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Multiple aerobic and anaerobic baffled constructed wetlands for simultaneous nitrogen and organic compounds removal

Harvinder Kaur Lehl[a], Soon-An Ong[a,*], Li-Ngee Ho[b], Yee-Shian Wong[a], Farah Naemah Mohd Saad[a], Yoong-Ling Oon[a], Yoong-Sin Oon[a], Chin-Yii Yong[a], Wei-Eng Thung[a]

[a]*Water Research Group (WAREG), School of Environmental Engineering, Universiti Malaysia Perlis, Arau, Perlis 02600, Malaysia, Tel./Fax: +04 9798986; email: ongsoonan@yahoo.com (S.-A. Ong)*
[b]*School of Materials Engineering, Universiti Malaysia Perlis, Arau, Perlis 02600, Malaysia*

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ABSTRACT

The objective of this study is to determine the reduction efficiency of chemical oxygen demand (COD) as well as the removal of NH_4^+-N and NO_3^--N by the Aerobic–anaerobic Baffled Constructed Wetland Reactor (ABCW). The ABCW reactor was planted with common reed (*Phragmite australis*), where the hydraulic retention times was set to 1 d and was fed with synthetic wastewater. Supplementary aeration was supplied in designated compartments of the ABCW reactor to control the aerobic and anaerobic zones. The COD reduction efficiency was 98%, while the NO_3^--N and NH_4^+-N removal was 36–98%, respectively, which was due to nitrification and denitrification processes. The outstanding performance of the baffled unit was due to the longer pathway as there is the up-flow and down-flow condition sequentially, thus allowing more contact of the wastewater with the rhizomes and micro-aerobic zones.

Keywords: Aerobic–anaerobic baffled constructed wetland; Sodium benzoate; Artificial wastewater; Nutrients

1. Introduction

Constructed wetlands are wastewater treatment systems composed of treatment cells in a built and partially controlled environment, which is designed to provide wastewater treatment [1]. The system may deal with a variety of pollutant loads with high concentration and flow rate and is based on physical, chemical and biological processes [2,3]. Over the years, constructed wetlands have been used in many countries to treat landfill leachate, municipal wastewater, agricultural, aquaculture and industrial wastewater [4,5]. Constructed wetlands are low cost, simple to operate and construct locally as compared to the conventional wastewater technologies [6]. Besides that, constructed wetlands are not only able to meet secondary treatment standards, but are also able to achieve high levels of total nitrogen removal through

*Corresponding author.

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carefully engineered wetlands [7]. These factors contribute to the widespread implementation of constructed wetlands [8].

There are various types of constructed wetlands used to treat wastewater. Free water surface (FWS) and subsurface flow (SF) are the common types of constructed wetlands. SF can be further categorised; depending on the flow direction into vertical flow and horizontal flow. However, these types of constructed wetland by themselves are unable to remove nitrogen efficiently due to the inability of these systems to provide both aerobic and anerobic conditions simultaneously. However, the use of hybrid systems (HS), which incorporate both FWS and SF in their systems is able to achieve a higher nitrogen removal [9–12]. There are many countries where hybrid constructed wetlands are in operation to treat a variety of wastewaters [4]. However, the hybrid constructed wetland requires a relatively large area and recycling system to be treated under oxidation and reduction conditions repeatedly [13].

Aerobic conditions in treatment wetlands are important for the removal of wastewater constituents, such as chemical oxygen demand (COD) and ammonium–nitrogen [14]. In SF constructed wetlands, the oxygen demand exerted by the influent exceeds the amount of existing oxygen within the system. Consequently, oxygen transfer within the SF treatment wetland is one of the significant factors in rate limiting processes. Hence, in this study aeration was provided in the Aerobic–anaerobic Baffled Constructed Wetland (ABCW) reactors to overcome the oxygen demand exerted by the influent which exceeds the amount of existing oxygen within the system [15].

