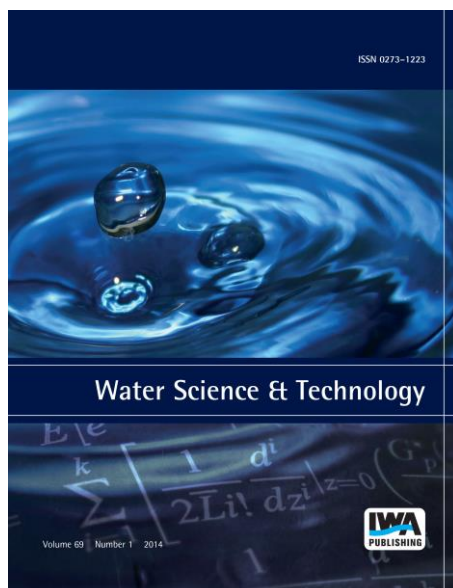


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Performance of airlift MBR for on-site treatment of slaughterhouse wastewater in urban areas of Vietnam

Anh Tien Do, Dung Quang Bach, Uan Khac Do, Ana Prieto and Huynh Thi Lan Huong

ABSTRACT

In many cities in Vietnam, wastewater generated in slaughterhouses is normally discharged directly into surface waters without treatment. Management of slaughterhouse wastewater (SHWW) is difficult due to the lack of infrastructure for conveyance to centralized facilities. On-site treatment presents one cost-effective way of managing SHWW compared to mass improvement of infrastructure. This study evaluates the application of an airlift membrane bioreactor (AL-MBR) for on-site treatment of SHWW. The concentrations of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN) and $\text{NH}_4^+\text{-N}$ in the simulated SHWW were $1,697 \pm 317$ mg/L, 891 ± 137 mg/L, 246 ± 65 mg/L and 171 ± 4.2 mg/L, respectively. The mixed-liquor volatile suspended solids in the aerobic and anoxic tanks were maintained at 5,000–6,000 mg/L. Air flow rate and cross flow velocity were maintained at 0.2 L/min and 0.8 m/s, respectively, to keep the trans-membrane pressure (TMP) stable at 0.8 bar and the membrane flux at 15–18 L/m² h bar (LMH/bar). The removal efficiencies of COD and TN were $95 \pm 1.9\%$ and $70 \pm 3.3\%$, respectively, at a hydraulic retention time (HRT) of 2.5 days. This study shows that GL-MBR is a promising on-site solution for SHWW treatment.

Key words | airlift MBR, membrane bioreactor, on-site treatment, slaughterhouse wastewater, ultrafiltration

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INTRODUCTION

Slaughterhouse wastewater (SHWW) is a high strength source of waste containing large amounts of protein, fat, and suspended organic matter (i.e., meat, blood, bones, and viscera). The characteristics of SHWW depend on the type and numbers of animals killed per day. Generally, SHWW contains high concentrations of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), $\text{NH}_4^+\text{-N}$, and total suspended solids (TSS) (Cao & Mehrvar 2011; Jia *et al.* 2012; Bustillo Lecompte *et al.* 2014; Khamtib & Reungsang 2014). The average concentrations of COD, BOD, TN and TSS in SHWW can reach 4,221 mg/L, 1,209 mg/L, 427 mg/L and 1,164 mg/L, respectively (Bustillo-Lecompte *et al.* 2014). For a country like Vietnam, with a total of over 29,000 slaughterhouses divided into large (>100 m³/day of SHWW), medium (30–100 m³/day) and household scale (<30 m³/day), the lack of treatment of SHWW is a major sanitary concern (Le *et al.* 2014). The SHWW is commonly discharged directly into surrounding streams, which pollutes natural waters and generates environmental and health problems for riverside

and downstream residents (Pham 2006). As in most developing countries, the current wastewater management infrastructure in Vietnam is outpaced by population growth. Therefore, the construction of additional sewer infrastructure for centralization of SHWW is unlikely to be an option in the near future. However, on-site treatment represents a viable option for SHWW management in Vietnam.

