

The application of UASB-MBR with partial nitrification-denitrification in wastewater reclamation in warm climate

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ABSTRACT

An up-flow anaerobic sludge blanket (UASB) process has been successfully applied for the treatment of municipal wastewaters with methane production for energy recovery. A membrane bioreactor (MBR) was coupled to the UASB to further improve carbon removal. Nitrogen removal was conducted with the UASB-MBR integrated system under optimum conditions which promoted nitrogen removal through a shortcut nitrification-denitrification process. The process achieved 69–86% of soluble chemical oxygen demand (COD_{solu}) removal and 56–80% of total nitrogen (TN) removal. Biogas production was between 25 and 76 L/m³ wastewater (50–75% methane content) for the treatment of high-strength municipal wastewater. As the anaerobic process combined with a shortcut nitrogen removal step can achieve reduction of footprint, lower greenhouse gas emission and a potential for bioenergy recovery, the integrated UASB-MBR system could be a better choice for municipal wastewater treatment than the conventional activated sludge treatment process in warm climatic conditions.

Key words | membrane bioreactor, shortcut nitrification-denitrification, UASB, water reclamation

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INTRODUCTION

Anaerobic processes have been used for the treatment of wastewater for well over a century (McCarty 1981; McCarty & Smith 1986). In spite of their early introduction, interest in anaerobic systems as the main biological step (secondary treatment) in wastewater treatment was not followed by much use until the development of the up-flow anaerobic sludge blanket (UASB) reactor in the early 1970s (Seghezzi *et al.* 1998). Anaerobic processes have been successfully applied to the treatment of a number of waste streams and are geared mainly towards high-strength industrial wastewater. Recently, however, more efficient anaerobic systems have been developed, and they are being successfully applied for the treatment of low-strength wastewaters such as domestic wastewater, particularly under tropical conditions where heating can be avoided, to reduce costs (Aiyuk *et al.* 2006). Cao & Ang (2009) have reported a coupled UASB-activated sludge process which is feasible for removal of chemical oxygen demand (COD) and nitrogen in municipal sewage treatment in Singapore with its warm climate.

Anaerobic treatment of wastewater can provide several benefits, such as lower energy cost, less sludge production, better sludge characteristics providing easy dewatering and a favorable energy balance due to biogas production. Additionally, anaerobic treatment of wastewater will also reduce greenhouse gas emissions (McCarty 2007). However, effluent from anaerobic reactors rarely complies with stringent effluent discharge specification, nor can it be reused directly in a water reclamation plant because of poor nutrient removal and incomplete carbon reduction. The application of membrane separation techniques allows excellent separation of bio-solids that can achieve superior effluent quality with a smaller footprint and absolute retention of all microorganisms which ensures a complete separation of the hydraulic retention time (HRT) and sludge retention time. An *et al.* (2008) developed an integrated UASB and aerobic membrane bioreactor (MBR) process which allowed performance of nitrification and denitrification via nitrite rather than nitrate; this is called a 'shortcut nitrification-denitrification process'.

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The UASB was specially designed not only to retain a high carbon level for denitrification via nitrite and for methanogenesis but also ensured low C/N ratio effluent feeds to the MBR to perform partial nitrification. This hybrid technology has attracted attention because it offers several advantages over conventional biological nitrogen removal via nitrate, such as a theoretical 25% saving in oxygen consumption, 40% carbon resource saving in the denitrification process, 1.5–2.0 times higher denitrification rate, lower sludge production and lower CO₂ emissions (Van Kempen *et al.* 2009; Peng & Zhu 2006). The objective of this study was to examine the feasibility of a combined UASB-MBR process for the treatment of municipal wastewaters in warm climatic conditions.

METHOD

Experimental setup

The laboratory-scale shortcut nitrification-denitrification system, consisting of a UASB and MBR, used in the study is shown in Figure 1. It consisted of two units, a

UASB unit and an aerobic MBR unit. The UASB unit was a cylindrical tank with a conical-shaped bottom (82 mm internal diameter, 700 mm total height). A three-phase separator was installed at the top of the tank to separate the biogas from the mixed liquor as well as to retain suspended particles in the reactor. An overflow line was located above the three-phase separator, which was connected to the aerobic MBR with a 6 L working volume. The MBR contained a flat-sheet membrane module (PVDF, hydrophilic, pore size: 0.22 μm, Millipore, USA). Membrane permeate was continuously removed from the MBR by a suction pump (Masterflex, Cole-Parmer, USA). The MBR mixed liquor was recirculated to the bottom of the UASB by a pump. The permeate flow rate was regulated by a level sensor so as to equal the feed flow rate.