Another study related to the operation of the ABCW reactor is by Tee et al. where the performance of baffled and conventional horizontal subsurface flow (HSF) constructed wetland in the removal of nitrogen at 2, 3 and 5 d hydraulic retention times (HRT) were studied. Based on this study, it was established that the baffled units achieved a relatively higher removal percentage of ammonia and nitrogen compared to the conventional units [13]. Besides that, Tee et al. researched regarding the usage of this constructed wetland units in the enhancement of azo dye, Acid Orange 7 removal [16]. The design of the baffled HSF in the published work of Tee et al. was related to the operation of ABCW used in this research; however, the parameters of the study varied in terms of supplementary aeration, number of compartments, wetland media and the type of emergent plant used [13].

The design of the reactor in this study aims to eliminate oxidised nitrogen produced via nitrification at the top region by denitrification process at the bottom region within the same constructed wetland, which eradicates the need of large land area. This study evaluates the performance of the ABCW reactor in terms of removing organic compounds and nutrients in synthetic wastewater with the use of supplementary aeration, *Phragmites australis* as emergent plant, gravel as wetland media and 1 d HRT. The ABCW reactor provided multiple aerobic, anaerobic and anoxic conditions for wastewater treatment enhancement. These conditions were achieved by adding vertical baffles along the width of the reactor to provide the upward and downward flow and also by providing supplementary aeration to control the respective zones.

2. Materials and methods

2.1. Reactor set up

The ABCW reactor as shown in Fig. 1 was fabricated using acrylic plates. The design of the ABCW reactor comprised of five planted compartments dimensioned 30 cm × 80 cm × 30 cm with the use of 1 cm thick acrylic plates. This reactor was placed outdoor sheltered by veranda at an average temperature of 28 ± 4˚C. The general climate is equatorial; being hot and humid throughout the year. The reactor was planted with *Phragmite australis*, also known as common reed, which was obtained from Tasik Melati, Perlis. The average plant height when newly transplanted into the reactor was 96 cm. Plant density in terms of number of plants per square cm^2 is about 3–4 stems per 450 cm^2 where 450 cm^2 is the area of each compartment in the ABCW reactor. The plants were planted at the middle section of the ABCW just above the supplementary aeration. Supplementary aeration was provided in compartments 1, 3 and 5, respectively, to control the aerobic and anaerobic

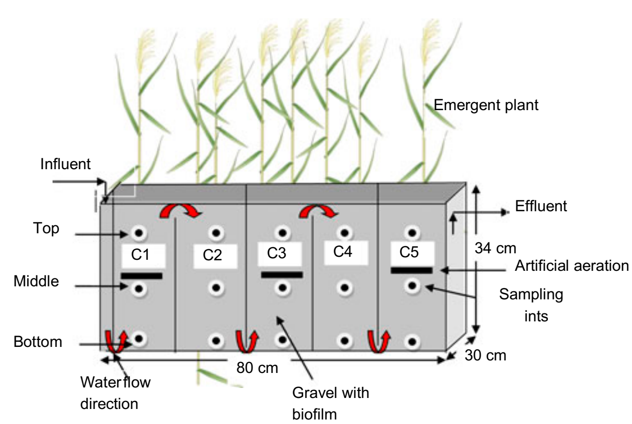

Fig. 1. Aerobic–anaerobic baffled constructed wetland reactor.

zones. Aeration was switched on and off at 3 h intervals. The air flowrate for this research was 0.38 L/min, which was the same for all compartments (compartments 1, 3 and 5). Once the reactor has been planted and filled with gravel up to 30 cm from the bottom, the void volume was measured by filling the reactor with tap water till slightly above gravel bed surface. Void volume of the ABCW was 29.63 L as shown in Table 1. The HRT was set to 1 d based on Eq. (1):

$$\text{HRT (D)} = \frac{\text{Void volume (L)}}{\text{Influent flow rate}\left(\frac{\text{L}}{\text{D}}\right)} \quad (1)$$

2.2. Seeding

The average gravel size was 1 cm. Gravel was washed and dried before seeding. Activated sludge was obtained from the nitrification tank at Shorubber (Malaysia) Sdn. Bhd, Jejawi, Perlis, which is a rubber-processing factory wastewater treatment plant. The COD, mixed liquor suspended solids and sludge volume index were the initial properties of the activated sludge used for seeding; which were 7,920 mg/L, 24,780 mg/L and 5.6 ml/mg, respectively.