Membrane bioreactor processes have been widely applied to wastewater treatment (Choi *et al.* 2002; Daigger *et al.* 2005; Asatekin *et al.* 2006) in decentralized settings. A few studies have reported the application of MBRs for SHWW treatment with very high treatment effectiveness, e.g. higher than 93% removal of COD (Saddoud & Sayadi 2007; Jensena *et al.* 2015). Biological processes coupled with membranes in SHWW treatment were found in both aerobic and anaerobic applications. Both aerobic and anaerobic MBRs showed very high removal of COD and TN, which varied from 90–97% and 44–90%, respectively (Saddoud & Sayadi 2007; Gurel & Büyükgüngör 2011; Jensena *et al.* 2015).

The cross flow MBR is used most generally for industrial wastewater treatment applications. The main characteristic of cross flow is that a part of the feed is withdrawn as permeate, while the other part is forced to flow along the membrane surface (Futselaar *et al.* 2004). The pressure pump pressurizes the feed, while the circulation pump recirculates the concentrate; part of the concentrate is purged to the bioreactor. The advantage is better control of the cake layer build-up, resulting in a sustained constant flux. However, the energy consumption for the typical cross flow MBR is still high, at a level of 1.7–2.2 kW hr/m³ product water (Futselaar *et al.* 2009). Therefore, the airlift MBR (AL-MBR) has been developed to reduce the energy consumption during operation. The AL-MBR is based on the same concept as the cross flow principle; however, the turbulence within the tubular membranes is achieved by sparging air into the vertically mounted membranes (Futselaar *et al.* 2007). In the case of an anaerobic process, using the produced biogas in an airlift configuration can provide membrane scrubbing and decrease membrane fouling (Prieto *et al.* 2013; Kijjanapanich *et al.* 2014). This study evaluates the application of a laboratory-scale (35 L total volume) AL-MBR for on-site treatment of SHWW in Vietnam. The study first evaluated the filtration ability of the AL-MBR and also identified the operational parameters for the airlift membrane. Then performance of the AL-MBR was tested over 130 days on SHWW. Finally, the energy consumption of the AL-MBR system was observed and reported.

MATERIALS AND METHODS

Activated sludge

Seed activated sludge was collected from a local wastewater treatment plant (Viet Ha Brewer Corporation, Bac Ninh province, Vietnam). Prior to use, the sludge was sieved through a 3 mm mesh sieve to remove any debris that could clog the membrane lumen or block the reactor tubing. The TSS and pH of the seed sludge were 1.6 ± 0.1 g/L and 7.24 ± 0.05, respectively.

Synthetic SHWW

To determine appropriate characteristics for a synthetic SHWW to use in the tests, wastewater from five pig slaughterhouses in Hanoi, North of Vietnam were sampled. The samples taken at each abattoir were mixed together. The

SHWW compositions were described in Table 1, which also includes the discharge standards in Vietnam.

The recipe for the SHWW was made based on the average composition in Table 1. The SHWW was made using 100 mL of pig blood and 3 L of solid waste from the viscera and stomach contents of a pig. These samples were collected twice a week and diluted with 100 L of tap water to formulate wastewater with the similar characteristics to typical SHWW.

Membrane filtration evaluation tests

In order to identify the filtration ability of the membrane modules and operational parameters such as cross flow velocity (CFV) and air flow rate (Q_{air}), a series of membrane filtration evaluation tests were conducted before operation of the AL-MBR. The concentration of mixed-liquor volatile suspended solids (MLVSS) for the test was managed at 6,000 mg/L. The first test was implemented with a controlled rate of air flow at 0.2 L/min and various CFVs of 0.4–1.2 m/s. The second test was operated at a constant CFV of 0.8 m/s and different values of Q_{air} (from 0–1.6 L/min).

AL-MBR fabrication

The AL-MBR system was designed and constructed as a 20 L anoxic tank followed by a 15 L aerobic tank coupled with 5 side stream tubular ultrafiltration membrane modules. The membranes (length × inside diameter) were 0.5 m × 5.0 mm polyvinylidene fluoride modules (model code: Laboratory unit MO PIU (0.5 m)_15_, Berghof, Germany) with a mean pore size of 0.03 μm and active filtration area of 0.008 m² per module. It should be noted