Wastewater characteristics

The wastewaters used in this study were collected from points after the primary settling tank at the Ulu Pandan Water Reclamation Plant (UPWRP) and Jurong Water Reclamation Plant (JWRP) in Singapore. The wastewaters in

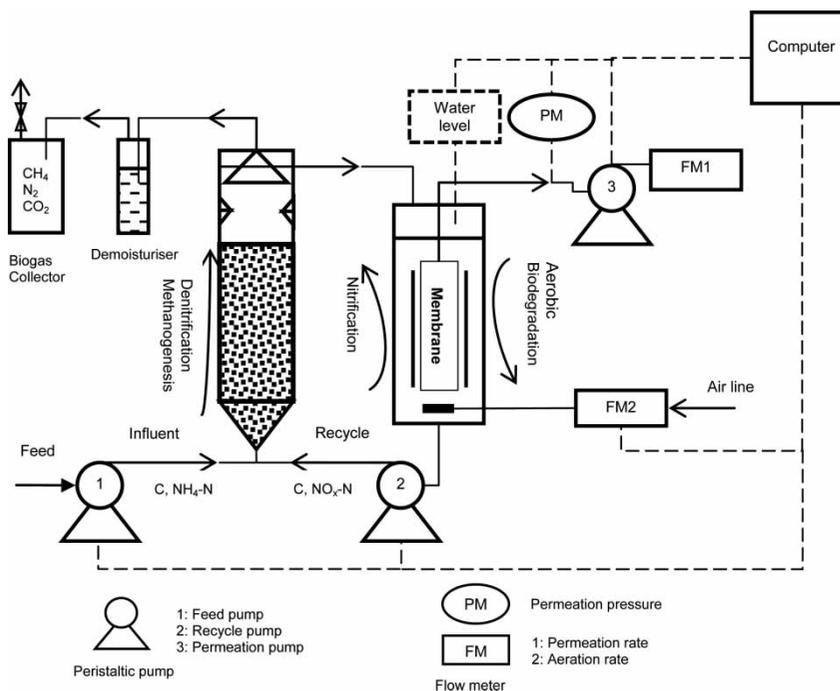


Figure 1 | Schematic of laboratory-scale reactor operation system.

Table 1 | Wastewater characteristics

Wastewater	COD _{solu} (mg/L)	TSS (mg/L)	NH ₄ ⁺ -N (mg/L)	COD _{solu} /NH ₄ ⁺ -N
UPWRP	40–70	50–100	27–38	1–2.4

(Continued)

Table 2 | Operation conditions of UASB-MBR system for wastewater treatment study

Parameters	Water reclamation plant		
	Ulu Pandan	Jurong	Jurong
Operation stage	UPWRP	JWRP1	JWRP2
HRT of UASB/MBR (hr)	3.5/5	8.4/12	4.7/6.7
Recirculation ratio (MBR:UASB)	200%		
pH	7.8–8		
Dissolved oxygen (mg/L)	3.5–4		
Temperature (°C)	30		
Membrane module	0.22 um, hydrophobic PVDF, flat sheet		

HRT: hydraulic retention time.

