Comparison of hybrid membrane aerated biofilm reactor (MABR)/suspended growth and conventional biological nutrient removal processes

Avery L. Carlson, Huanqi He, Cheng Yang and Glen T. Daigger

ABSTRACT

Mathematical modelling was used to investigate the possibility to use membrane aerated biofilm reactors (MABRs) in a largely anoxic suspended growth bioreactor to produce the nitrate-nitrogen required for heterotrophic denitrification and the growth of denitrifying phosphorus accumulating organisms (DPAOs). The results indicate that such a process can be used to achieve a variety of process objectives. The capture of influent biodegradable organic matter while also achieving significant total inorganic nitrogen (TIN) removal can be achieved with or without use of primary treatment by operation at a relatively short suspended growth solids residence time (SRT). Low effluent TIN concentrations can also be achieved, irrespective of the influent wastewater chemical oxygen demand (COD)/total nitrogen (TN) ratio, with somewhat larger suspended growth SRT. Biological phosphorus and nitrogen removal can also be effectively achieved. Further experimental work is needed to confirm these modelling results.

Key words | anoxic suspended growth, biological nitrogen removal, biological phosphorus removal, membrane aerated biofilm reactor (MABR), process modelling

Avery L. Carlson
Huanqi He
Cheng Yang
Glen T. Daigger (corresponding author)
Department of Environmental Engineering,
University of Michigan,
1351 Beal Avenue, Ann Arbor,
MI 48109,
USA
E-mail: *gdaigger@umich.edu*

HIGHLIGHTS

- Hybrid MABRs can achieve lower effluent TIN concentrations, and more carbon capture, at lower SRTs than conventional systems.
- Influent carbon composition affects denitrification, but modelling shows better performance in hybrid MABR systems.
- Primary treatment benefits carbon capture, but can be eliminated depending on treatment goals.
- Combined biological nitrogen and phosphorus removal is possible and improved in hybrid MABRs.

INTRODUCTION

Membrane aerated biofilm reactors (MABR's) (Downing & Nerenberg 2008a) represent a recently commercialized aerobic biofilm biological wastewater treatment process where air or pure oxygen is supplied to the inside of a gas permeable membrane (He *et al.* 2020). Oxygen diffuses through the membrane and into the attached biofilm, thereby allowing the aerobic growth of heterotrophs and nitrifiers. Substrates in the bulk liquid diffuse into the biofilm from the opposite direction, consequently creating a counter-diffusional process with distinct concentration profiles over other widespread biofilm technologies. If the biofilm is thick enough, an outer anoxic zone and inner

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aerobic zone can develop within the biofilm. More recently, researchers have incorporated MABR units into the anoxic zone of conventional suspended growth biological nutrient removal (BNR) processes, allowing the nitrate produced by nitrification in the MABR biofilm to serve as an electron acceptor for heterotrophs in the suspended growth, while reducing or eliminating the need for mixed liquor recirculation for total nitrogen removal (Downing & Nerenberg 2008b; Houweling & Daigger 2019; Sathyamoorthy *et al.* 2019). To date, the MABR component of the system has been sized to accomplish only a portion of the needed nitrification (often about 30% and less than 50%) (Houweling *et al.* 2017), and this has allowed a modest reduction in the size of the downstream aerobic suspended growth zone needed to complete the required overall extent of nitrification. These processes also benefit from the much higher oxygen transfer efficiency (OTE) achieved with MABR units, compared to the oxygen transfer systems available for suspended growth bioreactors (Li *et al.* 2008; Côté *et al.* 2015).

The success of these combined MABR/suspended growth processes (further referred to here as hybrid MABR processes) suggests that further benefits may result if most, or all, of the required nitrification is provided by the MABR units. Process energy requirements would be further reduced as an increased proportion of the oxygen demand for nitrification is satisfied by the more energy-efficient MABR units. Moreover, the size of the suspended growth aerobic zone could be significantly reduced, or even eliminated, further reducing process oxygen (and corresponding energy) requirements. Nitrogen removal would also no longer be limited by mixed liquor recirculation, potentially allowing for increased nitrogen removal. Reduction or elimination of the suspended growth aerobic zone could also result in a significant reduction in the suspended growth solids residence time (SRT), thereby reducing the fraction of influent biodegradable organic matter oxidized, thereby allowing more of the influent carbon to be captured for other purposes.

Previous work by this group using a simplified modelling approach demonstrated that these benefits could be realized. At that time, MABR modules had not yet been developed in any established biological process simulation software that we were aware of. Instead a surrogate completely stirred tank reactor (CSTR) performed complete nitrification on an influent stream, which then sent the oxidized product – nitrate-nitrogen – to a downstream anoxic tank performing denitrification on a separate stream of influent carbon (see Table 1 for those constituent loadings). Results were encouraging, and met the criteria above with achieved reductions to SRT (<3 days), effluent TIN, and oxidized particulate and colloidal organic matter during denitrification (Daigger *et al.* 2019). Fortunately, upgrades to the simulation software (SUMO, Dynamita) now include MABR unit processes, allowing additional important design parameters. This paper extends the previous work by incorporating MABR unit processes directly into suspended growth processes and compares results to modified Ludzack–Ettinger (MLE) and A^2/O suspended growth processes, conventional configurations often used in practice for their simplicity in performing nitrogen removal and combined nitrogen and phosphorus removal, respectively (Grady *et al.* 2011; Water Environment Federation 2018). The objectives were to: (1) further quantify differences between hybrid MABR process options, compared to these conventional suspended growth processes, and (2) identify hybrid MABR process operating conditions that may be interesting to pursue experimentally.