Table 1 | The SHWW characteristics used in this study

Parameters	SHWW	Vietnam Discharge Regulation Standard
BOD (mg/L)	891 ± 137	50
COD (mg/L)	1,697 ± 317	150
NH ₄ ⁺ -N (mg/L)	171 ± 4.2	10
TN (mg/L)	246 ± 65	40
TP (mg/L)	28 ± 9.9	6
pH	6.83 ± 1.2	5.5–9
TSS (mg/L)	662 ± 286	100
NO ₃ ⁻ -N (mg/L)	18.39 ± 2.6	–
Coliform (MPN/100 mL)	11.80 × 10 ⁹ ± 2,200	5,000

that the volume of mixed liquor in the membrane modules was about 450 mL. This amount is quite small compared with the reactor volume. The SHWW was pumped from a feed tank to the anoxic reactor by a centrifugal pump (Fore-run MKP80-1, Italy) at rate of 0.5 L/hour. This is a pre-denitrification process as in the modified Ludzack-Ettinger (MLE) process. MLE coupled with MBR has been used for treating many kinds of wastewater. It is particularly important for wastewater containing a high ratio of COD to nitrogen. The air compressor (Puny Air, model: 7-36, Taiwan) was controlled to provide compressed air at 2 bar to the 5 membrane modules and to the aerobic reactor. Dissolved oxygen in the reactor was maintained at around 4 mg/L. The system flow scheme is illustrated in Figure 1. The sludge was circulated through the membrane modules by a centrifugal pump (Forerun MKP80-1, Italy). The CFV was determined by taking the feed flow rate (Q_{in}) divided by the cross sectional area of the membrane channel spacer. The recycle flowrates were measured by the float style flowmeters (LZM Series, Rungrueng Instrument Co., Ltd, Thailand) installed in the recycle lines. The permeate flow was also measured by a floating flow meter, and sometimes was double-checked by a digital balance. The permeate was carried out by a vacuum pump (using a peristaltic pump, Masterflex, Model GT-150D, Green Tech, Korea). The vacuum pump has an inlet head pressure of about 0.1 bar (monitored by a pressure gauge), so that it could generate sufficient transmembrane pressure to suction

the permeate water from the membrane. The air flow rate to the membrane modules (Q_{air}) was controlled manually with a gas flow meter and a needle valve. The relationship between air and liquid present in the membrane lumen is represented by an air to liquid ratio, defined by the relationship as $Q_{air}/(Q_{air} + Q_{in})$.

The AL-MBR operation

The performance of the AL-MBR was tested and observed over more than 4 months (130 days) and with different concentrations of MLVSS in an aerobic bioreactor. The anoxic and aerobic reactors were operated at a hydraulic retention time (HRT) of 1.7 days and 20 hours, respectively. Initially, the anoxic and aerobic reactor was seeded to give an MLVSS concentration of 4,000 mg/L (Figure 2) using activated sludge from the Viet Ha Brewer Corporation wastewater treatment plant (Bac Ninh province, Vietnam). After 20 days, MLVSS concentration gradually increased and reached 6,000 mg/L by day 30. Then the sludge concentration was kept consistently at 6,000 mg/L by controlled wasting. The recycle flow from the aerobic to the anoxic tank for denitrification was provided by a centrifugal pump (Forerun MKP80-1, Italy). The internal recycle pump was set at different rates of $8Q_{in}$, $4Q_{in}$, Q_{in} and $0.5Q_{in}$ in order to identify the optimum operational conditions for denitrification. Each recycle rate was operated until the product water TN concentration became stable.

