Improving biological phosphorus removal in membrane bioreactors – a pilot study

S. Smith, G. Kim, L. Doan and H. Roh

ABSTRACT

With increasing water reuse applications and possible stringent regulations of phosphorus content in secondary and tertiary effluent discharge in Florida, USA, alternative technologies beyond conventional treatment processes require implementation to achieve low phosphorus (P) and nitrogen (N) concentrations. A pilot scale membrane bioreactor (MBR) system, operated in Florida, adopted the University of Cape Town (UCT) biological process for the treatment of domestic wastewater. The system operated for 280 days at a wastewater treatment facility with total hydraulic retention time (HRT) of 7 h and sludge retention time (SRT) of 20 days. Operating conditions were controlled to maintain specific dissolved oxygen (DO) concentrations in the reactors, operate at suitable return activated sludge (RAS) rates and to waste from the appropriate reactor. This process favored biological phosphorus removal and achieved 94.1% removal efficiency. Additionally, chemical oxygen demand (COD) and N removal were achieved at 93.9% and 86.6%, respectively. Membrane operation and maintenance did not affect the biological P removal performance but enhanced the process given the different operating requirements compared to that required with the conventional UCT process alone. Conclusively, the result of the pilot study demonstrated improvement in biological phosphorus removal. The UCT-MBR process tested achieved average effluent nitrogen and phosphorus concentrations of 5 mg/L as N and 0.3 mg/L as P.

Key words | enhanced biological phosphorus removal (EBPR), membrane bioreactor, phosphorus removal, water reuse

S. Smith (corresponding author)
G. Kim
L. Doan
H. Roh
Doosan Hydro Technology,
LLC, 912 Chad Lane,
Tampa,
FL 33619,
USA
E-mail: *ssmith@doosanhydro.com*

INTRODUCTION

Membrane bioreactors (MBRs) are becoming the advanced solution for water reuse as fresh water demands continue to increase and environmental contamination of drinking water sources becomes of greater concern. As stated by the National Research Council (NRC), wastewater reuse is intended to be utilized as a means to recover resources such as nutrients, energy and water (NRC 2012). In the case that water is being recovered for reuse or solely discharged as treated wastewater, water quality is important. Depending on the application, stringent effluent limits are specified for the protection of public health and the environment. For such reasons, MBRs are most practical to achieve suitable effluent quality that can be further treated for the additional removal of nutrient and contaminants using advanced technologies such as reverse osmosis technology (Comerton *et al.* 2005). The lack of US federal regulations governing water reuse treatment criteria then places responsibility on local and state agencies to develop such regulations (USEPA 2008). Water quality discharge limits, specifically nitrogen and phosphorus, established are dependent on the specific application and receiving water body for which effluent is discharged. These regulations are important for the protection of aquatic systems harmed by the effects of nutrient loading which can increase algae growth, develop algal blooms, deplete oxygen concentrations and decrease water clarity

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(USEPA 2009b). Several guidelines can apply and have been summarized by the United States Environmental Protection Agency (USEPA) in their 2012 Guidelines for Water Reuse Report.

Several US states, including California, Nevada, Arizona, and Texas, practice water reuse as a means for water conservation and groundwater recharge (USEPA 2012). The list extends to worldwide countries, including Singapore, Saudi Arabia, Australia and Israel (Bahri & Asano 2011). This further emphasizes the importance for appropriate water quality regulation, especially with regard to discharge of high nutrient concentrations and harmful contaminants. The California Department of Public Health (CDPH), for example, regulates wastewater reuse under the water recycling criteria, commonly known as the Title 22 reuse criteria (CDPH 2009a, b). However, these regulations do not address nutrient criteria on a statewide basis and are controlled depending on the geographical region and receiving water body type (King 2010). However, in other countries, as previous literature has referenced, such as Germany and the Netherlands, stringent regulations have already been implemented with discharge criteria of 0.5 and 0.15 mg/L as phosphorus (P) for the respective countries (Lesjean *et al.* 2003).

