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Research article

Achieving advanced nitrogen removal for small flow wastewater using a baffled bioreactor (BBR) with intermittent aeration

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ABSTRACT

Nitrogen discharge from decentralized and onsite wastewater treatment systems, such as recirculating sand filters, stabilization ponds, and septic tanks, is an important source of groundwater and surface water contamination. This study demonstrated a simple baffled bioreactor (BBR) technology, operated with an intermittent aeration mode, that effectively removed nearly all nitrogen for small flow wastewater treatment. The BBR is characterized by an aeration zone, followed by an integrated internal settler, which automatically retains a high biomass concentration of approximately 6 g/L without using a separate sludge return device. Long-term testing results indicated that this process had reduced the chemical oxygen demand and total nitrogen concentration to approximately 20 mg/L and less than 3 mg-N/L, respectively, under an operational temperature of 7.1 °C to 24.7 °C. The average effluent ammonia and nitrate concentrations were 0.75 and 0.61 mg-N/L, respectively, indicating that both nitrification and denitrification had been completed. In addition to nitrogen removal, this BBR had removed approximately 65% of the total phosphorus.

1. Introduction

Eutrophication has been one of the major environmental challenges in recent years (Powley et al., 2016). Nitrogen from treated or untreated domestic wastewater is one of the primary contributors to the eutrophication of many important water bodies, such as the Gulf of Mexico and Chesapeake Bay in the United States, the Mediterranean Sea in Europe, and Dianchi Lake in China (Oleszkiewicz and Barnard, 2006; Conley et al., 2009; Le et al., 2010; Powley et al., 2016). As a result, regulations to limit the discharge of total nitrogen (TN) from centralized wastewater facilities are becoming more and more stringent (Oleszkiewicz and Barnard, 2006). In addition to centralized wastewater treatment systems, many households in the U.S., Europe, and Australia are relying on septic tank systems for their wastewater treatment (Withers et al., 2014). In the coastal areas of North Carolina (NC), U.S., the percentage of households that use septic tanks could be 60% (Pradhan et al., 2007; Humphrey et al., 2012; Katie et al., 2014). In China, nearly 50% of the population live in rural aeras, with less than 10% of domestic wastewater being properly treated (Zhao, 2014). Traditionally, the toilet and kitchen wastewater and waste are used as fertilizer in the rural aeras of China. However, with the rapid growth of the population and the economy, and improved sanitation systems, the generation of domestic wastewater in the rural areas of China has been increasing significantly. This untreated domestic wastewater has posed signifcant adverse effects on adjacent watersheds, especially in the regions near large cities.

In Europe and the U.S., nutrient removal is not required for most decentralized or onsite small flow wastewater treatment systems (Withers et al., 2014). However, recent findings suggest that nitrogen-rich effluent from decentralized and onsite wastewater systems is an important nutrient source for the groundwater and surface water (US EPA 2002; McCray et al., 2005; Iverson et al., 2015). A recent survey conducted by the State Onsite Regulators Alliance (SORA) indicated that regulations for TN discharges were in place in about one half of the U.S. states, while 10 states also regulated total phosphorus (TP) discharges (SORA, 2012). In Hawaii,

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Coastal Zone Act Reauthorization Amendments (CZARA, Section 6217) required that at least 50% of the nitrogen must be removed from onsite wastewater treatment systems located near impaired water bodies (Babcock et al., 2015). However, approximately 38% of Hawaii's households were using onsite systems (such as septic tanks) that could not meet this requirement (Babcock et al., 2015). More states are concerned about nitrogen, rather than phosphorus, probably because the nitrogen species in the effluent of onsite wastewater systems are more mobile than the phosphorus species (Robertson et al., 1998). Ammonia could also pose signifcant toxicity to aquatic life, e.g., mussels (US EPA, 2013). Moreover, nitrate is associated with a number of adverse health problems, e.g., methemoglobinemia (Wang et al., 2013). In China, no separate discharge standards were established for onsite wastewater treatment systems in the guidelines recently published by the China Ministry of Environmental Protection (MEP) and the China Ministry of Housing and Urban-Rural Development (China MEP, 2013; China MHURD, 2010). However, the national discharge standard for centralized plants was recommended for decentralized systems when the effluent is directly discharged into surface water (China MEP, 2013; China MHURD, 2010). According to the national standard for centralized treatment plants, the most rigorous discharge limits for TN and TP are set at 10 mg/L and 0.3 mg/L, respectively (China MEP, 2015).