Table 1 | Wastewater flow and constituent loadings used in simulations (100,000 population)

Item	Value	Units	Value	Units
Flow	0.25	m^3/cap-day	25,000	m^3/day
COD	170	g/cap-day	17,000	kg/day
TKN	15	g-N/cap-day	1,500	kg-N/day
NH_3-N	65	% of TKN	975	kg-N/day
TP	2.5	g-P/cap-day	250	kg-P/day
COD/N	11.3	mg-COD/mg-N		

MATERIALS AND METHODS

Processes simulated

Process simulations were conducted to determine the impact of the suspended growth bioreactor SRT on effluent TIN for hybrid MABR biological nitrogen and combined biological nitrogen and phosphorus process options. TIN was the metric of effluent total nitrogen performance considered in this study instead of total nitrogen (TN) because the former captures the components of nitrification and denitrification, whereas the organic nitrogen components of the latter are wastewater specific and dynamic. Capture of influent chemical oxygen demand (COD) for productive purposes was assessed by the fraction of influent COD converted to biogas when primary sludge (when primary clarifiers were included) and waste activated sludge (WAS) is subjected to anaerobic digestion. Scenarios were also conducted with or without primary clarification. The results from simulation of the hybrid MABR processes are compared to those for the conventional MLE biological nitrogen removal and A^2/O biological nitrogen and phosphorus removal processes.

Figure 1 presents the model configuration used to simulate the hybrid MABR biological nitrogen removal process. The suspended growth process SRT is controlled by adjusting the bioreactor effluent waste flow rate, with a secondary clarifier effluent total suspended solids (TSS) concentration set to zero mg/L to simplify use of the model. Sludge from the secondary clarifier was recycled back to the head of secondary treatment. Waste sludge from the primary clarifier (when included) and suspended growth process were combined, thickened such that no solids (100% solids removal) were returned to the primary effluent stream, and directed to a single-stage anaerobic digester where an SRT of 20 days was maintained for all simulations. Simulations incorporating primary treatment were conducted using a primary treatment TSS removal efficiency of 60%, while simulations with no primary treatment were conducted by lowering the removal efficiency to 0%.

Numerous simulations (data not shown) were conducted to determine the hybrid MABR bioreactor configuration depicted in Figure 1 and consisted of a single MABR zone followed by an anoxic zone (ANX) and an aerated (AER) zone. The bioreactor may be viewed as a rectangular unit with MABR units located at the inlet end, followed by a zone with mechanical mixing for suspended solids suspension, and finally a moderate level of diffused aeration adjacent to the outlet. For this work, we defined the system ammonia loading as the influent ammonia mass per day divided by the MABR surface area. An ammonia loading of 2.7 g-N/m^2-day based on the influent ammonia loading for the high COD/TN case was determined to provide good performance, and a packing density of 150 m^2/m^3 was used to size the MABR zone in the model. The ammonia loading to the MABR is within the range of nitrification rates currently used to design commercial hybrid systems (1.5–3 g-N/m^2-day) (Côté *et al.* 2015; Kunetz *et al.* 2016). The ammonia loading under the low COD/TN condition pushed just beyond this at 3.1 g-N/m^2-day. A suspended growth mixed liquor suspended solids (MLSS) concentration of 3,000 mg/L was maintained for both the hybrid MABR and conventional processes so that the same size secondary clarifier would be required, allowing the suspended growth SRT to fully characterize the difference in required bioreactor volume for all process options. This required varying the suspended growth bioreactor volume. Sufficient bioreactor volume was provided by the MABR volume for the lowest SRT investigated, but volume for the downstream anoxic and aerobic zone was required to maintain the target 3,000 mg/L MLSS concentration as the suspended growth SRT increased. When these zones were added, the relative volumes for the system were maintained at 90% anoxic and 10% aerobic. The terminal aerobic zone was found to be necessary to oxidize residual ammonia, and a dissolved oxygen (DO) concentration of 1 mg/L was maintained for all simulations where this zone was included. Overall process performance was also found to be optimized if a minimal DO concentration of 0.1 mg/L was maintained in the anoxic zone. A small amount of residual oxygen blunted ammonia was released downstream of the MABR from anoxic hydrolysis of organic nitrogen and decay products. The settleability of anoxic suspended growth was also considered likely to be poor. Thus, a modest amount of aeration would be necessary in any bioreactor configuration in a full-scale facility.

The conventional MLE biological nitrogen removal process (Figure 2) was generally configured as described above. The MLE bioreactor secondary treatment consisted of two anoxic continuously stirred tank reactors (CSTRs) followed by three aerobic CSTRs with a mixed liquor recirculation (MLR) of 400% of the influent flow. The anoxic zone constituted 30% of the bioreactor volume, with the aerobic zone being the remaining 70% of the total. The total volume was varied to maintain a MLSS concentration of 3,000 mg/L. A DO concentration of 2 mg/L was