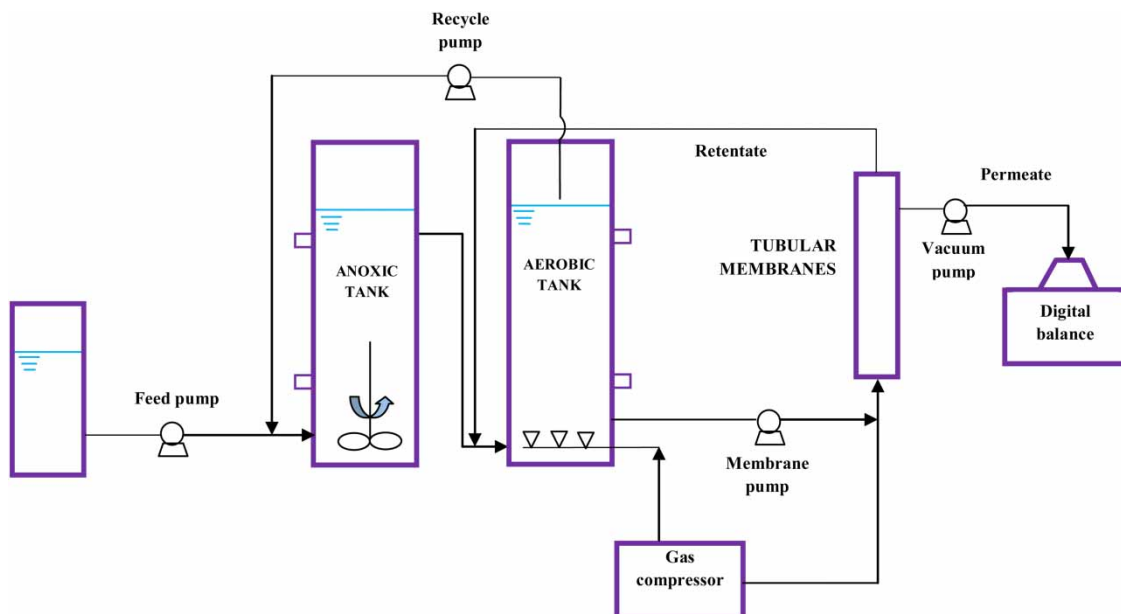


Figure 1 | Flow scheme of the AL-MBR for SHWW treatment.

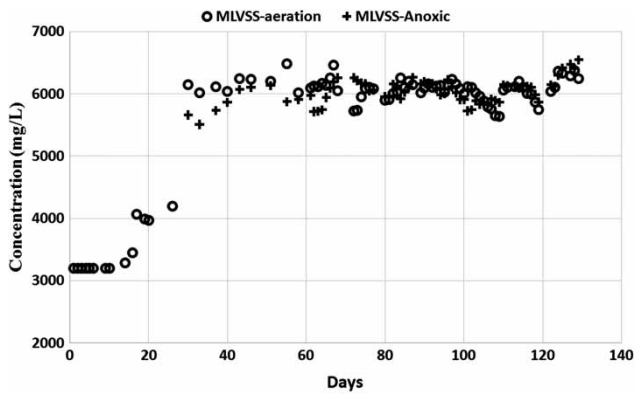


Figure 2 | Time series of MLVSS in the anoxic and aerobic tanks.

Analytical methods

Grab samples from the influent, mixed liquor in the aerobic and anoxic reactors, and permeate samples were taken daily to analyze the COD, NO_3^- -N, NH_4^+ -N, TN, mixed-liquor suspended solids (MLSS) and MLVSS according to *Standard Methods for the Examination of Water and Wastewater* by APHA (APHA 2005). Samples for COD, NO_3^- -N, TN and NH_4^+ -N were filtered through a 0.45- μm glass microfibre filter before measurement. COD was determined by the closed reflux, colorimetric method (Method 8000). TN was analyzed by the persulphate digestion method (Method 10071). Nitrate (NO_3^- -N) was measured by the cadmium reduction method (Method 8039). Ammonia (NH_4^+ -N) was measured by the salicylate method (Method 10031). MLSS and MLVSS were measured by using methods 2540D and 2540E, respectively. The permeate flow rate was determined using a digital balance connected to a data logger.

During operation, energy consumption was monitored by using a kWh meter (EMIC Corp., Vietnam). The energy consumption includes that for the feed pump, the recirculation pump, the internal recycle pump, the vacuum pump and the air blower. The specific energy consumption was estimated based on the flow rate of product water and the energy consumption recorded by the kWh meter.

RESULTS AND DISCUSSION

Evaluation of membrane filtration performance

As illustrated in Figure 3(a), an increase in flux from 7 to 12 $\text{L}/\text{m}^2 \text{ hr}$ (LMH) was observed when increasing the CFV