The seeding process was divided into aerobic and anaerobic conditions. Aerobic condition was set by supplying aeration in an open container containing 150 kg of gravel, while the anaerobic condition was created in a closed container with the same amount of gravel. The ratio of gravel to sludge was about 150 kg of gravel to 25 L of sludge. Throughout the seeding process, both the containers were supplied with synthetic wastewater as substrate for the microbes. Seeding period was about 1 month. After seeding, the gravel was transferred to the ABCW unit manually.

2.3. Analysis

Modified artificial wastewater was used with the total carbon and nitrogen concentrations of a standard artificial domestic wastewater [17], in addition acetate, benzoate and ammonia nitrate are being used as C and N compounds instead of casein, meat extract and urea. This modification was made to achieve more defined removal conditions using well-degradable compounds, which are easier to analyse. Synthetic wastewater of the following composition was pumped into the reactor on a daily basis. The inflow concentrations of the components used were (in mg l^{-1}): 107.1 C_6H_5COONa, 204.9 CH_3COONa, 176.1 NH_4NO_3, 36.7 $K_2HPO_4{\cdot}3H_2O$, 7.0 NaCl, 3.4 $MgCl_2{\cdot}6H_2O$ and 4.0 $CaCl_2{\cdot}2H_2O$. The wastewater characteristics were (in mg l^{-1}): 326 COD, 222 BOD_5, 122.3 total organic carbons, 61.6 total-N and 5 total-P [18]. Sampling and analysis were conducted from the day the system was in operation to observe the acclimatisation phase and stability of the system. However, the data-set included in this study is of the stabilised phase.

Water samples were collected at the influent, effluent and sampling points while the aeration was switched on and off during the end of aeration interval for COD, NH_4^+-N, NO_3^--N, oxidation reduction potential (ORP) and dissolved oxygen (DO) analysis to evaluate the treatment performance of the ABCW reactor. NH_4^+-N was analysed using the NH_4^+-N probe (Martini Instruments Mi 151 pH/ORP/Temperature bench meter, China) and NO_3^--N was analysed using the NO_3^--N probe (Bante Instruments 920 Precision pH/ORP meter, China). ORP was measured using an ORP metre (HANNA HI 8424 pH meter, USA). The reference electrode utilised was Ag/AgCl with platinum electrode. All samples were centrifuged (L500 Tabletop Low Speed centrifuge, China) before preparing for COD analysis. Colorimeter (HACH DR/890 Colorimeter) was used to analyse for COD concentration.

Table 1
Reactor characteristics

Reactor characteristics	Specifications
Height of gravel bed	30 cm
Volume of gravel bed	72 L
Average gravel diameter	1 cm
Average gravel bed porosity	37%
Average void volume	29.63 L
Hydraulic retention time (HRT)	1 d
Average flow rate	29 mL/min

3. Results and discussion

3.1. Oxidation reduction potential and dissolved oxygen along the ABCW reactor

ORP profile distinguishes between anaerobic/anoxic and aerobic conditions within the reactor system [19,20]. Redox potentials higher than 100 mV are known to be in an aerobic environment, while redox potentials lower than –100 mV are known to be in an anaerobic environment [21]. The ORP was measured at all the sampling points throughout the whole reactor while the aeration was switched on and off at 3 h interval as shown in Fig. 2(a) and (b). ORP measurement was carried out at the end of the 3 h interval.

Fig. 2(a) shows that while the aeration was switched on, the wastewater samples at the top region were anoxic as the ORP value obtained was between –20 and

60 mV. The middle region of compartment 3, 4 and 5 had higher ORP values compared to compartment 1 and 2. Tee et al. reported similar results, which were due to the contact of pore water with more rhizomes and micro-aerobic zones [13]. At the bottom region of the ABCW reactor, ORP values ranged from –260 to –40 mV, indicating anaerobic and anoxic conditions, which were due to the absence of rhizomes. When the aeration was switched off for 3 h, the ORP values decreased according to the flow as was demonstrated in compartment 1, 2 and 3 in Fig. 2. ORP values at the middle region and bottom region ranged from –250 to 50 mV and –230 to –20 mV, respectively. Wang et al. with the use of similar reference electrode to measure ORP gave an almost similar range of aerobic conditions, which is between 0 and 200 mV [22].