Septic tanks, lagoons, constructed wetlands, and recirculating sand filters have been used for single household and small community wastewater treatment for many decades in the U.S and in some countries in Europe (Kroeker and Hildebrand, 2007; Withers et al., 2014; Iverson et al., 2015; Gunady et al., 2015). These treatment systems are currently facing numerous problems, such as odor generation, difficulty in upgrading, operation failure and, most importantly, violation of possible new effluent nutrient limits needed to control eutrophication (Bahgat et al., 1999; Withers et al., 2014; Gunady et al., 2015). As a result, it is becoming prevalent that many small communities are currently looking to upgrade their wastewater treatment facilities to achieve better TN removal (Gunady et al., 2015).

The existing advanced biological treatment processes (such as the anaerobic-anoxic-oxic (A^2O), the University of Cape Town (UCT), and Bardenpho processes) can remove nutrients effectively (Metcalf and Eddy, 2003). However, these processes are complex to operate and, therefore, are not suitable for small flow applications. We recently introduced a novel baffled bioreactor (BBR) for small flow wastewater treatment (Liu et al., 2012). The BBR uses baffles to create an internal settler to retain the biomass within the reactor. The sludge is settled in the internal settler and then returned back to the aerobic zone by the flow current that results from aeration. Therefore, the BBR achieves maintenance-free sludge return. The BBR can effectively remove BOD_5, SS, and ammonia to less than 10, 10, and 1 mg/L, respectively. However, since the tested BBR only removes about 30% of TN in the summer and about 15% in the winter (Liu et al., 2012), it does not meet the enhanced nitrogen removal requirement. The objective of this research was to demonstrate a simple BBR process, with only one reaction zone, to significantly improve TN removal.

2. Methods and materials

2.1. Process description

A scheme of tested reactors is shown in Fig. 1. Compared with the previously tested BBR, the BBR unit for this research has eliminated the pre-anoxic zone, and only contains one reaction zone which was aerated in a cycling on and off pattern (i.e., intermittent aeration). To differentiate it from the previously tested BBR, we named it “intermittent baffled bioreactor” (iBBR). As shown in Fig. 1, this process contains one reaction zone (i.e., intermittent aeration zone), one internal settler, and one optional final clarifier. The aeration device in the process is operated in a cyclic on/off pattern. When the aeration is on, the intermittent aeration zone is under an aerobic condition to complete nitrification. When the aeration device is turned off, a mixing device is turned on to mix the content in the reactor, and the intermittent aeration zone turns into an anoxic condition to denitrify the nitrate accumulated during the aeration-on period. During the aeration-off period, the effluent ammonia and BOD concentrations will increase. However, this increase is not significant due to dilution.

The internal settler was used for solids-liquid separation. In the internal settler, the solids were settled to the bottom and returned back to the reaction zone by a cyclic stream created by aeration. Therefore, no sludge return pump was needed, and a high biomass concentration could also be maintained in the reaction zone due to a high sludge return ratio (Liu et al., 2012). A final polishing clarifier can be used to further remove the suspended solids from the effluent of the internal settler. Any solids settled within the final clarifier are periodically returned back to the reaction zone. When the sludge accumulates in the reaction zone, it can be periodically wasted or hauled away. A separate sludge storage tank is not needed.

2.2. Experimental setup

Two iBBRs were set up and tested using raw municipal wastewater after screening. The iBBR-I, with a total volume of 26.5 m^3 (7000 gallons), was designed for a small community with 20 homes or less in the U.S. The iBBR-II had an effective volume of 7.6 m^3 (2000 gallons), and was designed for a cluster of five homes or less. Although the volumes of the two reactors were different, their design was similar.