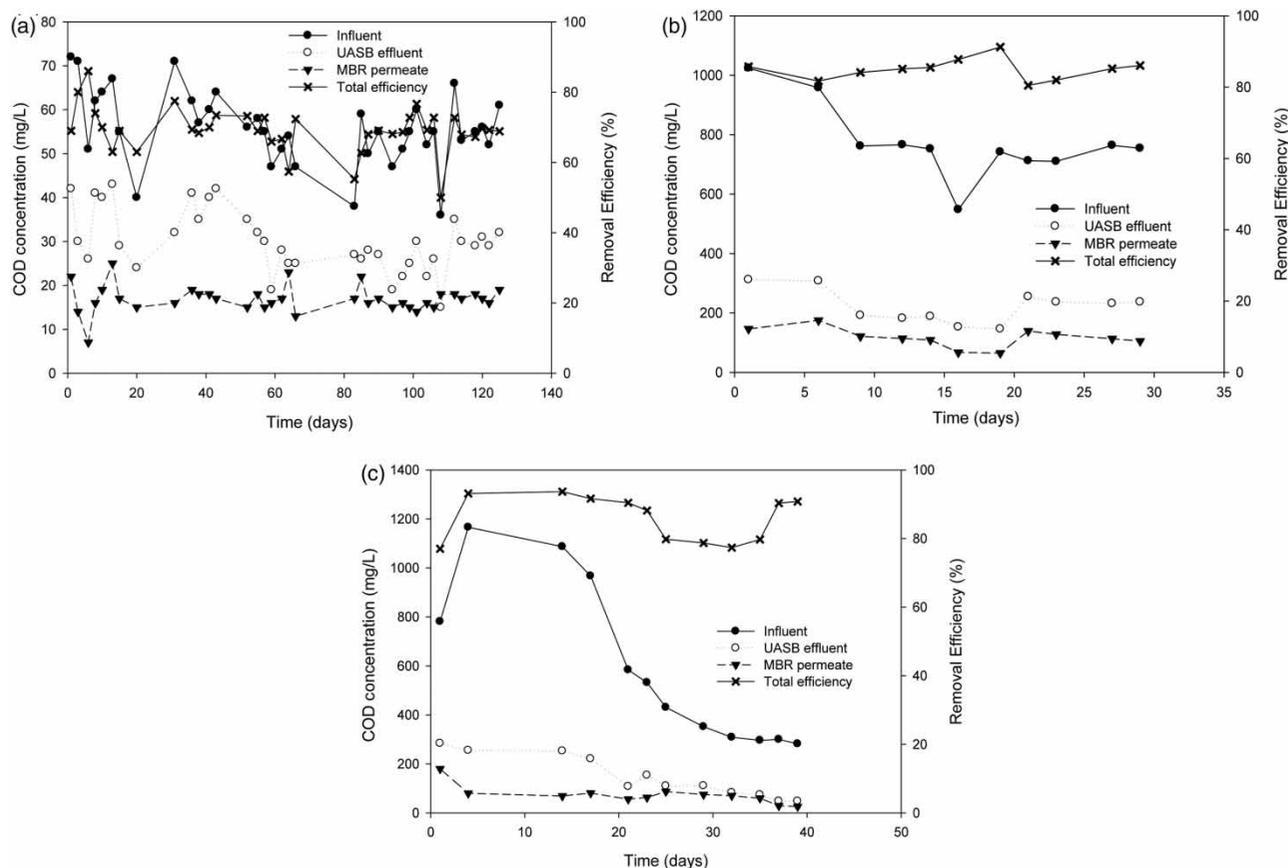
UPWRP and JWRP were both combined streams, which contained both domestic and industrial wastewaters. The main characteristics of the wastewater from UPWRP and JWRP are summarized in Table 1.

Operating conditions

For the treatment of wastewaters from UPWRP and JWRP, the system was operated in three stages and the operating conditions are summarized in Table 2.

Analytical methods

Soluble COD (COD_{solu}), NH₄⁺-N, NO₂⁻-N and NO₃⁻-N concentrations were measured using a spectrophotometer (HACH, DR/2400, Germany). Total nitrogen (TN) was analyzed using a TOC/TN analyzer (Shimadzu, TOC/TN VCSH, Japan). The biogas production was measured by

**Figure 2** | COD_{solu} removal performance in UASB and MBR: (a) UPWRP, (b) JWRP1, (c) JWRP2.

downward water displacement. Methane concentration in the biogas was determined by gas chromatography (Agilent, 6890N, USA).

RESULTS AND DISCUSSION

Figure 2 shows the COD_{solu} removal of the system. Overall removal efficiencies of 69, 85 and 86% were found for the treatment for UPWRP, JWRP1 and JWRP2 wastewaters, respectively. UASB played the major role in COD_{solu} removal as 46, 71 and 76% of COD_{solu} were removed by UASB for UPWRP, JWRP1 and JWRP2 wastewaters, respectively. A similar COD_{solu} removal efficiency (41.5%) using a UASB was reported for the treatment of UPWRP raw sewage by Cao & Ang (2009). The MBR was found to remove relatively small percentages of COD_{solu} compared to the UASB (23, 14 and 10% for UPWRP, JWRP1 and JWRP2, respectively).