ORP values in compartments 3, 4 and 5 were close to zero presuming a slightly aerobic environment could be due to the oxygen released by the root system. Such condition was not observed in the first two compartments as there could be intense microbial activity due to higher organic loading as observed in Fig. 4, which involves the utilisation of oxygen and other electron acceptors; thus, making the first two compartments anaerobic. No significant difference in ORP between aerated and non-aerated times at compartments 2, 4 and 5 was observed. This could be due to the dynamic wetland systems, owing to biochemical transformations and also a stabilised redox potential value is a portrait of the current situation [23].

Generally, it could be observed in Fig. 2 that the trends between aerated and non-aerated periods are similar. The main objective of providing aeration is to control the aerobic and anaerobic zones throughout the reactor. There was no significant difference between each aeration times as it requires longer time for the development of aerobic and anaerobic conditions.

DO concentration at the top region of the five compartments ranged from 1 to 4 mg/L, which could be observed in Fig. 3(a) and (b). Compartment 5 had the highest DO concentration, followed by compartment 3 and 4 compared to the other compartments, which could also be reflected in the ORP profile in Fig. 2. The DO concentration could be influenced by diffusion of oxygen from the atmosphere, the inflow of the wastewater and radial oxygen loss from plant rhizomes. Radial oxygen loss is an acclimatisation process by plants to provide anoxic environment around the roots to shield against the presence of phytotoxins in anaerobic environment [24].

Fig. 3 shows that the top region of compartments 3 and 5 had higher concentration of DO compared to compartments 1, 2 and 4 due to supplementary aeration and flow. Even though compartment 1 had supplementary aeration, the ORP and DO concentration is not as high as compared to compartment 3 and 5. This is due to aerobic biodegradation and the flow of the pore water which was not exposed for a longer period to the supplementary aeration. Based on the results obtained, the flow of the wastewater and the artificial aeration controlled the aerobic, anaerobic and anoxic zones as without the aeration all compartments would slowly stabilise and become anaerobic. The lower DO concentration in the first compartment could also be associated with the higher organic loading and the corresponding higher oxygen consumption rate in compartments 1 and 2 of the reactor, which is in accordance to COD profile as shown in Fig. 4(b).

There was a significant increase in the DO profile when the aeration was switched on during the 3 h

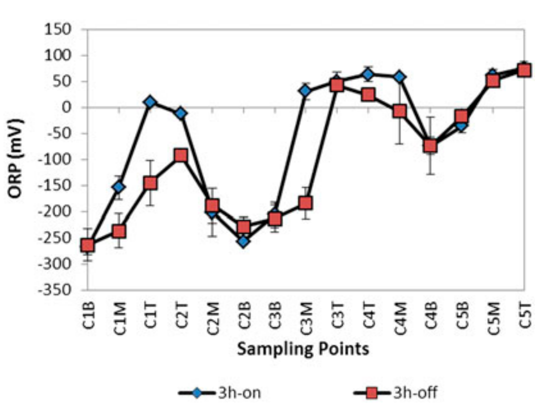

Fig. 2. ORP (mV) profile determined at all the sampling points according to compartment with different aeration times. Error bar represent standard deviation.

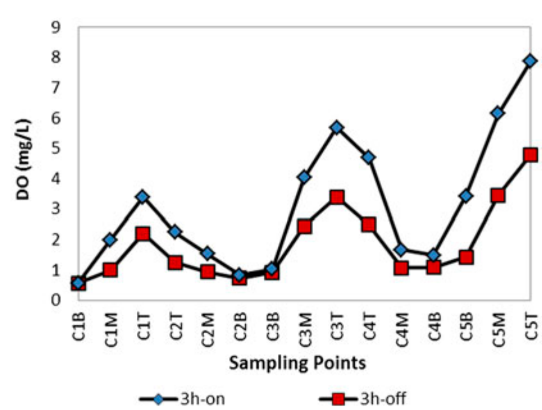

Fig. 3. DO (mg/L) profile determined at all the sampling points according to compartment with different aeration times.