For both reactors, a timer was used to control the cyclic aeration and mixing. For iBBR-I, the aeration was controlled by a DO controller (IQ SensorNet 2020 XT, YSI), with a DO probe located in the intermittent aeration zone. During the aeration-on period, when the DO was greater than 2.5 mg/L, the main blower was turned off, while a much smaller maintenance blower was turned on. If the DO was lower than 0.5 mg/L, the main blower was turned on while the maintenance blower was turned off. The actual DO concentration in the intermittent aeration zone ranged from 0.2 to 3.0 mg/L during the aeration-on period. During the aeration-off period, a mixing device was turned on to provide necessary mixing within the intermittent aeration zone.

For very small flow wastewater treatment, it is not economical to use a DO controller to control aeration during the aeration-on period, because the DO controller with a probe costs approximately $5000 and the probe has to be maintained regularly to ensure proper function. Without a DO controller, the reactor

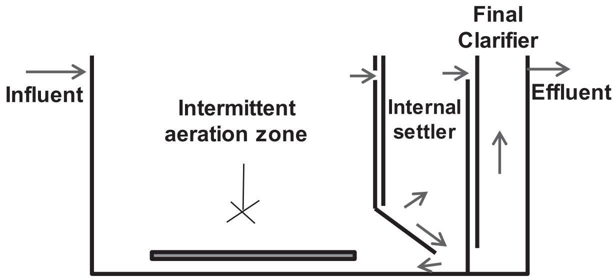

Fig. 1. Schematic of the pilot-scale intermittent baffled bioreactor (iBBR).

performance for nitrification and denitrification could be significantly impacted. Therefore, this scenario was also tested using the iBBR-II, with a constant aeration provided during the aeration-on period. Due to variations in the strength and temperature of influent, the DO concentration during the aeration-on period varied from 0.2 – 7 mg/L.

Screened raw wastewater was used to feed both reactors. As shown in Table 1, both processes were tested under high and low temperatures. The total hydraulic retention time (HRT) and solids retention time (SRT) for both reactors were approximately 24 h and 40 days, respectively. During the performance test, the mixed liquor suspended solids (MLSS) concentration in the intermittent aeration zone, the influent and effluent chemical oxygen demand (COD) and TN, and the effluent ammonia and nitrate were monitored one to three times a week. The influent and effluent TP and the effluent nitrite were checked occasionally. Composite samples were used for the influent quality analysis, while grab samples were used for MLSS and effluent quality analysis. The analysis methods were described previously (Liu et al., 2012; Liu and Wang, 2012).

3. Results and discussion

3.1. MLSS concentration

The MLSS concentrations in both reactors are shown in Fig. 2. As depicted in Fig. 2(a), the MLSS concentration in the iBBR-I ranged from 4.3 to 7.0 g/L, with average values of 5.87 and 5.90 g/L for Phases I and II, respectively. Fig. 2(b) indicates that the iBBR-II had the MLSS concentration stabilized at approximately 6 g/L after 90 days. The MLSS concentrations in both systems were significantly greater than those in conventional activated sludge processes, which were approximately 3 g/L. Increasing the MLSS concentration reduces the size of the reactor and, therefore, reduces the construction cost. It is also critical for stable operation of the reactor.

For the iBBR, the sludge in the reactor was mainly retained through the internal settler, while the final clarifier was used to polish the effluent from the internal settler to further remove SS. Due to the unique design, the aeration in the intermittent aeration zone had created a cyclic stream between the intermittent aeration zone and the internal settler. The solids that had settled in the internal settler were returned back to the reaction tank with a high return flow when the aeration was on. Due to the high return flow, the MLSS concentrations in the settling zone were similar to that in the intermittent aeration zone. Therefore, an internal settler could maintain the reaction zone with a much higher MLSS concentration than the conventional secondary clarifier could. The unique design of the internal settler in the small flow systems had improved the reactor performance without a sludge return pump and reduced the need for associated maintenance and energy use.

During the aeration-off period, sludge would accumulate in the bottom of the internal settler. However, the aeration-off period usually lasted for 1 to 2 h, and the accumulated sludge in the internal settler could be returned back to the reaction zone as soon as aeration started. During the experiment, no significant sludge accumulation was observed.