Current Florida general wastewater regulations permit discharge concentrations for phosphorus and nitrogen are 1 mg/L as P and 3 mg/L as nitrogen (N). Future regulations from the Florida Department of Environmental Protection (FDEP) may impose even more stringent nutrient discharge requirements on wastewater treatment and/or water reclamation plants if approved by USEPA (Matthews *et al.* 2011). More recently, the nutrient criteria for streams, lakes and estuaries has been approved by the USEPA in late 2012. The regulation is being implemented to protect high quality waters and to prevent further impairment of waters including estuarine, coastal and inland waters using a measurable criteria (King 2010). Phosphorus and nitrogen concentrations as low as 0.05 mg/L as P and 1.27 mg/L as N are to be implemented for secondary or tertiary effluent discharge to estuaries and rivers or lakes (USEPA 2010).

In general, the current water quality requirements for N and P can be achieved successfully using biological treatment, such as with the UCT (University of Cape Town) process, in conjunction with coagulant for the additional removal of phosphorus (Wentzel *et al.* 1986; Comeau *et al.* 1987; Rittmann & McCarty 2001; Tchobanoglous *et al.* 2003; USEPA 2009a). This is feasible due to the nitrogen removal process being well known and easily optimized based on the design and operating parameters of the biological system. Phosphorus, on the other hand, can be chemically or biologically removed. Chemical treatment involves direct precipitation (as implied earlier with the use of coagulant) for the physical removal of P compounds whilst biological removal involves bacteria removing phosphorus via their metabolic pathways (USEPA 2009a). Although enhanced biological phosphorus removal (EBPR) can be optimized for the general Florida P requirements, there are treatment limitations and performance instability, especially with fluctuating wastewater and sludge characteristics (Jenkins & Tandoi 1991; Liu *et al.* 1997; Mino *et al.* 1998). If biological phosphorus removal can be enhanced alongside MBRs, it potentially reduces the coagulation requirement with the UCT or other nutrient removal process (Galil *et al.* 2009; Lee *et al.* 2009; Monclús *et al.* 2010). With the new regulations to be implemented, increasing the potential for P removal prior to coagulant use will directly aid in reducing coagulant dose requirements to achieve the low P limit. Even more so, it can reduce the effluent P sufficiently for further reduction by additional membrane or ion exchange technologies (USEPA 2009b). This study evaluates the feasibility of a UCT biological process combined with membrane technology (MBR) for the efficient removal of both N and P concentrations, more specifically P, without additional chemical requirements.

MATERIALS AND METHODS

MBR pilot system

The pilot system was designed for the operation of the UCT process and consisted of an intake system, fine screen, biological reactors, and a membrane tank along with ancillary equipment as shown in the process flow

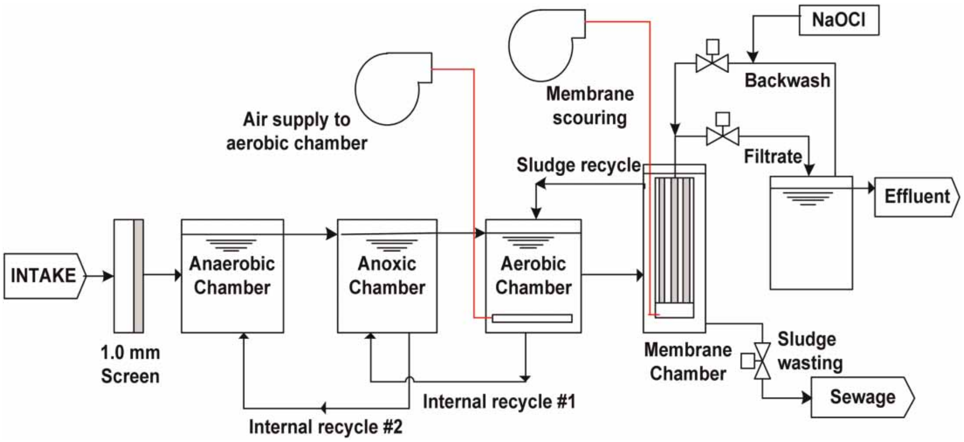

Figure 1 | Process flow schematic for the UCT-MBR pilot.