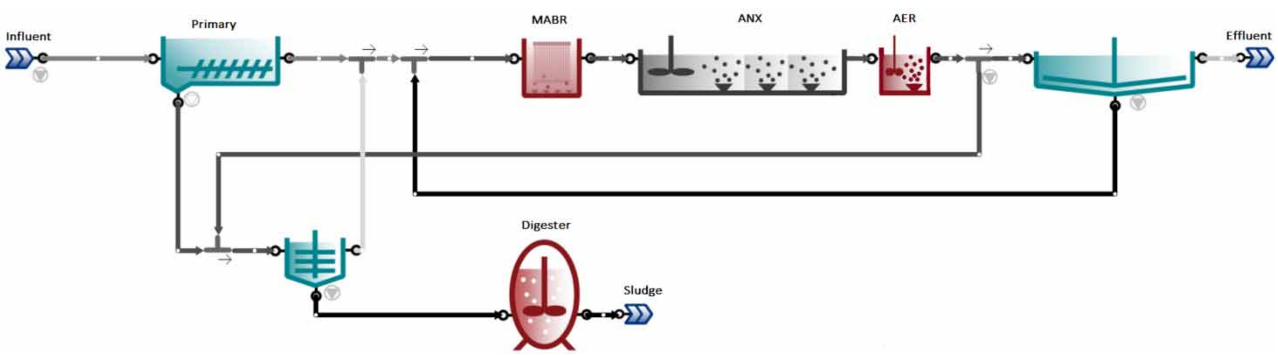

Figure 1 | Schematic of hybrid MABR biological nitrogen removal process.

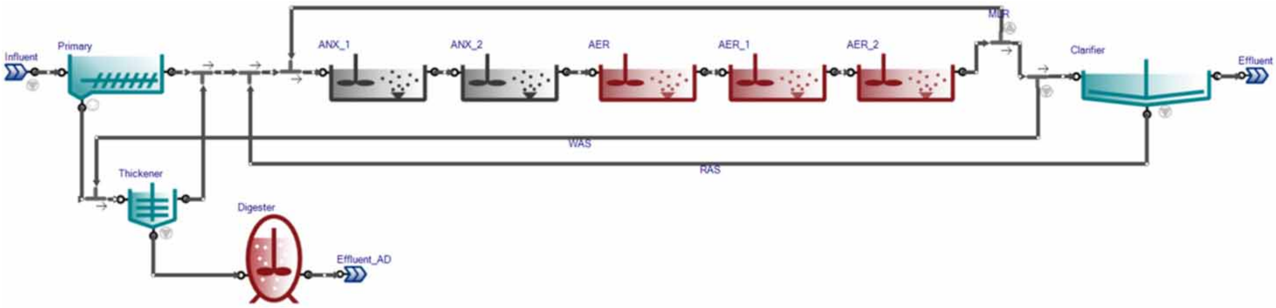

Figure 2 | Schematic of MLE nitrogen removal process.

maintained in the aerobic CSTRs. Primary and secondary clarification, sludge thickening, and anaerobic digestion were as previously described for the hybrid MABR process.

Hybrid MABR and conventional A^2/O processes for biological nitrogen and phosphorous removal are illustrated in Figures 3 and 4, respectively. The sole difference between the biological nitrogen removal options described above is the addition of an initial anaerobic zone (ANA) to both processes for hydrolysis of particulate and colloidal organic matter and volatile fatty acid uptake by phosphorus accumulating organisms (PAOs) (Grady *et al.* 2011). The sizes of the bioreactor zones were adjusted to provide optimal nutrient removal, as described below. The resulting relative volumes of the anaerobic, MABR, anoxic, and aerobic zones for the hybrid MABR bioreactor were 12%/12%/74%/2%, respectively. Likewise, the relative volumes of the ANA, ANX, and AER zones of the conventional A^2/O process were 13%/36%/51%, respectively. As above, the total volume was adjusted to maintain a MLSS concentration at 3,000 mg/L for both processes.

All simulations were run in steady-state mode in SUMO20. In this mode, the software solver looks for solutions that converge to a particular value and the system behavior does not change with run time (Dynamita 2019).

Wastewater flows and constituent loadings

Table 1 summarizes the influent wastewater flows and constituent mass loadings used, along with the per-capita values used to calculate them for a service population of 100,000

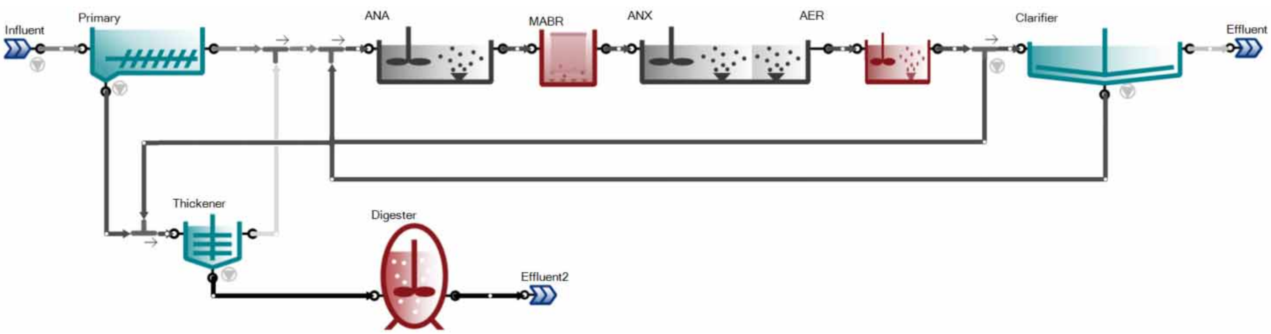

Figure 3 | Schematic of hybrid MABR biological nitrogen and phosphorus removal process.