This could indicate that the main biological process in MBR was nitrification instead of carbon removal, and nitrifying bacteria could dominate the microbial community in the MBR. The bulk of effluent COD (80–95%) from biological wastewater treatment has been reported to comprise of soluble microbial products (SMPs) (Aquino & Stuckey 2004, 2006; Chalor & Gary, 2007; Janga *et al.* 2007). Anaerobic SMPs were also found to be more complex than the aerobic ones (Zhou *et al.* 2009). So the COD in the UASB effluent in this study could contain mainly SMPs and other non- or slowly degradable organic substances, which are often referred to as ‘hard or refractory COD’ (Schiener *et al.* 1998). This ‘hard or refractory COD’ could explain the limited COD removal in the MBR. Improved COD_{solu} removal efficiencies were found when treating JWRP wastewaters. This could be due to the low COD_{solu} (56 mg/L) concentration in UPWRP wastewater compared to that of JWRP wastewaters (220–1,000 mg/L).

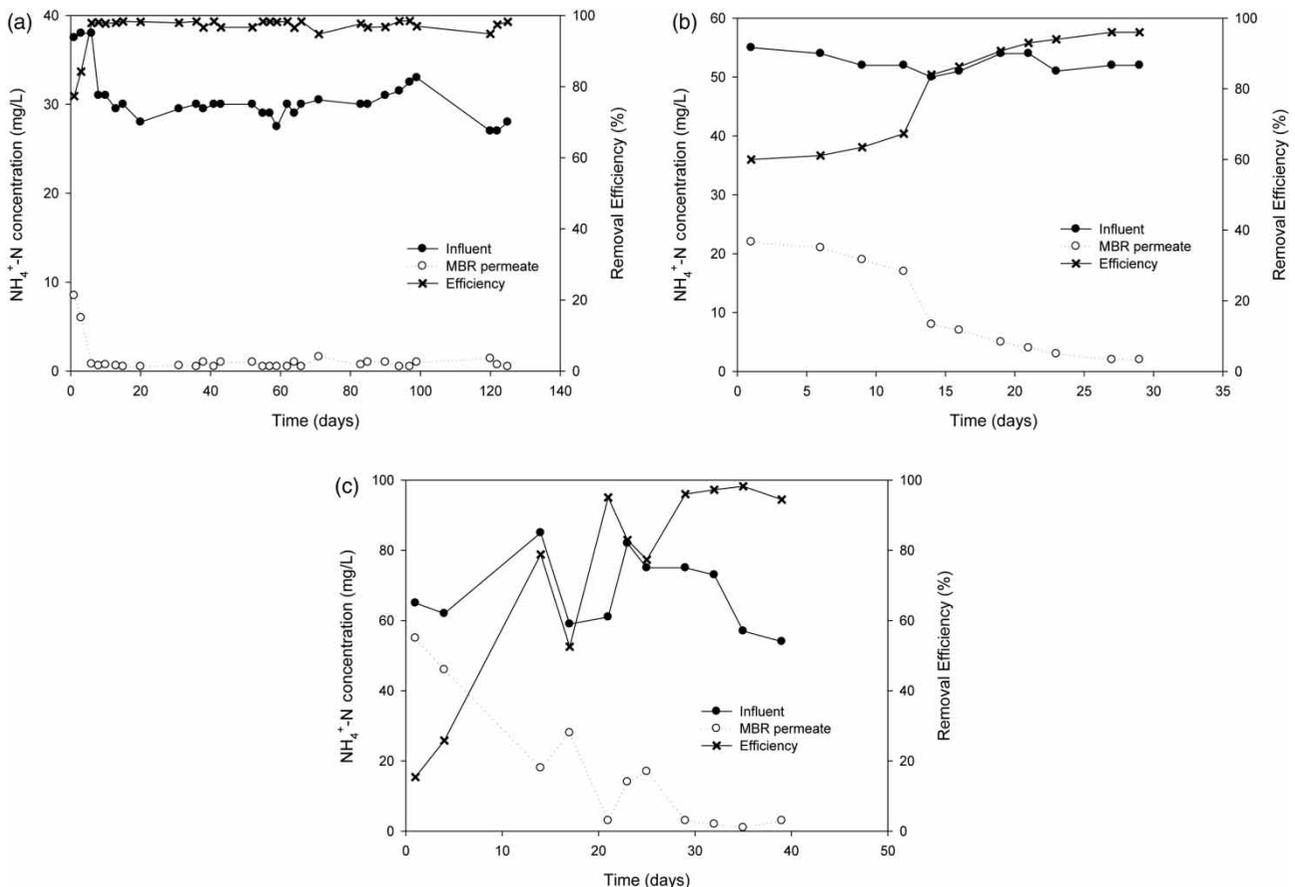


Figure 3 | $\text{NH}_4^+\text{-N}$ removal performance in UASB-MBR system: (a) UPWRP, (b) JWRP1, (c) JWRP2.

Figures 3–5 show the nitrogen removal performance of the system. As shown in Figure 3, the feed $\text{NH}_4^+\text{-N}$ concentrations were around 30 mg/L and 50–70 mg/L for UPWRP and JWRP wastewaters, respectively. Under steady state, up to 96% of $\text{NH}_4^+\text{-N}$ removal was achieved and the effluent $\text{NH}_4^+\text{-N}$ concentration was below 3 mg/L in all the three tests. Nitrite/(nitrite + nitrate) accumulation ratio was found to be 50, 69 and 64% for the treatments of UPWRP, JWRP1 and JWRP2 wastewaters, respectively. Shortcut nitrification could be promoted with the control of operational conditions, which include pH, temperature and dissolved oxygen (DO) concentration (Bae *et al.