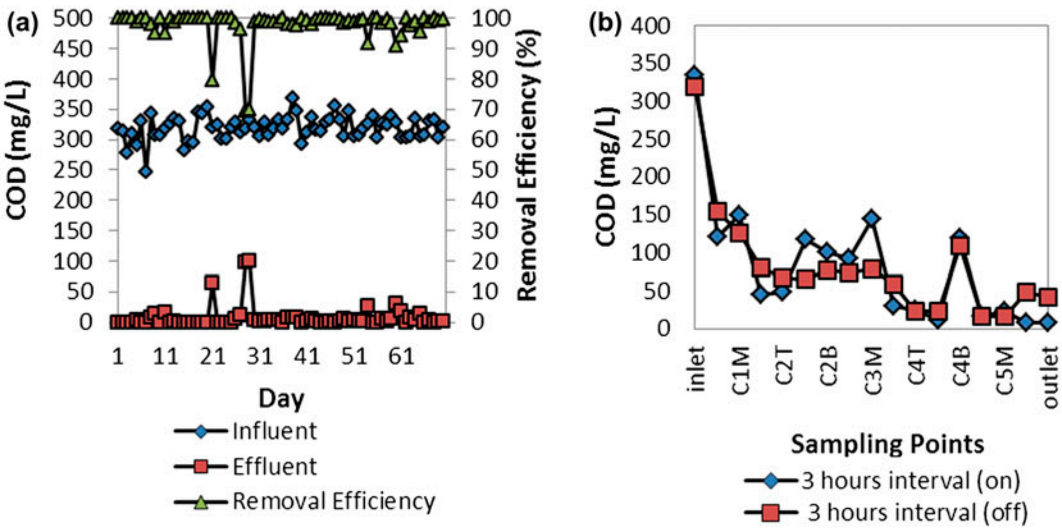

Fig. 4. Soluble COD (mg/L) (a) and reduction efficiency (%) (b) profile in the ABCW reactor.

interval, especially at the top region of compartment 1, 3 and 5, where the supplementary aeration was supplied. According to Armstrong et al. DO concentration could be influenced by diffusion of oxygen from the atmosphere [24]. The higher DO concentration at the top region of the aerated compartments was due to better oxygen diffusion from the atmosphere. These compartments had better oxygen diffusion as aeration ensures mixing and removes the thin film of algae from the surface of the water table, which facilitated the diffusion of oxygen at the surface.

3.2. COD monitoring

Fig. 4(a) shows the influent, effluent and reduction efficiency of soluble COD concentration in the ABCW reactor. The average COD reduction efficiency concentration was 98 ± 6%. The high COD reduction efficiency was contributed by the long pathway travelled along the ABCW reactor through the gravel media, where pollutants were degraded in the wastewater. The COD reduction was also due to the supplementary aeration, which resulted in an increase in microbial activities. Excellent COD removal was contributed by microbial activities in both aerobic biological decomposition and denitrification process [25]. Kaseva reported that COD reduction could also be contributed by the plant in treatment performance of HSF-constructed wetland [26]. However, Akratos and Tsihrintzis reported only a slight difference in the reduction in COD by plants in treatment performance of HF [27]. It is generally assumed that plants increase the reduction efficiency of COD due to the plant rhizosphere, which encourages microbial community density and activity by accommodating microbial growth via root surface, a provenance of carbon through root excretion and a micro-aerobic environment by means of root oxygen release [28,29].

In Fig. 4(b), it can be seen that the COD concentration gradually decreased throughout the reactor. There was not much difference in COD reduction between with and without aeration at 3 h interval. However, it could be seen that the COD concentrations in compartments 1, 3 and 5 were lower when the aeration was switched on as there was supplementary aeration placed in those compartments. Ong et al. also showed higher COD reduction in an aerobic condition [30]. Tee et al. reported a reduction efficiency of 59 ± 2% with the use of baffled HSF-constructed wetland, 66.5% rice husk and 33.5% gravel as wetland media, cattail as emergent plant, six operating compartments, influent concentration of COD 156 mg/L, and at 2 d HRT. Whereas, Lim et al. with the use of horizontal subsurface wetland unit and gravel as its wetland media, reported reduction efficiency of 89 ± 4% [13,31]. The high reduction in COD in the ABCW was due to the supplementary aeration and baffles which provided a longer treatment pathway thus allowing more micro-organisms to degrade the pollutants.

3.3. Removal of nitrogen

The removal of nitrogen mainly comprises aerobic nitrification and anaerobic denitrification [32]. Volatilisation, adsorption and plant uptake are of less importance in nitrogen removal especially in horizontal flow constructed wetlands [19].