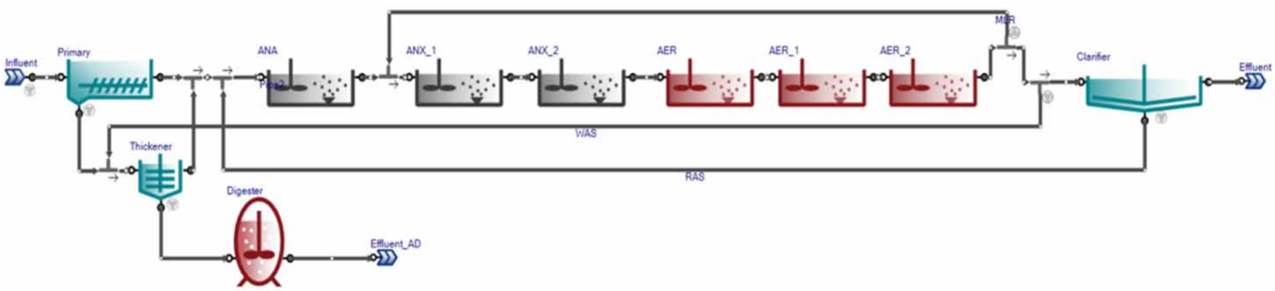

Figure 4 | Schematic of A^2/O N&P removal process.

people. The relatively low water use used (0.25 m^3/cap-day) results in a relatively strong wastewater (680 mg/L COD, 60 mg-N/L TKN, 10 mg-P/L TP). A sensitivity analysis (data not provided) using higher per-capita wastewater use, resulting in overall lower wastewater concentrations, resulted in similar performance patterns as those reported below. A wide range of operating conditions was simulated to provide an understanding of the opportunities and trade-offs available, depending on the desired objectives (e.g., maximize biogas production, nitrogen removal, nitrogen and phosphorus removal).

Results from the previous work (Daigger *et al.* 2019) and from this work (reported below) indicate that excellent TN removal can be accomplished. Since biological nitrogen removal via heterotrophic metabolism depends on the availability of sufficient organic matter, a sensitivity analysis was conducted to assess the impact of a lower wastewater COD/TN ratio on the effluent TIN. For this analysis, the per-capita COD loading was reduced from 170 to 100 g-COD/cap-day, resulting in a reduction in the influent wastewater COD/TN ratio from 11.3 to 6.7 mg-COD/mg-N. Table 2 presents the revised influent wastewater flows and constituent loadings used for this analysis.

Simulation methodology

Simulations were conducted using SUMO20 by Dynamita. Default wastewater characteristic and biological process stoichiometry and kinetics were used, except that the anoxic growth factor for ordinary heterotrophic organisms (OHOs), glycogen-accumulating organisms (GAOs), and PAOs which were adjusted from 0.6, 0.66, and 0.33, respectively to 0.83 for the hybrid MABR processes. This was done because anoxic operation of the suspended growth component of the hybrid process would select for a higher proportion of denitrifying organisms. Default anoxic growth factors were maintained for the conventional biological nitrogen and phosphorus removal processes. Oxygen input to the MABR units was adjusted to minimize effluent TN and the bleed through of oxygen out of the biofilm and into the suspended growth. The biofilm thickness was set at 175 μm, with the biofilm specific mass of 10 g TSS/m^2. The biofilm was divided into three layers, and the mass transfer boundary layer thickness (40 μm) was maintained. Water displaced by membrane and ratio of reactor volume filled by a membrane were 0.25 and 1.0, respectively. All simulations were conducted at a temperature of 20 °C.

Table 2 | Wastewater flow and constituent loadings used for low COD/N simulations (100,000 population)

Item	Value	Units	Value	Units
Flow	0.25	m^3/cap-day	25,000	m^3/day
COD	100	g/cap-day	10,000	kg/day
TKN	15	g-N/cap-day	1,500	kg-N/day
NH_3-N	75%	% of TKN	1,125	kg-N/day
TP	2.5	g-P/cap-day	250	kg-P/day
COD/N	6.7	mg-COD/mg-N		

RESULTS AND DISCUSSION

Biological nitrogen removal

The effect of suspended growth SRT on effluent total inorganic nitrogen (TIN) for the hybrid MABR and MLE biological nitrogen removal processes is presented in Figure 5 for the influent wastewater 11.3 mg-COD/mg-N case. The effluent TIN for the hybrid MABR process decreases sharply as the suspended growth bioreactor SRT increases from the lowest value simulation of 0.5 days and approaches minimal values of diminishing return at SRT values in the 2.5 to 3-day range. These low suspended growth SRTs can be maintained while achieving such high levels of nitrogen removal because nitrification is accomplished largely in the MABR biofilm. In contrast, a much longer suspended growth SRT is required for the conventional MLE process because a sufficient aerobic suspended growth zone must be maintained to allow nitrifiers to grow, in addition to the anoxic zone needed for denitrification. An effluent TIN for the MLE process of approximately 6 mg-N/L is indicated, which would be acceptable according to most current standards (Moore 2009). However, compared to an effluent TIN concentration of 1 mg-N/L or less for the hybrid MABR process, these simulation results illustrate the opportunity to greatly improve upon the existing system. Likewise, effluent TIN directly comparable to that achieved with the MLE process (i.e. 6 mg-N/L) can be achieved with the hybrid MABR process at a suspended growth SRT of around 1 day. The rapid decrease in effluent TIN estimated in the hybrid MABR process (with or without primary clarification) occurs because of increased hydrolysis and metabolism of particulate and colloidal organic matter as the suspended growth SRT increased from the lowest value of 0.5 days to around 2 days. Similar effluent TIN for the MLE process simulated with and without primary treatment implies that denitrification in the anoxic zone is limited principally by nitrate recirculation from the downstream aerobic zone by the MLR.

