ng, 2014).

No significant variation in effluent COD concentration was observed against the different membrane pore sizes and configurations (Figure S2), confirming that although the membrane has a critical role in separation of the mixed liquor from the treated effluent in MBRs, the organic removal performance is less dependent on the membrane configuration and material. Reviewed evidence suggests the modification of system configuration or the application of advanced membrane can have a positive effect on enhancing organic removal performance but at increasing operational cost or lack of process maturity, hence highlighting the continued effort needed on exploring cost-effective system and membrane configuration.

Energy recovery

It is established that biogas produced by AnMBRs consists of more than 70% CH_4 (Skouteris et al., 2012) with the yield increasing linearly with the organic loading rate (Yeo et al., 2015). Under optimized condition, AnMBRs can convert up to 98% of the influent COD into biogas, equivalent to seven times the energy required for system operation (Song et al., 2018). In practice, actual biogas yields are considerably lower than the theoretical value due to the high solubility of CH_4 in water and process limitations caused by inhibitory substances. CH_4 loss due to its solubility (22.7 mg/L, 20 °C) in the effluent is significant during AnMBR treatment, particularly for low strength municipal wastewater (Smith et al., 2012). Dissolved CH_4 in the permeate does not only reduce the energy efficiency of AnMBR treatment, but also contributes to global warming as the greenhouse potency of CH_4 is 25 times higher than carbon dioxide (Jacob et al., 2015).

Factors known to affect biogas production include OLR and influent sulfate concentration. Although no correlation between OLR and organic removal has been reported, a link to biogas production performance has been observed whereby dissolved CH_4 concentrations decrease as the OLR increases (Galib et al., 2016). Reviewed systems show improved biogas production with increasing OLR (PFPS-H1) and AnMBRs as a net energy producer (GS-F6). As demonstrated in several studies, sulfate-rich municipal wastewater reduces methane yield which results in lower energy recovery potential (Giménez et al., 2011; Petropoulos et al., 2019; Pretel et al., 2016). Low conversion of COD to methane for UASB-H1 was attributed to the presence of SO_4, due to scavenging of up to 50% of COD in the influent and accumulation of un-hydrolysed lipids in the mixed liquor. For GS-H1, a higher COD/S O_4^2-S ratio was reported to result in a rapid increase of methane yield. The COD/SO_4-S ratio strongly affects the methane yield by methanogenic archaea MA and sulfate reducing bacteria (SRB) competition, as COD is removed by SRB. Furthermore, GS-H13 had confirmed when treating sulfate-rich municipal wastewater the SRB could reduce all the influent sulfate to sulfide and the organic matter typically available for methanogens which reduced the methane yield. The increase of sulfide levels has been shown to lead to a decrease in Fe^{2+} bioavailability, an increase in soluble COD in the reactor and increasing VFA levels, but a decrease in methane yields (Seco et al., 2018). The dosing of ethylenediaminedisuccinic acid in a 1:1 M ratio with Fe^{2+} as part of the GS-F4 study reduced soluble COD and VFAs resulting in an increase of 9.46% in methane yields under comparable sulfide levels. Since reuse provides an opportunity to both maximize the conversion of CH_4 from the influent and recover it from the effluent, increasing the operational organic loading rate and maintaining a low influent sulfate concentration can also help improve energy recovery potential.

Considering the tradeoff between energy use and effluent quality, AnMBRs are more suitable for regions with warmer climates such as South-East Asia. Higher ambient temperatures can offset the limitations of operating under psychrophilic temperatures highlighted above (Dolejs et al., 2017; Martin et al., 2013; Smith et al., 2012; Yoo et al., 2014). In cooler climates, underground installations might be considered, known to improve public perception, reduce footprint, provide more consistent (warmer) ambient temperatures, and mitigate biogas odors but incur higher construction expenditure (Sun et al., 2019).