In this study, the average removal efficiency of NO_3^--N and NH_4^+-N was 36 ± 13–98 ± 2%, as shown in Fig. 5(a) and (b), respectively. The fluctuating pattern observed in Fig. 5(a) was due to the fact that there was artificial aeration at 3 h interval in the continuous system, which instigated a mostly anoxic and aerobic environment in the ABCW reactor. These conditions promoted a high NH_4^+-N removal as illustrated in Fig. 5(b), which was mainly due to nitrification by chemoautotrophic nitrifying bacteria. Provision of supplementary aeration to the system enhanced the nitrification process due to the presence of nitrifying bacteria. Tee et al. reported NH_4^+-N removal efficiency of 74% with the use of baffled HSF-constructed wetland, which relates to the operation of the ABCW reactor and used cattail as emergent plant, six operating compartments, influent concentration of NH_4^+-N 32.7 mg/L and at 2 d HRT [13]. Removal of NH_4^+-N could be contributed by the uptake of emergent plant [33–35]. Huett et al. reported 96% of nitrogen was removed by *Phragmites australis* in a SF constructed wetland at 3.5 HRT and was mainly contributed by roots and rhizomes [35].

It could be seen based on Fig. 6(a) and (b) that there were aerobic nitrification and anaerobic denitrification as NO_3^--N concentration from compartment 3 onwards increased, while the NH_4^+-N concentration decreased which was due to the aerobic condition as reflected in the ORP and DO profile in Figs. 2 and 3, respectively. The ABCW reactor during aeration and non-aeration operation mode showed slight difference in the NO_3^--N concentration. Based on Fig. 6(a), it is shown that during the non-aeration period the concentration of NO_3^--N was lower at the outlet compared to during the aeration period by 21 mg/L.

Removal efficiency of NO_3^--N should be higher in anaerobic conditions due to the conversion of nitrates to nitrogen gas during denitrification process. The removal of NO_3^--N was higher in compartment 1 and 2 compared to the other compartments due to denitrification, which was reflected in the ORP and DO profile. Since organic biodegradation is piloted by aerobic heterotrophic bacteria, inadequate oxygen supply would deteriorate aerobic biochemical oxidation. This could be clearly seen at compartment 1 and 2, where there was limited oxygen supply, the ammonium could not be converted to nitrate, thus resulting in low NO_3^--N removal. The sharp increase and decrease in NO_3^--N and NH_4^+-N, respectively in compartment 3 was due to the higher concentration of DO in compartment 3 onwards, which was contributed by the flow of pore water in the ABCW reactor. The low NO_3^--N removal rate at the last compartment could also be attributed to short reaction time as the HRT in each compartment was about 4.8 h. This might not be enough for the removal of nitrates formed by nitrification, which could be solved by an additional compartment to extend reaction time, thus enhancing nitrate removal. Besides that, the low NO_3^--N removal rate at the last compartment could also be due to the possibility of organic carbon depletion as shown in Fig. 4. The low organic loadings in compartments 4 and 5 could