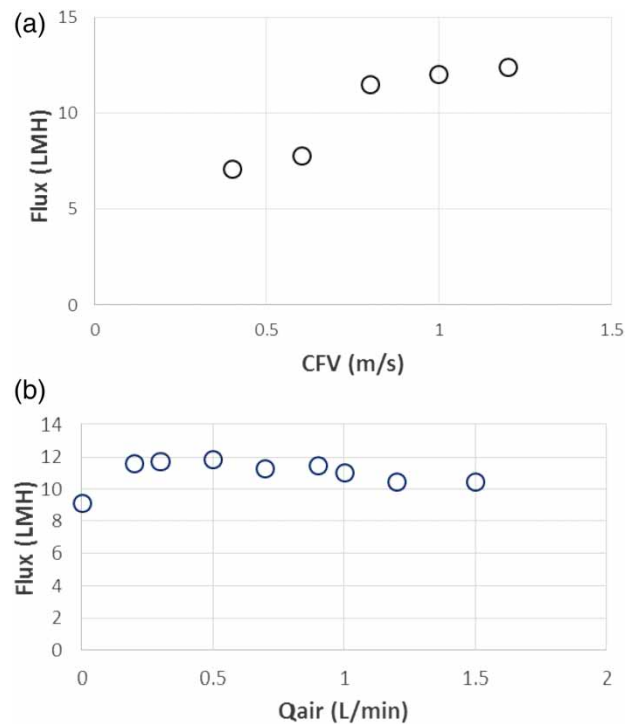


Figure 3 | Membrane filtration evaluation: (a) Q_{air} vs Flux (at $\text{CFV} = 0.8 \text{ m/s}$); (b) CFV vs Flux (at $Q_{\text{air}} = 0.2 \text{ L/min}$).

from 0.4 m/s to 1.2 m/s at a controlled air flow rate of 0.2 L/min. The flux was stabilized at 12 LMH after CFV reached 0.8 m/s. The result, showing that CFV does not have any effect on flux after a certain value of CFV, was also identified in Prieto's study in 2013. This result implies that a CFV of 0.8 m/s could be an appropriate operating value at a constant air flow rate of 0.2 mL/min. However, this typical value of air flow rate of 0.2 mL/min may not be the optimum value for this AL-MBR system. The filtration membrane was then also evaluated at a constant value of CFV of 0.8 m/s with various air flow rates ranging from 0 to 1.6 mL/min (Figure 3(b)). Figure 3(b) indicates that there is a slight increase in flux as Q_{air} increases from zero to 0.2 L/min. The maximum flux was identified at a value of 12 LMH at an air flow rate of 0.2–0.9 L/min. Beyond the value of 0.9 L/min, the flux appeared to be negatively affected. A higher air flow rate contributes to a higher proportion of gas phase and lower proportion of liquid phase in the mixture. This may be the reason for the apparent decrease in flux.

The results of these tests suggested that the optimum CFV is 0.8 m/s and the optimum Q_{air} is 0.2 L/min, and these were adopted for subsequent continuous operation of the AL-MBR.

The AL-MBR performance

Membrane performance in the AL-MBR system

The maximum flux of the membrane was observed to be 35 LMH/bar when starting operation of the system, and the flux decreased over the next 20 days of operation (Figure 4). After 20 days, the flux was stable at 18 LMH/bar and did not vary with the MLVSS concentration. During operation, the membrane was cleaned by using product water as backwash for 20 minutes on days 60 and 100 to improve the flux. The flux temporarily increased to 25 LMH/bar after cleaning but then stabilized at 18 LMH/bar. The constant flux implies that the turbulence caused by the airlift cross flow system kept fouling of the membranes at a constant level over the 3 months. This was also shown in the study of Prieto *et al.* (2013).

Organic matter reduction

The SHWW contains various components such as blood, urine, fat and meat tissues. COD in the influent was $1,868 \pm 203$ mg/L. The removal of organic matter by the AL-MBR during operation was consistently of high efficiency, as shown in Figure 5. After the biological processes, the soluble COD was reduced to 192 ± 57 mg/L and reduced further to 94 ± 34 mg/L after the membrane process. The efficiency of soluble COD removal by the whole system was $95 \pm 1.9\%$. The biological process removed $90 \pm 3.4\%$ and the membrane process contributed an additional $5 \pm 0.1\%$. It should be noted that, during operation, the food to microorganism (F/M) ratio, which was estimated based on the kg of filtered COD per day divided by the kg of MLVSS in the system, was maintained at around 0.1 to 0.15 d^{-1} (Figure 6).