Trace organic compounds

Amongst complex contaminants in wastewater, trace organic compounds (TrOCs) present arguably the most vexing challenge to water reuse (Schwarzenbach et al., 2006). TrOCs also called organic micro-pollutants (OMPs), include pharmaceuticals, endocrine disruptors, pesticides and personal care products. Recent studies have also demonstrated that the removal of TrOCs by AnMBR varied significantly from negligible to more than 90%. Their removal is governed mostly by intrinsic physiochemical properties of the compound. The removal of 38 TrOCs by AnMBR was studied and reported over 90% removal for nine compounds, while the others were removed by less than 50% (Monsalvo et al., 2014). A predictive framework was successfully developed to assess the removal of TrOCs by AnMBR, which relates to their hydrophobicity and molecular structures (Wijekoon et al., 2015). GS-C1 had reported a complete removal of the TrOCs by integrating AnMBR with membrane distillation. The synergy between the biological treatment and the MD membrane rejection contributed to 76% to complete removal of all 26 selected TrOCs (Song et al., 2018). GS-F9 studied the removal of pharmaceuticals in AnMBR with the addition of powdered activated carbon. The sludge adsorption contributed significantly within 10 days when pharmaceuticals first entered the systems. After that the removal efficiency is depended on the biodegradability (Xiao et al., 2017). With one-time PAC addition, within the first 5 days all five pharmaceuticals removal were also improved by enhancing the biotransformation, but the removal of refractory compounds was still low which requires further treatment to satisfy the stricter reuse consent. SAFMBR-1 examined the removal of pharmaceuticals in municipal wastewater with a staged Anaerobic fluidized membrane bioreactor. By being positively charged at neutral pH and/or hydrophobic, the pharmaceuticals were initially adsorbed onto the sludge, and then desorbed when sludge decayed after long operating hour (Chen et al., 2019). Processes responsible for the removals of pharmaceuticals were more complicated as the HRT adjustment had a limited effect rather than apply a post-treatment process. Consequently, TrOCs removal by membrane process is largely governed by their molecular properties, regardless of the presence or absence of oxygen in the bioreactor (Tadkaew et al., 2011; Wijekoon et al., 2015). Therefore, for environmental and recreational reuse or potentially potable water reuse, post-treatment is compulsory to produce an effluent of sufficient quality.

Post-treatment

Although AnMBRs have been shown to produce high quality effluents, those standards requiring tighter consents for organics, nutrients and pathogens cannot always be met and consequently post-treatment will be needed. Biogas produced during anaerobic processes, along with the dissolved CH_4, will also require additional treatment to produce an effluent safe for reuse and maximize energy recovery. Recovery of nutrients from AnMBR effluent constitutes another step toward enhanced resource sustainability *via* water reuse schemes. As noted above, AnMBRs do not remove nutrients, turning nitrogen and phosphorus to ammonium (NH_4^+) and phosphate (PO_4^{3-}), respectively (Song et al., 2018). Recent reviews by Mai et al. (2018a, 2018b) and Rongwong et al. (2019) have described post-treatment technologies for use prior to discharging or reusing anaerobic effluent. Table 1 presents a summary of post-treatment options that are well suited to pairing with AnMBRs in order to meet non-potable reuse standards.

Carbon based post-treatment processes could help meet organic consents up to the strictest levels, providing the level of treatment required for agricultural or landscape irrigation purposes (20 mg/L BOD_5) but no nutrients removal is required. Additionally, carbon based filtration can effectively remove traces of organic carbon. Good removal of ciprofloxacin (CIP) and VFAs has been achieved by treating AnMBR effluent with Granular Activated Carbon (GAC) and Powdered Activated Carbon (PAC) (Mai et al., 2018a). However, poor removal rates for low molecular weight compounds has been reported when using GAC and PAC (Trzcinski et al., 2011; Vyrides et al., 2010), and high manufacturing cost for carbon nanotubes (Amin et al., 2014) are a significant barrier to carbon based post-treatment technologies.

Additional membrane processes can deliver high quality effluent with some organic, nutrient, and pathogen removal, the produced effluent being suitable for a broad range of reuse purposes. NF can be used to produce a low organic, ammonia and phosphorus concentration effluent (Wei et al., 2016), which satisfies all non-potable reuse standard consents. Reverse Osmosis can deliver water of even higher standards (4 mg/L BOD_5, 0.2 mg/L NH_3-N) and also removes trace organics (Mamo et al., 2018). However, the energy demand of RO (Gu et al., 2019), means that it may only be suitable for potable reuse applications. Another advantage of membrane-based post-treatment (NF, RO, FO and MD) is concentrating N and P compounds in the brine hence offer the potential of resource recovery while producing clean water as a permeate (Rongwong et al., 2019).