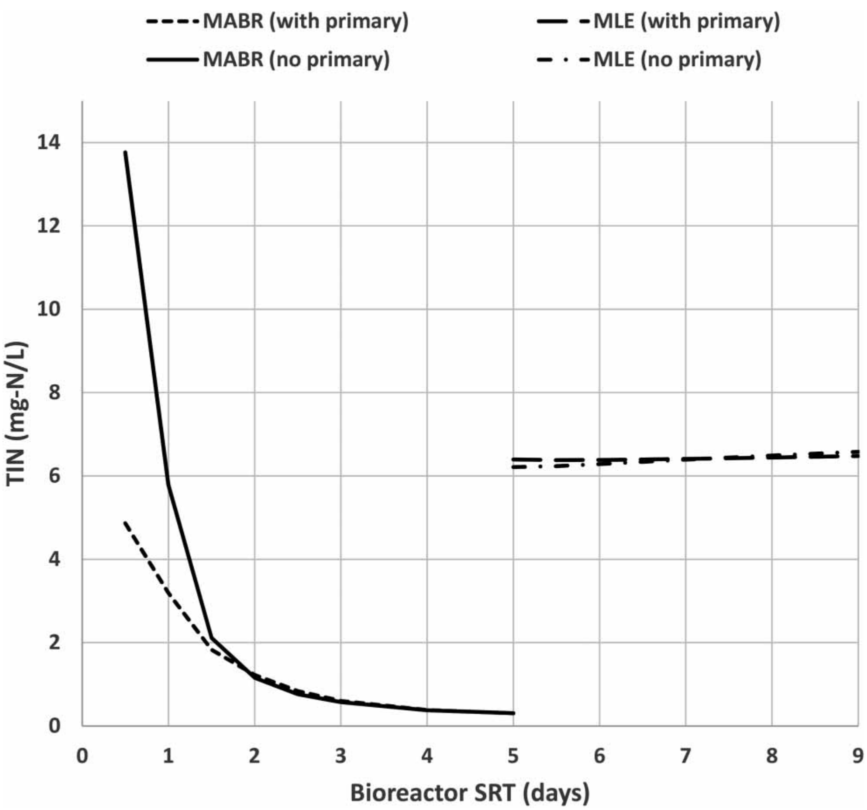

Figure 5 | Effect of suspended growth bioreactor SRT on effluent total inorganic nitrogen for influent wastewater COD/N of 11.3 mg-COD/mg-N.

The results of simulations conducted to investigate the impacts of reduced influent wastewater COD/TN on process performance are presented in Figure 6. Notice the change in the vertical scale from Figure 5. Effluent quality for the conventional MLE process is adversely impacted by the reduction in influent wastewater COD/TN, and effluent TIN is higher with primary treatment than without (approximately 25 mg-N/L and 20 mg-N/L, respectively). This suggests that denitrification is now carbon limited in the anoxic zone. Effluent TIN concentrations are also elevated for the hybrid MABR process, again regardless of primary treatment, but are much lower than for the conventional MLE process (<5 mg-N/L). In fact, effluent TIN concentrations achieved by the hybrid MABR process at the higher influent wastewater COD/TN ratio discussed previously are approached for the hybrid MABR process at unfavourable influent conditions without primary treatment, as the suspended growth SRT is increased to around 5 days. As above, the hybrid MABR process can achieve better effluent TIN concentrations than the MLE process at a suspended growth SRT of around 1 day. In short, the results presented in Figures 5 and 6 indicate that the hybrid MABR process provides increased flexibility using influent carbon for denitrification, regardless of influent carbon composition.

The results presented in Figure 7 provide further insight into the metabolism of carbon in the biological nitrogen removal process options. The effect of bioreactor suspended growth SRT on the fraction of plant influent COD that is converted into biogas (expressed as COD) in an anaerobic digester operating at a 20 day SRT in this figure is indirectly related to the process operating conditions previously depicted in Figures 5 and 6. This parameter provides one metric of the capture of useful carbon for the treatment process over the range of influent wastewater options evaluated. The flow of carbon directed to the digester includes primary sludge, during simulations where primary clarifiers were provided, and pumped WAS from secondary treatment. Increased suspended growth SRT results in less biodegradable organic matter available to direct to the anaerobic digester (i.e. a lower fraction of plant influent COD converted to biogas), suggesting that more plant influent biodegradable organic matter is oxidized in the hybrid MABR or MLE processes. The benefit of primary treatment, along with the negative impact of increased suspended growth SRT, on the capture of usable carbon are clearly