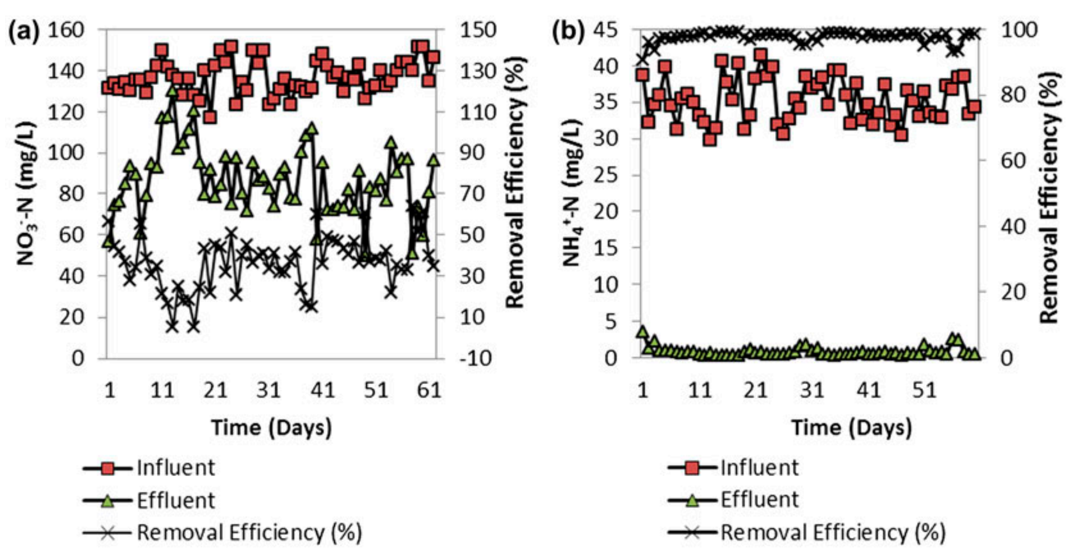

Fig. 5. Removal efficiency of (a) NO_3^--N (mg/L) and (b) NH_4^+-N (mg/L) concentration in the ABCW reactor while aeration was switched on and off at 3 h interval. Error bars represent standard deviation.

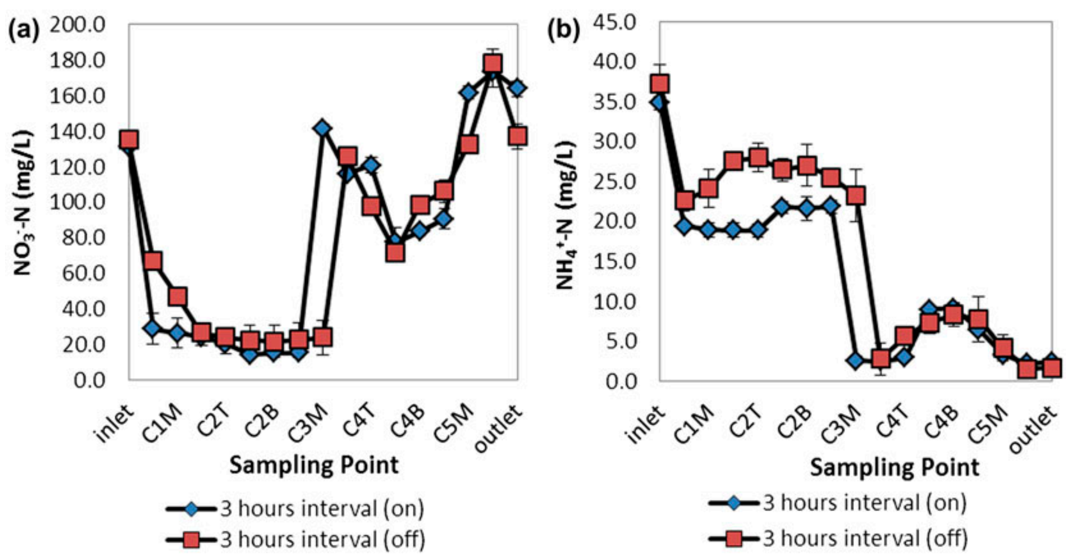

Fig. 6. (a) NO_3^--N (mg/L) and (b) NH_4^+-N (mg/L) profile in the ABCW reactor while aeration was switched on and off at 3 h interval. Error bars represent standard deviation.

affect the activity of denitrifiers, which could be handled by the addition of external carbon source to increase nitrate removal efficiency.

4. Conclusion

The performance of the ABCW was evaluated in terms of removal efficiency of COD, NH_4^+-N, and NO_3^--N. COD concentration gradually decreased throughout the reactor with insignificant difference between aeration intervals. Nitrification takes place after compartment 3 resulting in a reduction in NH_4^+-N and an increase in NO_3^--N, while, the influent nitrate nitrogen is completely removed at the first compartments. The removal efficiencies of both organic compounds and nitrogen were 98% for COD, 36% for NO_3^--N and 98% for NH_4^+-N concentration. The baffles in this reactor provided the upward and downward flow, which allowed the wastewater to travel a longer path through the gravel media, enhanced the removal of organic compounds and nitrogen. The results indicated that supplementary aeration was also essential in ensuring the high removal efficiency of both organic compounds and nutrients.

Acknowledgements

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