Effective removal of nutrients and dissolved methane has also been reported with membrane biofilm reactors (Chen et al., 2015) and membrane contactors (Rongwong et al., 2019). Other options available to remove dissolved methane and nutrients include membrane distillation (Song et al., 2018), and electrodialysis (ED) (Xie et al., 2016). Interestingly, where complete nutrient removal is required (e.g. for environmental and recreational uses), the effluent from membrane biofilm reactors and membrane contactors requires further treatment to remove phosphorus, whereas membrane distillation requires a further treatment step to remove nitrogen. This suggests that a combination of different membrane processes may provide a suitable option for removal and potentially recover target compounds based on the reuse purpose. As Xie et al. (2016) reported, the integration of FO, MD and ED can potentially achieve complete nutrient recovery. However, none of these technologies have been tested as a post-treatment option for AnMBR effluent and require further study to understand how their energy use can be lowered. Combining and optimizing suitable process steps is again a tradeoff between the targeted recovery rate and cost intensity combined with the different effluent quality requirements of reuse applications.

Other post-treatment options that show promise include microalgae, ion exchange, and coagulation-flocculation with $FeCl_3$. Microalgae are capable of removing COD, NH_4^+ and PO_4^{3-} and also produces biomass for bio-fuel generation (Ruiz-Martinez et al., 2012). IEX processes are reported to have the advantage of lower costs and greenhouse gas emissions and be effective at nutrient recovery (Huang et al., 2020; Liu et al., 2016). Coagulation-flocculation with $FeCl_3$ could be applied as a single stage post-treatment process to remove up to 96% PO_4^{3-} (Penetra et al., 1999) also directly dosing into an anaerobic reactor to enhance the MBR performance (Dong et al., 2016) and the efficiency of the recovery cleaning protocol (Shin & Bae, 2018).

Candidate post-treatment technologies experiences a significant variation on the removal performance of OMPs, both on the category and the removal efficiency. Carbon based process exhibits the narrowest OMPs removal performance, while microalgae displays poor removal on both width and depth of OMPs. Membrane based technologies performs the widest removal range as well as higher removal rate compared to other competitors, with a general trend of increasing OMPs removal performance as function of decreasing membrane pore size. Recent advances on membrane technology has reported the functionalization using hydrophilic

Table 1. Post-treatment options for AnMBR based non-potable reuse applications.