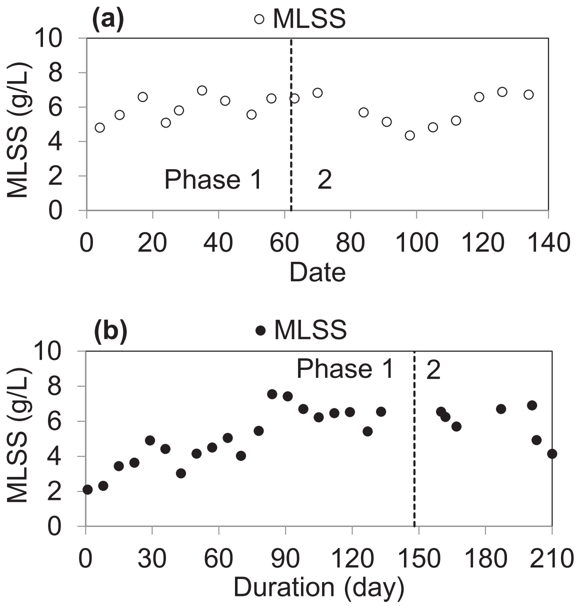

Fig. 2. MLSS concentrations in the (a) iBBR-I (with DO control) and (b) iBBR-II (without DO control).

3.2. COD removal

The influent and effluent COD concentrations are shown in Fig. 3, with averaged values in Table 2. As depicted in Table 2, the iBBR-I had average influent COD concentrations during Phases I and II of 288 and 341 mg/L, respectively. The volumetric COD loadings were 0.27 and 0.38 kg-COD/m^3·d for Phases I and II, respectively. Since the average BOD_5/COD ratio was 0.28 for this influent, determined based on a previous study (Liu et al., 2012), the volumetric BOD_5 loading was 0.08 and 0.11 kg-BOD_5/m^3·d. For the iBBR-II (Fig. 3(b)), the average influent COD concentrations during Phases I and II were 371 and 407 mg/L, respectively (Table 2), with an estimated BOD_5 loading of 0.11 and 0.12 kg-BOD_5/m^3·d.

Fig. 3 shows that the effluent COD concentrations in both systems were consistently low. For the iBBR-I, the average effluent COD concentrations during Phases I and II were 13 and 23 mg/L, respectively, indicating that more than 93% of the COD had been removed. For the iBBR-II, the average effluent COD concentrations during Phases I and II were 14 and 10 mg/L, respectively, indicating that more than 95% of the COD had been removed. Low effluent COD suggested that intermittent aeration did not impact COD removal, even under low temperature conditions. The effluent SS concentration was not analyzed in this study. Because the SS in the effluent of a municipal wastewater treatment plant was mainly composed of organic matter, the very low effluent COD also indicated a low effluent SS.

3.3. Nitrogen removal

Fig. 4 shows the influent and effluent TN concentrations for both

Table 1
Operational conditions for iBBR-I (with DO control) and iBBR-II (without DO control).

Reactor		Duration (day)	Temperature (°C)	Flow (m^3/d)	Total HRT (h)	SRT (day)	Aeration on vs. off
iBBR-I	Phase I	1–46	7.1–12.1 °C	23–28	~24 h	~40	2 h vs 2 h
	Phase II	47–134	15.3–24.7 °C				1.5 h vs 1.5 h
iBBR-II	Phase I	1–148	15.7–24.0 °C	7	22 h	~40	1 h vs 2 h
	Phase II	149–210	6.1–10.1 °C				1.5 vs 3 h

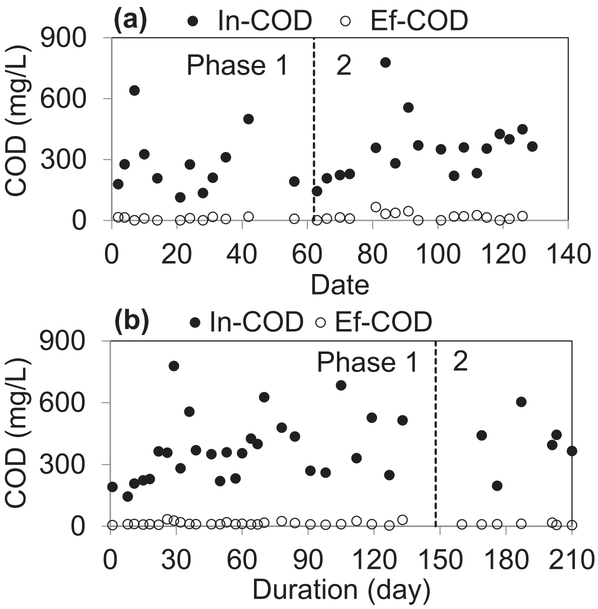

Fig. 3. Influent and effluent COD concentrations for the (a) iBBR-I (with DO control) and (b) iBBR-II (without DO control).