* 2001; Ruiz *et al.* 2006). In this study, pH was controlled at 7.8–8 and temperature was 30 °C which were similar to the reported values (Bae *et al.* 2001; Ciudad *et al.* 2005; Ruiz *et al.* 2006). DO concentration was controlled at 3.5–4 mg/L which was higher than the reported optimal values of 0.7–1.5 mg/L (Bae *et al.* 2001; Ciudad *et al.* 2005; Ruiz *et al.* 2006). Only a low

aeration rate (0.2–0.5 L/min) was required for the MBR operation, which resulted in a very gentle hydraulic mixing in the MBR. This probably enhanced the development of biofilm in the MBR. Since mass transfer is more efficient for suspended biomass than biofilm biomass, it was suspected that a higher DO level was required for the bulk solution in order to provide an optimum DO level inside the biofilm matrix to perform partial nitrification. This problem was solved later by installing a mixer in the MBR to provide a stronger hydraulic mixing and the DO concentration could be lowered to 0.5–1 mg/L with satisfactory ammonia removal through partial nitrification.

TN removals are shown in Figure 5. About 56% of TN removal efficiency was achieved in the treatment of UPWRP wastewater. Better TN removal efficiency was achieved when treating JWRP wastewaters. About 80 and 73% of removal efficiencies were found in the treatment of JWRP1 and JWRP2 wastewaters, respectively. Higher