Technology	Targeted components with removal rate (if available)	Advantages	Disadvantages	Sources
GAC	80% COD; Phenols; VOC; PhCs; Metals; EDs; PCPs	Wide targeting range, easy to apply, low cost, effectively eliminate PhCs, EDs and PCPs	Adsorption of low MW compounds is limited	(Mai et al., 2018a; Nguyen et al., 2012; Snyder et al., 2007; Trzcinski et al., 2011; Vyrides et al., 2010)
PAC	84% COD; Phenols; 80% DOC; VOC; PhCs; Metals; EDs; PCPs	Wide targeting range, effectively removing traces of organic carbon, effectively eliminate PhCs, EDs and PCPs		
Carbon Nanotubes	COD; Phenols; VOC; PhCs; Metals; AOCs; NOM; EDs; PCPs	Wide targeting range, no diffusion required compared to AC, effectively eliminate PhCs, EDs and PCPs	High manufacturing cost	(Amin et al., 2014)
MD	98% COD; 10% NH_4^+; >99% PO_4^{3-}; 65% dissolved methane; 76–100% OMPs	Complement very well with AnMBR for energy and water recovery	Flux strongly depends on the temperature and pressure, require further treatment for TN	(Jacob et al., 2015; Kim et al., 2015; Song et al., 2018; Xie et al., 2016)
NF	COD; NH_4^+; Up to 95% PO_4^{3-}; Multivalent ions; 80–92% OMPs;	Produce high quality effluent for reuse	Lower energy demand than RO, effluent contains monovalent ions	(Wei et al., 2016)
RO	88% COD; >99%TOC; 91% TKN; 99% PO_4^{3-}; Multivalent ions; Monovalent ions; >90% OMPs	Produce the best quality effluent with nearly all removal of organics and nutrient	Very high energy demand, limited removal on hydrophilic organics with low MWs	(Grundestam & Hellström, 2007; Gu et al., 2019; Liu et al., 2020)
FO	61-88% COD; 98-99% NH_4^+; 89–94% PO_4^{3-}; Particles, Pathogens; 2–100% OMPs	Low energy consumption	Draw solution require	(Chen et al., 2014; Ding et al., 2014; Lutchmiah et al., 2014)
Microalgae	67% NH_4^+; 98% PO_4^{3-}; COD; 0–8% OMPs	Suitable for high quality effluent from AnMBR, Generated biomass could be used to generate renewable biofuel	Need optimum operation condition, poor removal on OMPs	(Ruiz-Martinez et al., 2012; Wu et al., 2022)
IEX (Zeolites)	83–94% NH_4^+	Selectively remove and recover of nutrients, Short contact time and small footprint	Regeneration dominated the operational cost and energy consumption	(Deng et al., 2014)
IEX (HAIX)	97% PO_4^{3-} (PhosXnp)			(Sendrowski & Boyer, 2013)
Coagulation-Flocculation ($FeCl_3$)	96% PO_4^{3-}	Widely applied to Aerobic system for enchanted chemical phosphorus removal	Produce excess wastes	(Penetra et al., 1999)
Membrane Contactor	98.9% Dissolved Methane; 90% NH_4^+; Up to 100% OMPs	High methane and ammonium recovery	Membrane fouling and wetting, economic viability and process safety have not been fully evaluated, require further treatment for TP	(Christiaens et al., 2019; Cookney et al., 2016; Rongwong et al., 2019)
Membrane biofilm reactor	96% NH_4^+; 98% dissolved methane; 90% nonpolar, hydrophobic and hydrophilic OMPs; 22–69% negatively charged and acidic OMPs	Could both remove dissolved methane and TN	Require both energy and membrane cost, also further treatment for TP	(Chen et al., 2015; Sanchez-Huerta et al., 2022)

Abbreviations: GAC: Granular Activated Carbon; PAC: Powdered Activated Carbon; VOC: Volatile organic compounds; PhCs: Pharmaceutically Compounds; DOC: Dissolved Organic Carbon; AOCs: Aromatic Organic Compounds; NOMs: Natural Organic Matter; AC: Activated Carbon; MW: Molecular Weight; EDs: Endocrine Disruptors; PCPs: Personal Care Products; MD: Membrane Distillation; NF: Nano-Filtration Membrane; FO: Forward Osmosis Membrane; RO: Reverse Osmosis Membrane; TN: Total Nitrogen; TP: Total Phosphorus; TKN: Total Kjeldahl Nitrogen; OMPs: Organic Micropollutants; AOP: Advanced oxidation Process; IEX: Ion Exchange; HRT: Hydraulic Retention Time.

monomers over the membrane PA layer and the incorporation of nanomaterials led to better MPs repel performance by enhancing membrane physiochemical properties (Khoo et al., 2022). However, other post-treatment options, such as advanced oxidation processes (AOPs), are evidenced to satisfactorily remove the recalcitrant OMPs to meet stringent reuse water quality standards, but remain practical limitations with high operational expenditure (James et al., 2014).

The ultimate target of complementing AnMBRs with additional treatment steps should not only be to satisfy reuse standards, but also to create a multi-functional resource recovery treatment train. Studies reporting the combination of AnMBR with MD, NF, RO, FO and RO + IEX have demonstrated significant potential in providing a permeate satisfying non-potable water reuse standards with a potential of resource recovery (Lim et al., 2020). However, it is not only the post-treatment for effluent quality requirements that needs to be considered, but also the impact which the AnMBR effluent may have on a post-treatment process when specifically targeting a reuse application. So far, there is only one published study that has documented the use of AOPs as a post-treatment step for AnMBR effluent, in which UV/H_2O_2 acted as an efficient and safe strategy to remove both biological and chemical contaminants from an ammonia rich AnMBR effluent (Augsburger et al., 2021). Other example is the presences of N and P has been associated with biofilm formation in reverse osmosis processes (Liu et al., 2020). We would note that nutrients and other dissolved low molecular weight components may have an impact on post-treatment processes. Overall, this shows that high quality effluent can be achieved with the implementation of post-treatment but further analysis is required to establish the cost benefit of the combined system for these applications.