Table 2
Summary of the reactor performance.

Reactor		COD (mg/L)			TN (mg-N/L)			Ef-NH$_3$(mg-N/L)	Ef-NO$_3^-$ (mg-N/L)	TP (mg-P/L)		
		In.	Ef.	Re.	In.	Ef.	Re.			In.	Ef.	Re.
iBBR-I	Phase I	288 ± 158	13 ± 4	96%	18.1 ± 6.3	3.5 ± 1.2	81%	1.0 ± 0.9	0.7 ± 0.4	3.0 ± 2.1	1.0 ± 1.1	67%
	Phase II	341 ± 149	23 ± 17	93%	20.9 ± 8.6	2.7 ± 1.0	87%	0.6 ± 0.4	0.6 ± 0.5	3.2 ± 1.5	1.2 ± 0.6	63%
	Overall	332 ± 146	21 ± 14	94%	20.7 ± 7.9	2.9 ± 2.1	86%	0.6 ± 0.4	0.6 ± 0.5	3.2 ± 1.7	1.1 ± 0.8	65%
iBBR-II	Phase I	371 ± 157	14 ± 8	96%	23.1 ± 8.2	4.3 ± 3.5	81%	1.1 ± 1.7	1.7 ± 2.2	3.4 ± 1.5	1.3 ± 1.0	61%
	Phase II	407 ± 132	10 ± 4	98%	27.2 ± 12.0	10.9 ± 3.9	60%	2.2 ± 2.5	6.7 ± 4.5	NA	NA	NA
	Overall	378 ± 152	13 ± 7	97%	23.7 ± 8.7	5.3 ± 4.3	78%	1.4 ± 2.0	3.1 ± 3.7	3.4 ± 1.5	1.3 ± 1.0	61%

iBBRs. During the performance test of the iBBR-I, the influent TN ranged from 6.2 to 37.1 mg-N/L, with an average concentration of 20.7 mg-N/L. For the influent used in this study, approximately 70% of TN was ammonia and 30% was organic nitrogen. Most of the organic nitrogen in the influent was converted to ammonia during the treatment. As shown in Table 2, the effluent TN ranged from 1.3 to 5.6 mg-N/L, with average values of 3.5 and 2.7 mg-N/L for Phases I and II, respectively. Its removal efficiency was 81% and 87% for Phases I and II, respectively. As illustrated in Fig. 5(a), the effluent ammonia ranged from 0.01 to 2.7 mg-N/L, with average values of 1.0 and 0.6 mg/L for Phases I and II, respectively. This indicated that complete nitrification was achieved in the iBBR-I, even with a low temperature of approximately 10 °C. This also suggested that the intermittent aeration had not posed a significant impact on ammonia removal. Effluent nitrate concentration ranged from 0.04 to 1.9 mg-N/L, with average values of 0.7 and 0.6 mg-N/L for Phases I and II, respectively. This demonstrated that denitrification was also completed in the iBBR-I, even with low temperatures of 7.1 °C to 12.1 °C. The effluent nitrite was checked occasionally, and its concentration was always found to be less than 0.5 mg-N/L (data not shown). The sum of the average effluent ammonia + nitrate was less than 2 mg-N/L, indicating that approximately 1 mg-N/L of effluent TN was organic nitrogen associated with the effluent SS.