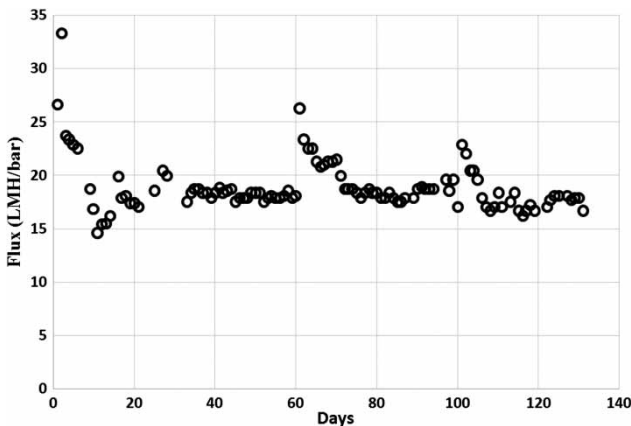


Figure 4 | Variation of flux during operation.

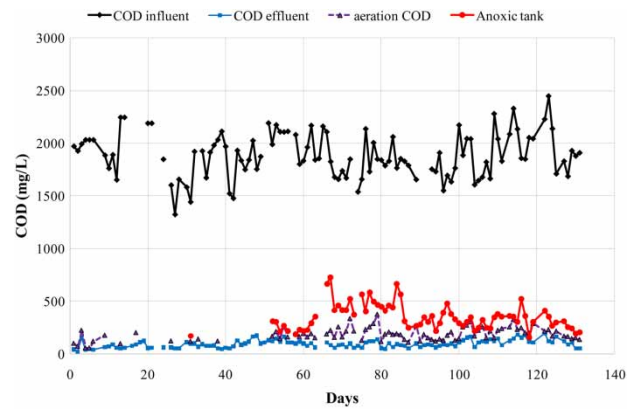


Figure 5 | Variation of filtered COD in the influent, effluent, anoxic and aerobic tanks.

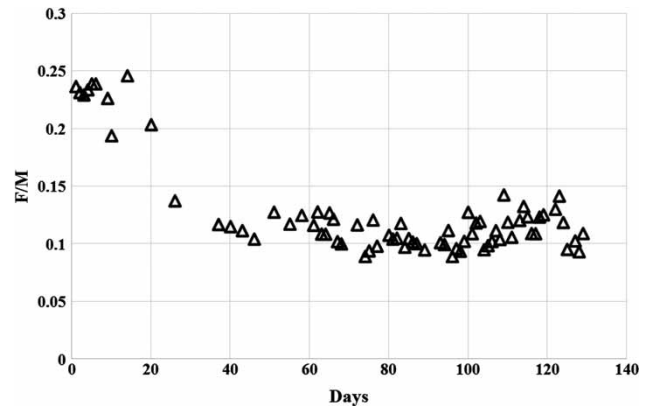


Figure 6 | Food to Microorganism ratio profile.

Nutrient removal

In the influent, the concentration of phosphorous was approximately 20 to 30 mg/L. The concentration of TN in the influent is quite high. Nitrogen in the influent was mostly contributed by $\text{NH}_4^+\text{-N}$. The concentration of

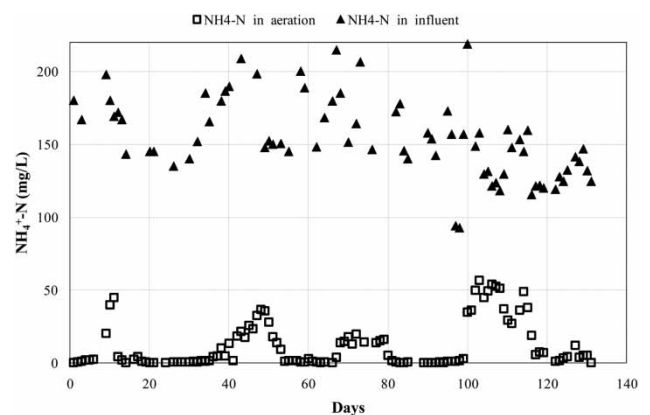


Figure 7 | Profile of $\text{NH}_4^+\text{-N}$ in aerobic tank and in influent.