Concluding remarks and future research

Literatures documented so far have not reported the application of full scale AnMBRs for municipal wastewater treatment, let alone for water reuse. The evidence base and regulations from different regions suggests that, except in the cases of nutrients and residual chlorine concentration, AnMBRs could directly produce an effluent satisfying the strictest consents for all non-potable reuse applications. However, the wide variability observed between literatures indicates the necessity of identifying optimum operational conditions based on the quality requirements for different reuse purposes. Analysis of documented operating data suggests that influent water matrix, temperature and hydraulic retention time are key operational parameters affecting organic removal performance, with system and membrane configurations influencing the cost of AnMBR operation but providing a low nutrient effluent and resource recovery potential. Combinations or replacements of different membrane processes with an anaerobic reactor provides nutrient removal before or after the AnMBR process and enhance contaminant removal to produce an effluent of sufficient quality for water reuse applications. Finding the right balance between performance and operational expenditure is critical to ambitions to exploit the potential of AnMBRs for water reuse.

As higher OLRs can enhance methane yields and deliver improved energy recovery rates, and low TSS and no inorganic COD leads to low pump energy consumption, lower membrane fouling rates and higher biodegradability, which ultimately suggesting that settled wastewater is most likely the best source-water option for AnMBR reuse applications with a rich influent and reduced total operational cost. The negligible nutrient removal performance of AnMBRs means that they are well suited to agricultural and landscape irrigation reuse contexts as crops can directly extract the nutrients from the effluent. However, for other purposes such as in-building (e.g. toilet flushing) or recreational waters augmentation post-AnMBR treatment would be required to remove organics and nutrients down to acceptable levels.

There has been limited research conducted on the application of post-AnMBR treatment technologies for reuse with the vast majority of AnMBR studies focused on treatment for discharge. Leaving the gap of evaluating the feasibility of different technology treating AnMBR effluent for reuse purposes. Further from post-treatment process aiming to meet reuse consents, combination of resource recovery with post-treatment process brings promising insight of applying AnMBR to water reuse applications. A combination of pre- or post- treatment processes to recover nutrients would not only result in improved effluent quality but also provide a supply of nutrients for reuse.

To conclude, the tradeoff between cost and effluent quality is central to the successful application of AnMBRs to water reuse. Ultimately, with post-treatment, AnMBRs can deliver water that meets any non-potable reuse standards but further study is required to outline a pathway to maturity for effective treatment trains. In particular, the following specific knowledge gaps require urgent attention:

1. More comprehensive water quality analysis is needed to better understand the operation of AnMBRs, as well as fully examine the feasibility of AnMBR effluent against standards for water reuse. This will boost understanding of not only the impact of reusing the AnMBR effluent but also options for post-treatment technologies to enable the achievement of stricter reuse standard consents.
2. Optimizing the operational sweet spot is suggested when treating municipal wastewater for reuse purposes. Stable operation of AnMBRs requires deeper understanding of how multiple parameters interact. Finding the balance between effluent quality and energy consumption requires further study.
3. Using authentic wastewater as the influent for pilot scale work will provide more accurate and credible findings on which to base system design. Results obtained using synthetic wastewater are unconvincing to regulators and scheme approvers. We urge researchers to work with authentic wastewater in future studies so as to generate a more accurate understanding of process potential for reuse applications.
4. Exploring different AnMBR configurations and couplings with secondary technologies (pre- and post-treatment) may result in better overall performance both on contaminant removal and energy use and recovery. The search for ways in which a satisfactory effluent quality can be produced with low operational expenditure will involve investigation of new membrane materials, configurations and fouling mitigation methodologies. The impact of nutrients and low molecular weight substrates on post-treatment technology performance will require further investigation.
5. Advanced understandings of the effectiveness of disinfection processes when coupled with AnMBRs will support treatment train design for applications requiring a chlorine residual. Additional research is required to provide confidence in the inactivation or removal of different virus species, particularly where tighter reuse cycles are being planned.
6. The fate of organic micro-pollutants through AnMBR and coupled post-treatment still need further study to understand the risks of reusing the AnMBR effluent.

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