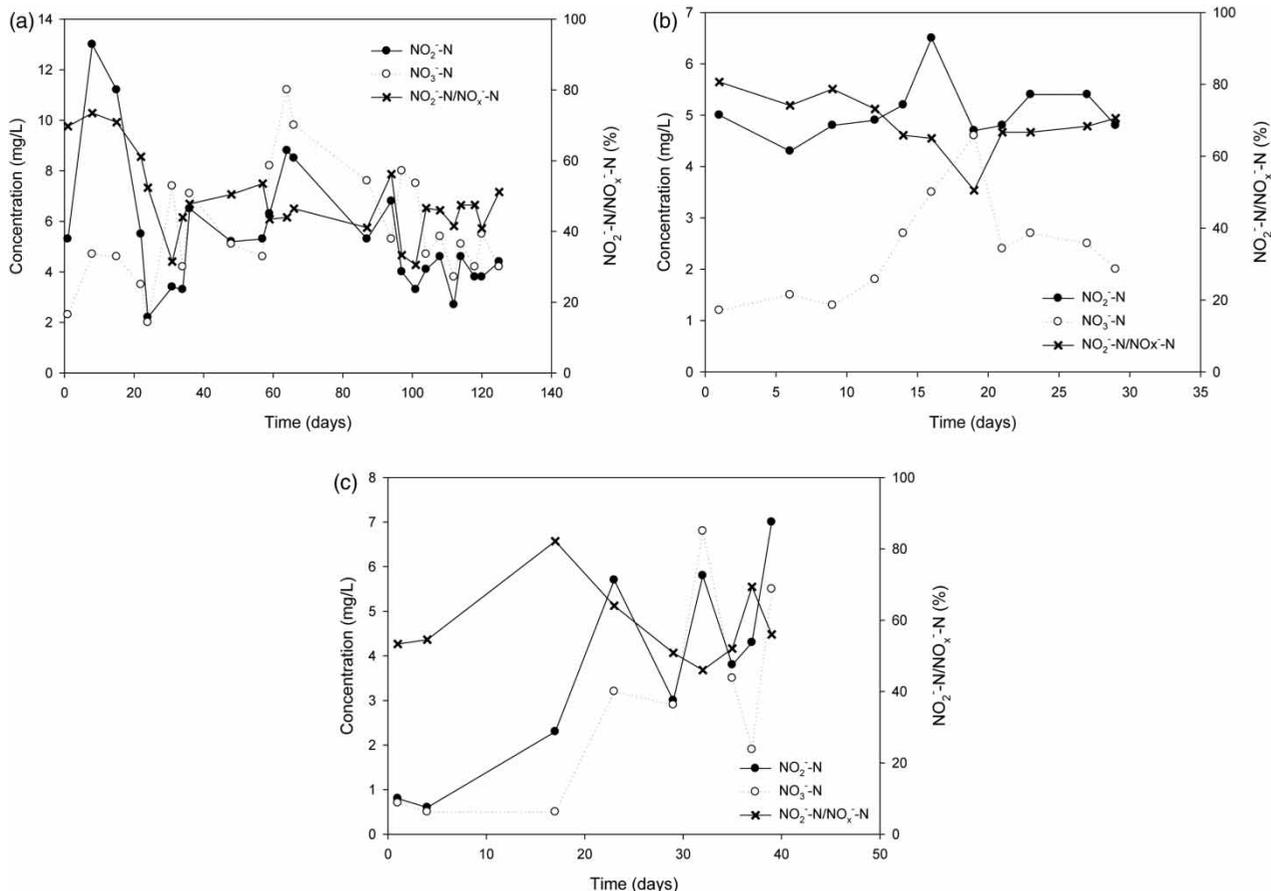


Figure 4 | Nitrite accumulation in UASB-MBR system: (a) UPWRP; (b) JWRP1; (c) JWRP2.

COD/TN ratio could be the cause of higher TN removal in JWRP wastewaters compared to UPWRP wastewater. Average feed COD/TN ratios were 13.2 and 7.6 for JWRP1 and JWRP2 wastewaters, respectively. The feed COD/TN ratio of UPWRP wastewater was only about 1.9. The organic carbon concentration might be too low for the denitrification process in UASB when treating UPWRP wastewater.

Biogas production from the anaerobic process was monitored. Around 1 L biogas per m³ wastewater was produced in the treatment of UPWRP wastewater. Much higher biogas production rate was found when treating JWRP wastewaters: 25–76 L/m³ wastewater. Gas chromatographic analysis showed that the methane composition in the biogas varied from 50 to 75% in different stages of the operation. The extremely low biogas production in the treatment of UPWRP wastewater could be due to the low feed carbon concentration and also the low C/N ratio. Denitrification is a preferential pathway for organic carbon utilization in the

UASB rather than methanogenesis when denitrification via nitrite is proceeding in the UASB (El-Mahrouki & Watson-Craik 2004; Evren Tugtas & Pavlostathis 2007; An *et al.* 2008). So a low C/N ratio might lead to incomplete denitrification and, as a consequence, methanogenesis might be inhibited when treating UPWRP wastewater. Loss of methane via dissolution in effluent from the UASB could also have further contributed to the low volume of biogas in the treatment of UPWRP wastewater in addition to the low carbon concentration of the wastewater.