DO control was not implemented for the iBBR-II. As depicted in Fig. 4(b), the influent TN ranged from 8.6 to 40.4 mg-N/L, with an average concentration of 23.7 mg-N/L during the entire experimental period (Table 2). In Phase I, with an operational temperature that was greater than 15 °C, the effluent TN concentration ranged from 1.6 to 18.2 mg-N/L. However, its average concentration was still low, 4.3 mg-N/L, indicating that 81% of TN had been removed. In Phase II, with an average operational temperature of 8.5 °C, the average effluent TN concentration was 10.9 mg-N/L, and the removal efficiency was 60%. This showed that low temperature significantly decreased TN removal efficiency in the iBBR-II when the DO was not controlled. As illustrated in Fig. 5(b), the effluent ammonia ranged from 0.02 to 7.5 mg-N/L, with average values of 1.1 and 2.2 mg-N/L for Phases I and II (Table 2), respectively. The effluent nitrate concentration in Phases I and II ranged from 0.01 – 11.1 and 0.6–14.7 mg-N/L, respectively, with averages of 1.7 and 6.7 mg-N/L. The significantly higher effluent nitrate concentration in Phase II indicated that, with low temperatures, denitrification could be significantly impacted if the DO was not controlled.

The absence of DO control did not impact COD removal in the iBBR-II. However, the implementation of DO control improved and stabilized nitrification and denitrification performances, especially under low temperature conditions. Without using DO control, the selection of blower capacity became a challenge. If the blower was selected based on average loading, the aeration would not be sufficient to accommodate peak loadings. However, it could be over aerated most of the time if the blower was selected based on peak loading, especially during winter. When it was over aerated, the

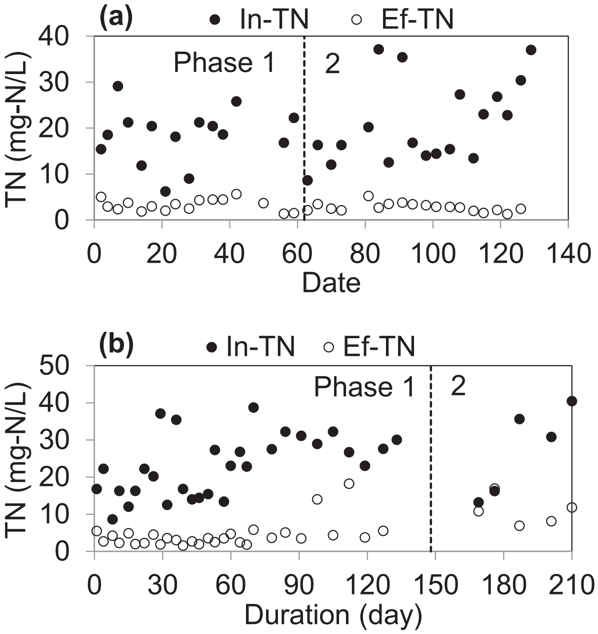

Fig. 4. Influent and effluent TN concentrations for the (a) iBBR-I (with DO control) and (b) iBBR-II (without DO control).

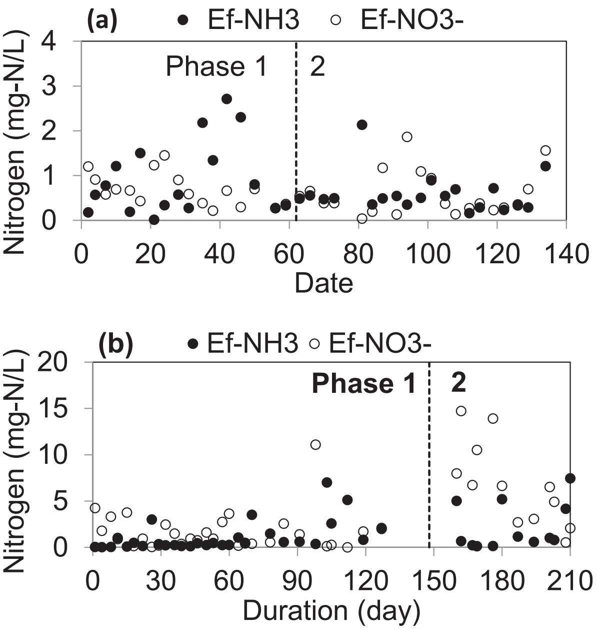

Fig. 5. Effluent ammonia and nitrate concentrations for the (a) iBBR-I (with DO control) and (b) iBBR-II (without DO control).

high residue DO concentration would adversely impact denitrification during the aeration-off period, especially with low temperature conditions. In our test of the iBBR-II, a relatively large blower was used and, as a result, the effluent ammonia and nitrate fluctuated significantly. In addition to stabilizing treatment performance, the implementation of DO control could also save energy. However, it would not be economical to use a DO control for a small flow system because DO probe cleaning (the major maintenance requirement) should be done every 3 to 6 months by professionals. On the other hand, DO control is recommended for large community wastewater treatment plants when regular operators are available.