diagram in Figure 1. The total volume of the biological reactors was 6.3 m^3 including the anaerobic, anoxic and aerobic reactors while the MBR membrane tank volume was 1.5 m^3. The system was designed to isolate membrane filtration from the biological process and allow sludge wasting from the membrane tank as opposed to wasting from the aerobic reactor. The intake was screened through a 1.0 mm perforated drum screen (Cleantek Water Solutions, Sweden). Each reactor was designed as a completed mixed reactor using industrial mixers (Lightnin, USA). Rotary lobe pumps (Boerger LLC, Germany) recirculated sludge from the aerobic to the anoxic and from the anoxic to the anaerobic reactor and sludge pump (Mudsucker, USA) controlled the sludge retention time (SRT) by wasting from the MBR tank. Return activated sludge (RAS) from the MBR tank occurred by gravity overflow. Additional equipment required for membrane operation, air scouring, and aeration include self-priming centrifugal pumps for the feed (Pacer Pumps, USA) and filtrate (Iwaki America, USA) and rotary lobe blowers (Dresser Roots, USA) for aeration and air scouring.

The MBR system utilized a submerged, polyvinylidene fluoride (PVDF) hollow fiber microfiltration membrane of nominal pore size 0.1 μm. Two membrane elements were installed into the MBR tank, each with 25 m^2 surface area. Pilot design capacity varied between 19–26 m^3/d and was dependent on membrane flux operation between 18–24 LMH (L/m^2 h). General MBR operational set points and values were in accordance with the manufacturer's specifications for filtration, backwash, maintenance cleaning and clean-in-place (CIP) cleaning.

Process operation

The MBR pilot system was operated over 280 days at the Howard F. Curren advanced wastewater treatment plant (AWTP) in Florida, USA, with domestic wastewater over seasonal periods – summer and winter. The pilot system was installed near the influent end of the primary clarifier and was seeded with mixed liquor gathered from the AWTP aerobic and denitrification (anoxic) return activated sludge (RAS) lines. The concentration of the seeded sludge was 3 g/L. Wastewater was withdrawn at the influent of the clarifier and pumped to the pilot system through a coarse screen prior to the system drum screen.

The UCT process hydraulic retention time (HRT) was fixed at 7 h and the SRT was controlled at 20 days. Wasting also controlled the mixed liquor suspended solids (MLSS) below 10 g/L in the biological reactors and below 12 g/L in the MBR tank. Fixed blower operation maintained the dissolved oxygen (DO) concentration in the aerobic reactor at 2 mg/L. Membrane operation included four operational steps including filtration, backwash, chemical enhanced backwash (CEB) and CIP.

Maintenance cleaning was completed with sodium hypochlorite (NaOCl) and citric acid (if necessary). CEB cleaning was performed once a week using a filtration/backwash cycle counter or based on a trans-membrane pressure (TMP) trigger set point. MBR filtrate flow was controlled according to the variable frequency drive. This, in turn, fixed the HRT of the biological process. CIP cleaning was triggered based on elapsed time of operation (every 6 months) and based on the TMP observed. Table 1 describes the operating parameters of the UCT process and the MBR membrane during this study.

Analytical methods

The pilot system was monitored utilizing online sensors and through laboratory analyses conducted on weekly samples collected. Online sensors installed included pH, ORP (oxidation reduction potential), DO and turbidity (Hach, USA). The pH, ORP and DO sensors were installed at the beginning and end of each reactor to monitor the water quality. The DO sensor in the aerobic reactor was utilized to control the DO concentration in the aerobic tank by means of controlling the operational speed of the aeration blower. A portable multi-probe sensor (WTW, Germany) was used for system monitoring and for online sensor verifications especially for DO, pH and ORP.