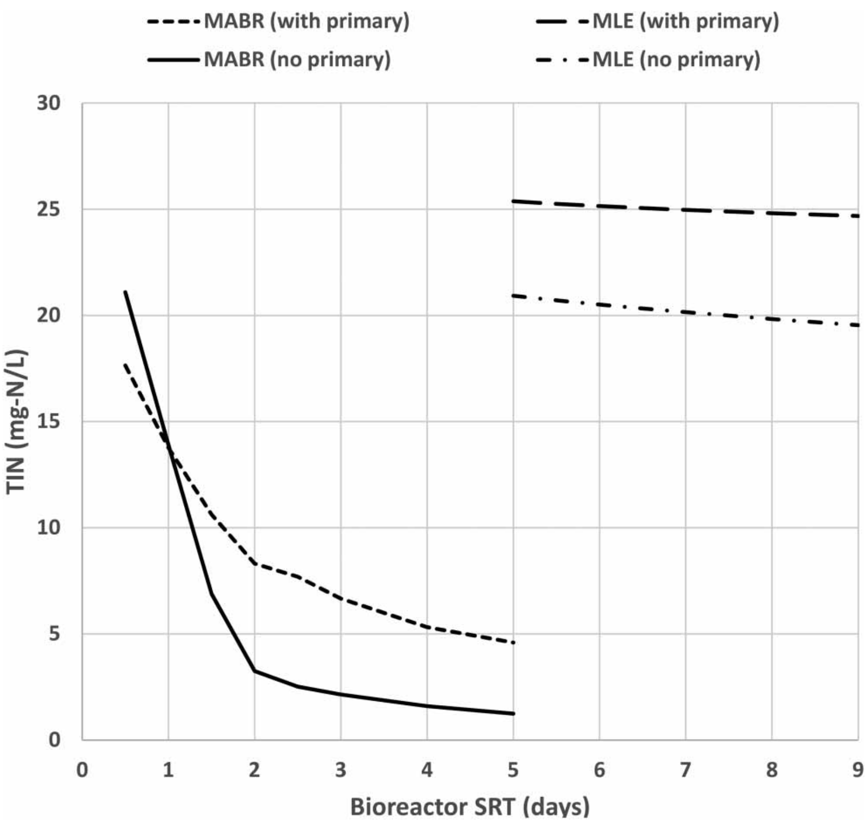

Figure 6 | Effect of suspended growth bioreactor SRT on effluent total inorganic nitrogen for influent wastewater COD/N of 6.7 mg-COD/mg-N.

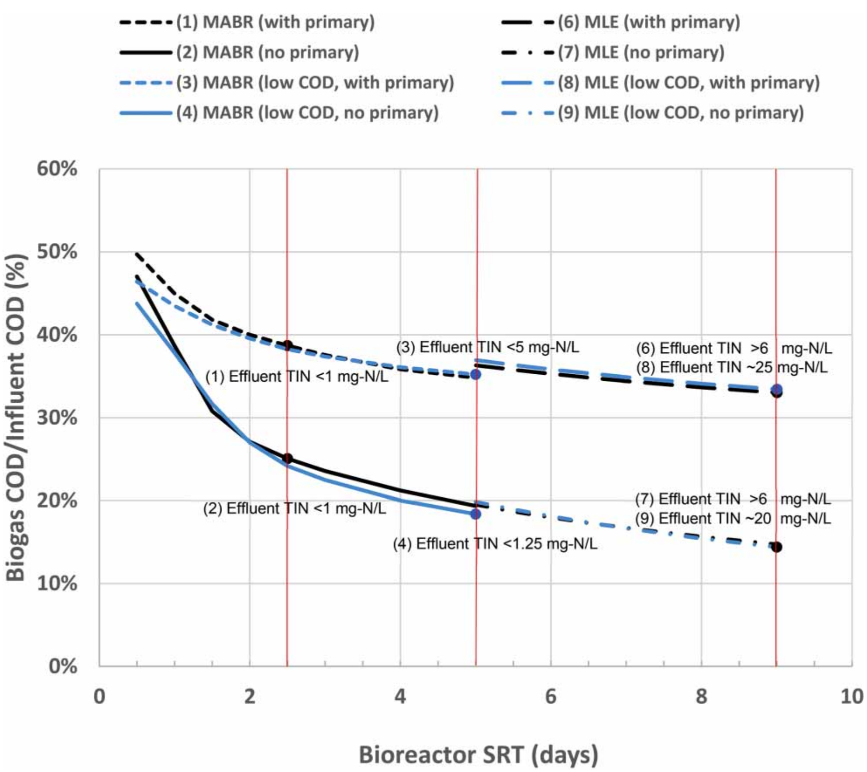

Figure 7 | Effect of suspended growth bioreactor SRT on biogas production as a percentage of influent COD.

illustrated in Figure 7 when the slopes diverge around the 1-day SRT mark. Remember, the benefits provided by the hybrid MABR process were a lower suspended growth SRT requirement to produce a high-quality effluent with low effluent TIN, which now also translates into enhanced carbon redirection to biogas. Interestingly, the fraction of influent COD captured as biogas is essentially the same irrespective of the COD/TN ratio of the influent wastewater. However, the reason for this becomes clear when viewing the results with Figures 5 and 6: denitrification is hindered with lower influent COD/TN and low suspended growth SRTs leading to a higher effluent TIN concentration, and therefore, a higher suspended growth SRT is required to achieve similar effluent quality, which results in less influent COD captured as biogas, as indicated in Figure 7. In short, a higher fraction of the influent biodegradable organic matter must be used for denitrification to achieve the same effluent TIN with the hybrid MABR process when the COD/TN of the influent wastewater is lower and less favourable. Comparison of Figures 5–7 highlights the trade-offs that exist between effluent TIN and carbon capture for the hybrid MABR process. Operation at an SRT of 2.5 days with higher strength influent wastewater (11.3 mg-COD/mg-N) allows effluent TIN reductions less than 1 mg-N/L; however, carbon capture is higher with the addition of primary treatment (roughly 40% versus 25% without primary treatment). When influent carbon is diminished, i.e. COD/TN is decreased to 6.7 mg-COD/mg-N, a higher effluent quality (1.25 mg-N/L) but less effective carbon capture (18%) is the result of the system at a 5-day SRT without primary treatment. Conversely, a slightly higher effluent but more carbon capture is achieved at the same operation including primary treatment. Reduced suspended growth SRT results in increased effluent TIN, but in almost all cases the concentrations achieved by the hybrid MABR are generally less than that achieved under equivalent conditions by the MLE process (Figures 5 and 6), and increased carbon capture as quantified by the fraction of influent COD as biogas (Figure 7). Carbon capture for the conventional MLE process can only be improved by including primary treatment when the influent wastewater COD/TN decreases (Figure 7), and in this instance effluent TIN concentrations also increase substantially (Figures 5 and 6).