3.4. Phosphorus removal

The iBBR was not designed for phosphorus removal. However, the removal of TP was monitored and the results are presented in Fig. 6. For the iBBR-I, the average influent TP concentrations during Phases I and II were 3.0 and 3.2 mg-P/L (Table 2), respectively. The effluent TP concentrations were 1.0 and 1.2 mg-P/L, respectively. This indicated that about 65% of the TP had been removed. A similar effluent TP concentration and removal efficiency were obtained using the iBBR-II without DO control. The fairly good phosphorous removal performance could be due to low effluent nitrate. As previously shown, the effluent nitrate concentrations were usually less than 1 and 2 mg/L in the iBBR-I and the iBBR-II (Phase I), respectively. The low concentrations of nitrate within the intermittent aeration zone could be quickly depleted during the aeration-off period, causing the intermittent aeration zone to be under an anaerobic condition before aeration started. This cycling of aerobic-anoxic-anaerobic conditions promotes the growth of phosphorus accumulating organisms and, therefore, enhances phosphorus removal.

4. Discussion

For the iBBR-I with DO control, the average effluent ammonia, nitrate, and TN concentrations during the test were 0.75, 0.61, and 2.9 mg-N/L, respectively. These low nitrogen concentrations in the unfiltered effluent represent the lowest values that a biological treatment process can achieve if no chemicals (such as an external carbon source) are used. The cycling of the aeration on and off operations exposed the activated sludge to aerobic and anoxic conditions, thereby promoting the accumulation of both nitrifiers and denitrifiers. When the aeration device was turned on, the intermittent aeration zone became aerobic. The accumulated ammonia during the aeration-off period was oxidized into nitrate. When the aeration was turned off, the condition gradually became anoxic (after depleting the residual DO), and the nitrate was reduced to nitrogen gas. The accumulation of ammonia during the aeration-off period, and the accumulation of nitrate during the aeration-on period were not significant due to dilution. In the Modified Ludzack-Ettinger (MLE) process, mixed liquor was returned to the preanoxic zone, and only fractions of the nitrate contained in the return mixed liquor and in the return secondary sludge were removed. The rest of the nitrate was still carried out of the reactor in the effluent. Therefore, the denitrification could not be comprehensive. For the post-anoxic process, however, an external carbon source was usually needed to improve denitrification.

Septic systems, stabilization ponds, and constructed wetlands are commonly used onsite wastewater treatment technologies in North America and in some European countries. Most septic systems have two basic components, a septic tank and a leach field. Only a very limited amount of COD can be removed by a septic tank; the effluent in the septic tank is then discharged into the vadose zone where better removal efficiency of the COD is achieved. De and Toor (2016) found that, in the leach field, approximately 33% of N was leached, 23% was accumulated in the soil, 6% was taken up by grass, and 38% of the nitrogen was denitrified. Clogging was a major issue for the leach field, which could reduce the aerobic layer in soil and significantly decrease nitrogen removal efficiency (Withers et al., 2014). In a hot climate, the lagoon system could remove BOD_5 and ammonia by 68–91% and 10–50%, respectively, with an effluent BOD_5 of 20–80 mg/L (Mburu et al., 2013). In a cold climate (such as in Canada), however, the effluent of BOD_5 from stabilization ponds was generally higher than 100 mg/L, while