Weekly sampling and analyses were conducted for evaluation of nutrient removal and membrane performance. Standard methods and Hach Test'N Tube Plus™ kits (HachTNTplus™) with the UV-visible spectrophotometer (Hach, USA) were used for analyses (APHA/AWWA/WEF 2012). These utilized USEPA methods including Methods 365.1 and 365.3 for P and Method 410.4 for chemical oxygen demand (COD) and soluble COD (sCOD). Ammonia utilized Method 350.1, 351.1 and 351.2. Nitrate, nitrite, and phosphate concentrations were confirmed using ion chromatography (Dionex, USA) based on the Standard Method SM4110B. Turbidity of the filtrate was also verified using the Standard Method SM2130B using the portable and online sensor (Hach, USA). Lastly, biochemical oxygen demand (BOD) was measured based on the AWWA Standard Method (SM 5210B). MLSS and mixed liquor volatile suspended solids (MLVSS) were also measured using AWWA Standard Methods (SM2540D and SM2540E respectively).

Table 1 | MBR membrane operating parameters for UCT

Parameter	Value/Set point
Filtrate flow rate	15–23 L/min (Q)
Filtrate flux	18–24 LMH
Air scouring flow rate	54–170 L/min
MBR tank feed flow rate	5Q (75–115 L/min)
RAS recirculation to aerobic and anaerobic tank	3Q-4Q (45–92 L/min)
Filtration:Backwash	9 min:1 min
CEB	Every 1,000 filtration cycles
CIP	Every 6 months or TMP > 28 kPa

RESULTS AND DISCUSSION

Biological performance

Evaluation of the pilot results indicated that the modified UCT-MBR process efficiently removed phosphorus beyond previous technological limitations. Complete nitrification was achieved in the system as indicated by the low concentration of ammonia in the effluent. Denitrification, however, was incomplete contributing to N effluent concentrations averaging above 4 mg/L as N. The minimum effluent N and P achieved was 1.23 and 0.001 mg/L, respectively. However, these were not achieved in conjunction with each other. Evaluation of the overall UCT process indicated efficient removal of COD, BOD, nitrogen, phosphorus and ammonia from the wastewater throughout the study and each are shown in Table 2 below.

The MLSS concentration was monitored during the study by means of sampling. Wasting was not conducted initially until the MLSS concentrations increased above 6 g/L in the aerobic reactor. This occurred approximately 30 days after start-up operation. Figure 2 shows the MLSS trend throughout the study. Solids concentration

Table 2 | Biological performance of UCT-MBR

	Unit	Influent		Effluent		Removal efficiency
		Total	Soluble	Total	Soluble	
COD	mg/L	513 ± 102	214 ±35	31 ± 14	–	93.9 ± 2.7
BOD	mg/L	173 ± 58	–	2 ±4	–	98.8 ± 2.4
Total nitrogen	mg/L as N	37 ± 7	30 ± 4	5 ± 3	5 ± 2	86.6 ± 5.7
Total phosphorus	mg/l as P	5.39 ± 1.12	2.53 ± 0.10	0.28 ± 0.32	0.29 ± 0.40	94.1 ± 8.3
Ammonia	mg/L as N	–	27 ± 4	–	0.17 ± 0.55	99.4 ± 2.0
Nitrate	mg/L as N	–	0.04 ± 0.05	–	3.5 ± 2.7	–

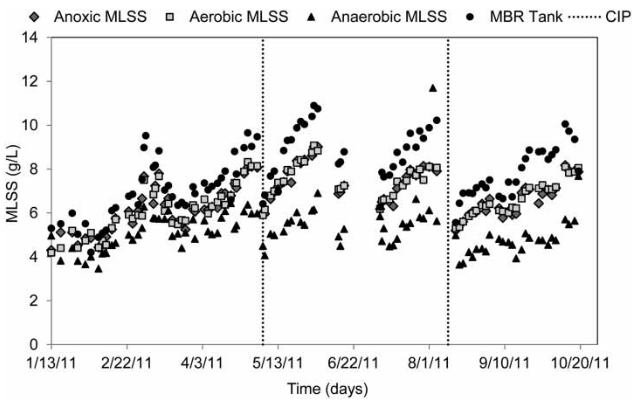

Figure 2 | MLSS Concentration for the UCT-MBR pilot.

continued to increase even after commencing wasting indicating rapid growth in the reactors. The variations observed were as a direct result of sludge loss during CIP cleaning. Additionally, operation of the UCT process with 4Q showed even distribution of sludge within the biological system. However, energy consumption lowered feasibility for future application. For this reason, just prior to the first CIP, the internal recirculation rates were lowered to 3Q.