The above results further indicate significant performance and economic advantages for the hybrid MABR process options relative to conventional biological nitrogen removal processes such as MLE. Table 3 summarizes a series of comparisons intended to illustrate these differences. The SRT selected for the hybrid MABR process for influent wastewater with a COD/TN ratio of 11.3 mg-COD/mg-N is the minimum value which achieves an effluent TIN less than 1 mg-N/L, rounded to the nearest 0.5-day SRT, while the SRT selected for the hybrid MABR process for influent wastewater with a COD/TN ratio of 6.7 mg-COD/mg-N is the highest value considered. The suspended growth SRT required for the hybrid MABR process treating the influent wastewater with a COD/TN of 11.3 mg-COD/mg-N is half that required for the conventional MLE process, while achieving a much lower effluent TIN concentration. This results in a much smaller suspended growth bioreactor for the hybrid MABR process, a reduction of roughly 40% the MLE volume. The same suspended growth SRT values are used for all options for the influent wastewater with a COD/TN of 6.7 mg-COD/mg-N, which translates to similar bioreactor sizes but a dramatically lower effluent TIN concentration (approximately 20 mg-N/L) for the hybrid MABR process compared to the MLE design. In all cases, there is a clearly illustrated benefit of reduced bioreactor volume when primary treatment is provided; however, the relationship to effluent TIN is also dependent on influent COD/TN conditions.

Examination of Table 3 for system process energy inputs and outputs, shows that the hybrid MABR process displays significantly reduced energy requirement versus the MLE system. Ancillary reductions are found in the form of the required mass of oxygen, as a substantial proportion is transferred by the much more energy-efficient MABR units. Estimates of OTE for hybrid MABRs in the field range from 50 up to 100%, compared to 25% or less in conventional systems (Li *et al.* 2008; Houweling *et al.* 2017). Direct reductions, such as elimination of mixed liquor recirculation that is not needed for the hybrid MABR process, cuts energy inputs even further. Energy for necessary items such as mixing were not considered in this assessment, but research has shown any potential increases to energy demand for MABR system mixing are modest when compared to total system requirements (Aybar *et al.* 2012). Evaluation of the results with unfavorably low COD/TN influent conditions provides opportunities to save some energy without sacrificing effluent quality; for instance, the mass of oxygen required per unit of influent COD is higher in all cases for the lower influent COD/TN wastewater, but influent COD can be captured as biogas to a greater extent when primary treatment is provided. Carbon capture is also higher for the hybrid MABR than the MLE process without primary treatment. The fraction of influent COD captured as biogas is similarly independent of the influent wastewater COD/TN ratio, thus enabling decision-making as to the extent of desired carbon capture to revolve around treatment goals

Table 3 | Performance comparison for nitrogen removal process options

	Hybrid MABR		Conventional MLE	
Item	**With primary**	**Without primary**	**With primary**	**Without primary**
COD/TN = 11.3 mg-COD/mg-N				
Suspended growth SRT (days)	2.5	2.5	5	5
Effluent TIN (mg-N/L)	0.8	0.8	6.4	6.2
MLR (%)	N/A[a]	N/A	400	400
AOR/COD (mg O_2/mg influent COD)				
MABR	0.18	0.19	N/A	N/A
Conventional	0.10	0.21	0.42	0.57
Total	0.28	0.40	0.42	0.57
Mixed liquor recirculation (%)	N/A	N/A	400	400
Bioreactor volume (m^3)[b]	4,520	7,620	7,150	12,700
Biogas (mg biogas COD/mg influent COD, %)	38.7	25.1	36.3	19.4
COD/TN = 6.7 mg-COD/mg-N				
Suspended growth SRT (days)	5	5	5	5
Effluent TIN (mg-N/L)	1.2	5.3	25.4	20.9
MLR (%)	N/A	N/A	400	400
AOR/COD (mg O_2/mg influent COD)				
MABR	0.30	0.33	N/A	N/A
Conventional	0.09	0.21	0.67	0.80
Total	0.39	0.54	0.67	0.80
Bioreactor volume (m^3)[b]	4,600	8,000	4,340	7,540
Biogas (mg biogas COD/mg influent COD, %)	38.3	24.2	37.0	19.8

[a]Not applicable.
[b]3,000 mg/L MLSS.

and available infrastructure. Overall, a reduced suspended growth SRT can be selected for the hybrid MABR process, leading to increased effluent TIN, but increased carbon capture, lower energy requirements, and reduced bioreactor volume. Note that these simulations were conducted at a wastewater temperature of 20 °C. Advantages for the hybrid MABR process would increase at lower temperatures because of the greater impact of temperature on nitrifier than heterotroph growth kinetics.