CONCLUSION

The combined UASB-MBR system was shown to be feasible for treating municipal wastewater for carbon removal with methane production for energy recovery. Shortcut nitrification-denitrification was successfully applied for nitrogen

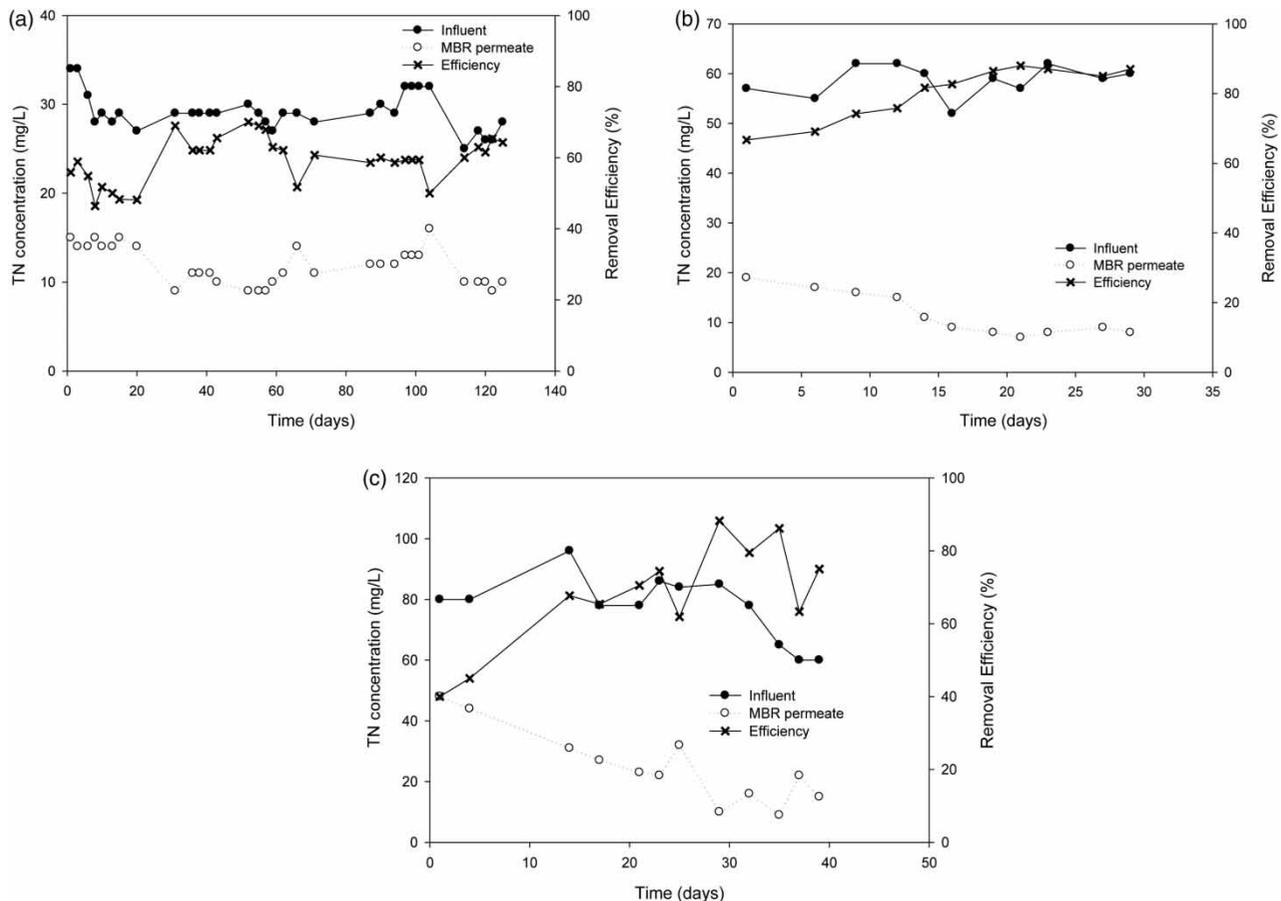


Figure 5 | TN removal performance in UASB-MBR system: (a) UPWRP, (b) JWRP1, (c) JWRP2.

removal. Higher carbon and nitrogen removal was observed when treating more concentrated wastewater (JWRP) with higher energy recovery (higher methane production) compared to lower-strength wastewater (UPWRP). This combined system could potentially be superior to the conventional treatment processes, e.g., activated sludge process, in terms of energy saving, footprint reduction and greenhouse gas emission, especially in warm climate countries.

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