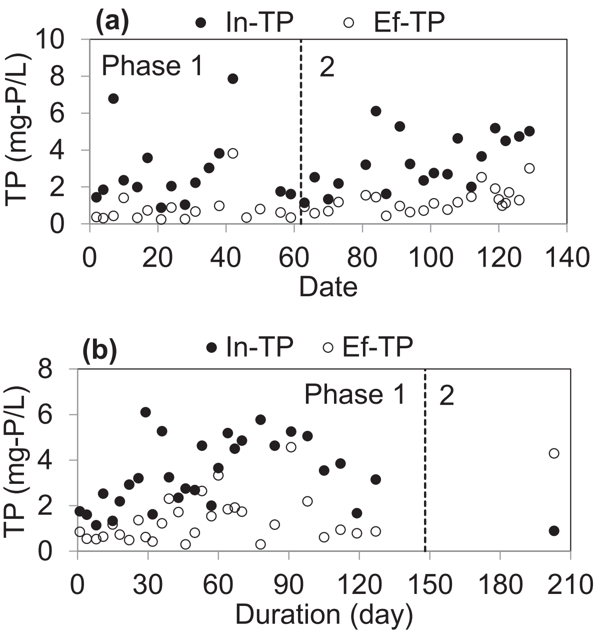

Fig. 6. Influent and effluent TP concentrations for the (a) iBBR-I (with DO control) and (b) iBBR-II (without DO control).

almost no ammonia was removed (Ragush et al., 2015). A survey indicated that, with an operational HRT of 1.2–10 days, wetlands with a free water surface removed 45%, 65%, 66%, 61%, 43%, and 49% of COD, BOD_5, TSS, ammonia, TN, and TP, respectively (Zhang et al., 2014). For subsurface flow wetlands, the average removal efficiency for COD, BOD, TSS, ammonia, TN, and TP were 66%, 75%, 80%, 53%, 52% and 66%, respectively (Zhang et al., 2014). Generally, a constructed wetland and a lagoon have similar performance in removing BOD and ammonia (Zhang et al., 2014).

Those natural treatment systems are very simple to design and operate. However, they have had poor treatment performances, which has posed a threat to groundwater and surface water quality (U.S. EPA, 2002; McCray et al., 2005; Iverson et al., 2015). Currently, these systems encounter numerous problems, such as odor, limited upgrade potential, and failure to meet stricter discharge regulations (Bahgat et al., 1999; Withers et al., 2014; Gunady et al., 2015). Accordingly, aerobic treatment systems are becoming more prevalent. However, various operational and maintenance needs pose major barriers in the application of aerobic treatment systems for small flows. The iBBR, a simplified aerobic system, could reduce COD, ammonia nitrogen, and TN to approximately 20, 1, and 3 mg/L in one single tank, and meet the most rigorous discharge limits, even under low temperature conditions. Its TN removal efficiency with appropriate DO control was greater than that in conventional systems (such as the MLE process and the A^2O process), which generally remove 70% of TN with an effluent TN of higher than 8 mg-N/L (Vaiopoulou and Aivasidis, 2008; Lee et al., 2009; Wang et al., 2012). Without a DO control, there was no impact on COD removal and the effluent ammonia was approximately 1.0 and 2.0 mg-N/L in warm and cold temperatures, respectively. Though the TN removal had been impacted by the absence of DO control, it could still reduce the effluent TN to approximately 5 and 10 mg-N/L in warm and cold temperatures, respectively. The unique design of the internal settler could automatically maintain a high biomass concentration without using a sludge return pump. In addition to improved nutrient removal, these features have also simultaneously reduced at least 30% of both the construction cost and the maintenance needs, as compared to other packaged wastewater treatment technologies.

5. Conclusions

A simplified aerobic iBBR treatment system, characterized by an internal settler and intermittent aeration, was designed to achieve advanced nitrogen removal for small flow wastewater treatment. During a long-term performance test, a high MLSS concentration of approximately 6 g/L was automatically maintained in the reactor. A very low effluent COD of approximately 20 mg/L, or less, was achieved by the iBBR in both low and high temperatures. Although the intermittent aeration significantly enhanced denitrification, it did not have a significant impact on ammonia removal. The average effluent ammonia and nitrate concentrations in the iBBR with DO control were about 0.71 and 0.61 mg-N/L, respectively, with the effluent TN being as low as 3 mg-N/L. Therefore, both nitrification and denitrification were completed, even under a winter low operational temperature of 8 °C. The smaller iBBR unit (that does not have a DO control) could also extensively remove COD and ammonia, as well as 60–81% of TN during the experimental period.

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