Biological nitrogen and phosphorus removal

One of the major unknowns in hybrid MABR technology is how to best design specifically for biological phosphorus removal. Although early evidence suggests that enhanced biological phosphorus removal (EBPR) is possible at larger scale treatment facilities (Peeters *et al.* 2017; Li 2018; Bicudo *et al.* 2019), there is little research currently projecting how and why an integrated MABR system treating domestic wastewater would decrease effluent phosphorus. Incorporating biological phosphorus removal into the hybrid MABR process necessitates use of a somewhat longer suspended growth SRT to accommodate the slower growing PAOs, compared to typical denitrifying heterotrophs (Grady *et al.* 2011; Sun *et al.* 2014). Using a total SRT of 4 days, and a typical domestic influent COD/TN composition (11.3 mg-COD/mg-N), the hybrid MABR process achieved optimal performance with an effluent ortho-phosphorus (OP) concentration of 0.17 mg-P/L and TIN concentration of 0.5 mg-N/L. The conventional A^2/O system achieved optimal performance at an SRT of 6.8 days. Even though good effluent OP concentrations can be achieved in either case, the hybrid MABR process can achieve significantly lower effluent TIN at lower SRTs. Effluent TIN was already quite low for the hybrid MABR process as total SRT was increased to 4 days, while adverse effects on phosphorus removal was experienced by the conventional system at longer SRTs. Deteriorated phosphorus removal performance in the A^2/O

Table 4 | Comparison of hybrid MABR with conventional biological nitrogen and phosphorus removal process with primary treatment

Item	Hybrid MABR	Conventional A^2/O
SRT (days)		
Anaerobic	0.55	0.85
Anoxic	3.35	2.45
Aerobic	0.1	3.5
Total	4.0	6.8
MLR (%)	N/A[a]	400
AOR/COD (mg O_2/mg influent COD)		
MABR	0.20	N/A
Conventional	0.10	0.42
Total	0.30	0.42
Effluent TP (mg-P/L)	0.17	0.30
Effluent TIN (mg-N/L)	0.5	6.8
Biogas (mg biogas COD/mg influent COD, %)	37.3	36.1
Bioreactor volume (m^3)[b]	6,290	9,750

[a]Not applicable.
[b]3,000 mg/L MLSS.

system at longer SRTs are due to: (1) nitrification in the aerobic zone resulting in nitrate-nitrogen recycle into the anaerobic tank; and (2) less PAO biomass is wasted at longer SRTs, which directly decreases phosphorus-rich biomass wastage from the system (Grady *et al.* 2011).

Operation and performance characteristics of the hybrid MABR biological nitrogen and phosphorus removal process, compared to the conventional A^2/O biological nitrogen and phosphorus removal process, are presented in Table 4. Primary treatment was included in both treatment trains because, similar to previous discussion, longer SRTs correlate to increased metabolism of biodegradable organic matter leading to low effluent TIN. Thus, primary treatment was included to reduce the size of the bioreactor and to provide increased carbon capture.

Process oxygen requirements are lower for the hybrid MABR process compared to the conventional A^2/O process, while the capture of influent COD as biogas is similar. Approximately two-thirds of the total oxygen required for the hybrid MABR process would be transferred using the more efficient MABR units, and the need for mixed liquor circulation would be eliminated, leading to a significant reduction in energy requirements compared to a conventional biological nitrogen and phosphorus removal process, similar to previous discussions above. The lower suspended growth SRT required for the hybrid MABR process results in a smaller bioreactor (35% smaller). These results highlight important advantages of the hybrid MABR biological nitrogen and phosphorus removal process compared to conventional configurations, particularly the ability to achieve lower effluent TIN. The principal impact of incorporating biological phosphorus removal into the hybrid MABR process is a larger bioreactor than designs for nitrogen removal only. Experimental results are needed, of course, to further evaluate the process options outlined here, specifically elucidating what factors influence PAO growth in hybrid MABR systems and what phosphorus removal mechanisms exist under designed bulk liquid anoxic suspended growth. The modelling results herein provide a framework for designing such experiments.

CONCLUSIONS

In conclusion, the results provide further proof of concept for the envisioned hybrid MABR process. It is well demonstrated elsewhere that incorporation of an appropriately sized MABR in a non-aerated suspended growth zone can provide a nitrifying biofilm to produce the nitrate-nitrogen required for denitrification in that zone. Sizing the MABR to accomplish a substantial proportion of the total required nitrification allows the aerated zone required within a conventional suspended growth biological nitrogen removal process to be significantly reduced in size, or eliminated, and allows the suspended growth SRT to be reduced significantly. Conversion of ammonia to nitrate in the initial portion of the suspended growth bioreactor also eliminates the need to recirculate nitrate from a downstream aerobic zone to the anoxic zone, allowing more complete denitrification to occur. This configuration also allows biodegradable organic matter influent to the biological reactor to be used more efficiently for denitrification (little or no oxidation in a downstream aerobic zone), reducing biodegradation of influent organic matter, and the potential to capture a higher fraction of the influent organic carbon for other purposes. Reduced metabolism of biodegradable organic matter reduces the process oxygen requirement, and this, coupled with the higher oxygen transfer efficiency for MABR compared to conventional oxygen transfer systems and elimination of the need for mixed liquor recirculation, results in further reduction of process energy requirements for the hybrid MABR process compared to conventional biological nitrogen removal systems.

The hybrid MABR process offers the potential to maximize carbon capture while minimizing process energy requirements while also achieving significant but incomplete nitrogen removal by operating at lower suspended growth SRT. The hybrid MABR process can also accommodate an influent wastewater with reduced COD/TN by increasing the suspended growth SRT to allow increased metabolism of influent biodegradable organic matter, as needed, to accomplish the desired effluent TIN concentration. Biological phosphorus removal can also be incorporated into the hybrid MABR process by addition of an anaerobic zone upstream of the anoxic zone containing MABR units. This is likely to result in modestly increased process oxygen requirements and reduced carbon capture, but still provides important advantages compared to conventional suspended growth biological nitrogen and phosphorus removal options, including lower effluent TIN and reduced bioreactor volume.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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