The wastewater characteristics indicated stable COD and BOD concentrations incoming to the plant during summer and winter periods with a minor dilution in the summer. Importantly, COD concentrations were sufficient to support biological P release and uptake along with denitrification. The optimized DO control of the aeration in the aerobic reactor maintained oxygen transfer despite increase in MLSS concentrations allowing for complete nitrification and organic oxidation. The COD and BOD trend are shown in Figure 3.

As previously mentioned, high phosphorus removal was achieved during this study. Figure 4 demonstrates the phosphorus and nitrogen removal trend throughout the study and the effects of process operation on P removal including variations in wastewater characteristics. More so, the changes in internal sludge recirculation (RAS) did have some effect with some decrease in removal efficiency observed for both P and N removal especially after the second CIP clean. Towards the end of the pilot study, nitrogen removal was beginning to decline and become more unstable as further demonstrated by the effluent N and P concentrations in Figure 5. This interference was directly caused by the changing wastewater characteristics and lower internal recirculation rates (3Q). Furthermore, this demonstrated competition of phosphorus removing organisms (phosphorus

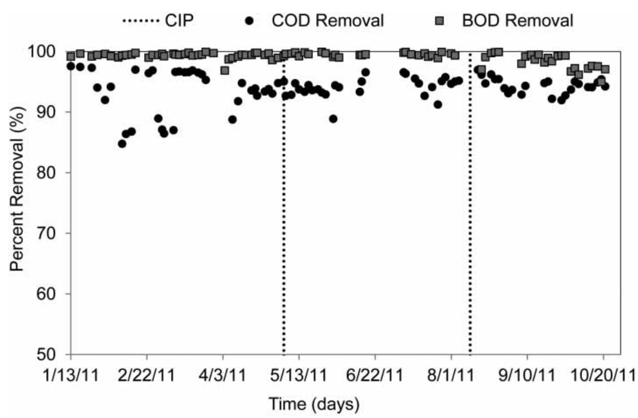

Figure 3 | COD and BOD removal efficiency in UCT process.

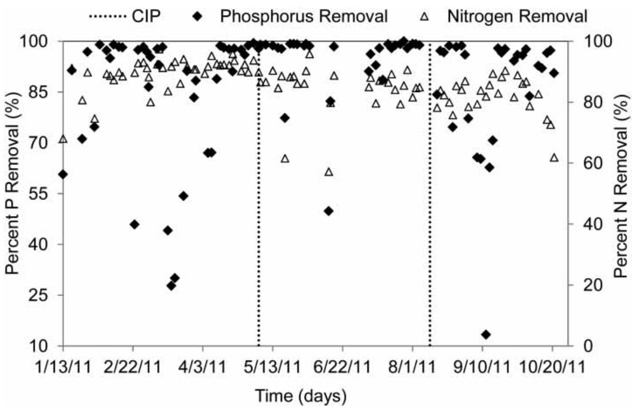

Figure 4 | Nutrient removal efficiency with UCT process.

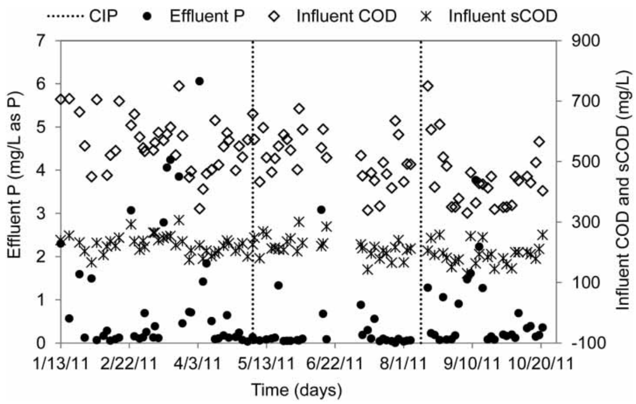

Figure 6 | Effluent phosphorus and influent sCOD concentrations in pilot system.