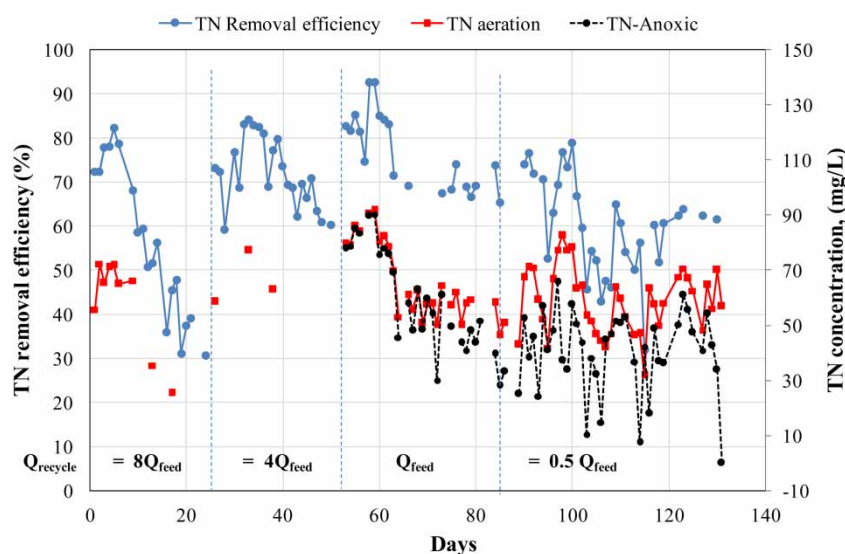


Figure 8 | Profile of TN in the AL-MBR system.

$\text{NH}_4^+\text{-N}$ in the influent ranged between 157 ± 28 mg/L and contributed $77 \pm 14\%$ of TN (Figures 7 and 8). The concentration of $\text{NO}_3^-\text{-N}$ and $\text{NO}_2^-\text{-N}$ in the influent was only a few mg/L, and could be considered negligible if compared to the total amount of nitrogen. Organic nitrogen most likely contributes the remainder of the TN.

In the aerobic tank, the concentration of $\text{NH}_4^+\text{-N}$ was negligible most of the time. The nitrification process in the aerobic tank occurred readily and converted $\text{NH}_4^+\text{-N}$ to $\text{NO}_3^-\text{-N}$. The concentration of $\text{NO}_3^-\text{-N}$ was observed at 46.9 ± 20.9 mg/L. The $\text{NO}_3^-\text{-N}$ was transported to the anoxic tank by the internal recycle pump for denitrification. The pump was set at various speeds to determine the optimum operating condition for denitrification. Figure 8 shows that initially, when the recycle pump was set at 4 L/hr, which is 8 times higher than Q_{feed} , the efficiency of nitrogen removal was around 30%. The removal efficiency stably reached 60%, 70% and 61%, respectively at $Q_{\text{recycle pump}} = 4 Q_{\text{feed}}$, Q_{feed} and $1/2 Q_{\text{feed}}$. The higher $Q_{\text{recycle pump}}$ could result in introducing more oxygen from the aerobic tank to the anoxic tank, which would inhibit denitrification. At lower $Q_{\text{recycle pump}}$, $\text{NO}_3^-\text{-N}$ was not transferred adequately to the anoxic tank resulting in lower nitrogen removal efficiency.

Energy consumption

Electrical energy consumption for the feed pump, the recirculation pump, the internal recycle pump, the vacuum pump and the compressor was measured at about 1.45 kW hr/m³ of product water. The energy consumption for the typical

cross flow MBR is the level of $1.7\text{--}2.2$ kW hr/m³ product water (Futselaar et al. 2009). Therefore, the AL-MBR could reduce energy consumption by about 14% compared to a typical cross flow MBR. It should also be noted that in the past 50 years, developments in MBR technology have resulted in an energy demand reduction from about 5.0 kW hr/m³, needed for the first side-stream MBRs (Buer & Cumin 2010). The energy requirement of the first tubular side-stream MBR installations was reported to be typically $6.0\text{--}8.0$ kW hr/m³ (Van Dijk & Roncken 1997), mainly due to energy intensive cross flow pumping of the liquid.

CONCLUSION

The lack of appropriate treatment for SHWW has created a severe environmental problem in Vietnam. AL-MBRs are potentially an option well suited to treating SHWW, considering Vietnam's inadequate centralized treatment infrastructure. Results from the operation of a laboratory-scale AL-MBR over more than 130 days show that the system is capable of achieving Vietnamese discharge standards with high COD and TN removal efficiencies of 98% and 70% respectively. The AL-MBR in this study provided a consistent flux of 18 LMH/bar at low pressures (0.8 bar) without regular membrane cleaning. The energy consumption of this system was 14% lower than an average cross flow MBR. The results of this small pilot-scale system indicate that decentralized treatment of SHWW can be undertaken efficiently and with a lower than expected energy demand.

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