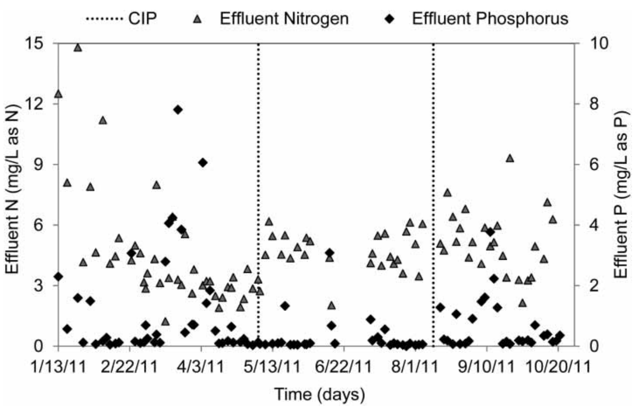

Figure 5 | Comparative evaluation of effluent phosphorus and nitrogen concentration.

accumulating organisms) with denitrification bacteria for available COD and is trended in Figure 6.

The average N removal did not satisfy the Florida regulation of 3 mg/L as N. Future improvements through increased RAS rates or by increasing the HRT in the anoxic reactor can improve N removal.

Membrane performance

Throughout pilot operation, membrane performance was stable and demonstrated effluent water quality with turbidity $\leq$0.01 NTU. Throughout the study, flux operation varied between 18 and 24 LMH in order to evaluate membrane performance and fouling trends. Membrane permeability was closely monitored through the observation and recording of membrane TMP given flux operation was fixed. Fouling was not rapid in this study and TMP values were stable for flux values 18–20 LMH. In addition to this, membrane air scouring was fixed at 170 L/min which contributed to the high DO concentrations observed in the MBR tank. Concentrations varied between 4 and 6 mg/L and were dependent on the MLSS concentration. Overall, membrane performance indicated a robust membrane which can recover after maintenance or CIP cleaning and can be seen in Figure 7.

Biological phosphorus removal

Given the results of the study, a general mass balance of phosphorus must be conducted in order to determine the mechanism of phosphorus removal and to confirm

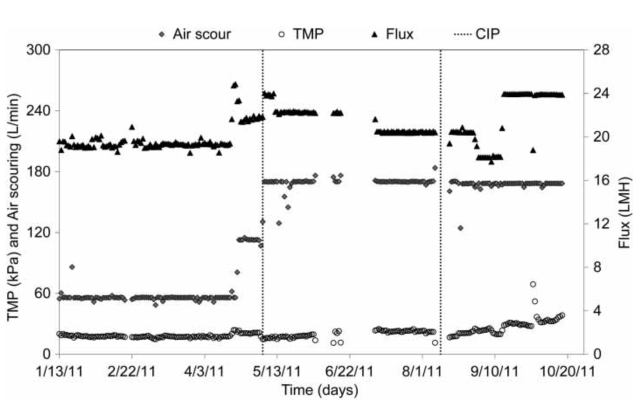

Figure 7 | Membrane performance trend with UCT process.

biological phosphorus removal by 'luxury uptake' (Jeyanayagam 2005). The phosphorus mass balance can be directly determined based on the complete analysis of the soluble P content within the biological process, as well as the P content within the biomass from the RAS and waste activated sludge (WAS) lines. The boundary layer for phosphorus mass balance was determined and is shown in Figure 8.

Samples analyzed during the study provide the phosphorus profile of the biological process and are listed in Table 3. Initial evaluation of the phosphorus profile within the biological reactors demonstrates suitable phosphorus release in the anaerobic reactor and significant uptake in the anoxic, aerobic and MBR reactors. Further evaluation of the profile demonstrates additional P uptake in the MBR tank from which sludge is wasted. P uptake in the aerobic reactor was suitable due to the fixed DO concentration at 2 mg/L. Membrane air scouring contributed to the additional P uptake as DO concentrations above 4 mg/L were maintained in the membrane tank. More so, this condition enhanced nitrification and ammonia removal as evident by the ammonium concentrations observed within the system and shown in Table 3. Hence, wasting to control SRT occurs from the reactor with the highest uptake of phosphorus. This aided in the efficient removal of phosphorus. The effluent concentrations observed also suggest some colloidal rejection of phosphorus further reducing the effluent phosphorus concentration or by additional phosphorus uptake at the surface of the membrane by the biofilm attached at the surface. This requires additional study and evaluation for confirmation.

Additionally shown in Table 3 are the nitrogen and sCOD profiles within each biological reactor. This also demonstrates the effect of nitrogen, particularly nitrate, on the phosphorus removal mechanism by biological uptake. The results demonstrate consistent low nitrate concentration in the anaerobic reactor. This directly contributed

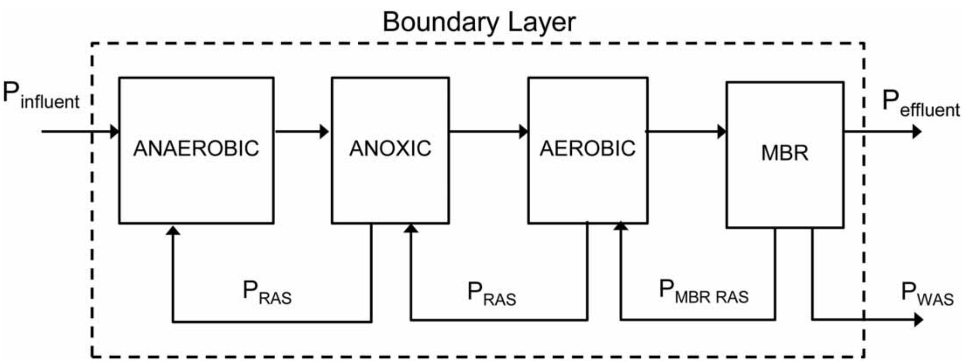

Figure 8 | Mass balance boundary layer for phosphorus.

Table 3 | Phosphorus and nitrogen concentrations in reactors

Sample	Soluble COD (mg/L)	Soluble phosphorus (mg/L as P)	Soluble total nitrogen (mg/L as N)	Soluble nitrate (mg/L as N)	Ammonium (mg/L as N)
Influent	214 ± 35	2.53 ± 0.10	30 ± 4	–	27 ± 4
Anaerobic	49 ± 13	9.42 ± 5.21	8 ± 3	0.74 ± 3	5 ± 3
Anoxic	47 ± 21	1.75 ± 0.94	4 ± 2	2 ± 3	0.57 ± 0.80
Aerobic	45 ± 13	1.02 ± 1.43	4 ± 2	3 ± 3	0.48 ± 0.89
MBR	46 ± 14	0.48 ± 1.07	4 ± 2	3 ± 3	0.13 ± 0.51
Effluent	31 ± 14	0.28 ± 0.32	5 ± 2	4 ± 3	0.17 ± 0.55

to the efficient phosphorus release observed in the anaerobic reactor and reduced competition.

CONCLUSIONS

The UCT-MBR pilot system was evaluated for improvement of the EBPR process as a solution to the upcoming stringent regulations for P content in secondary and tertiary discharge in Florida, USA. The EBPR was enhanced by sustaining optimal conditions favorable for the release and uptake of phosphorus. Important design factors and operating parameters were controlled and were observed to enhance biological performance whilst eliminating biological competition. Phosphorus concentrations in the effluent averaged at 0.3 mg/L as P under appropriate operating conditions. Nitrification was also further enhanced within the MBR system where nitrogen removal achieved average effluent concentrations of 5 mg/L as N.

The results of this study provided information relevant for parallel assessment of both the UCT process and MBR membrane performance. The process configuration maintained optimal DO and recirculation rate conditions supporting phosphorus luxury uptake and biological nitrogen removal. These key operating parameters enhanced EBPR without the use of coagulants or precipitation mechanisms. Therefore, enhanced biological phosphorus removal with MBR process application is feasible and is dependent on the appropriate biological process utilized and importantly, the operating conditions of the biological process.

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