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Modified cesspool system with upflow sludge tank and low-cost photobioreactor treating blackwater

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ABSTRACT

Cesspool system is widely used for household's blackwater treatment in developing countries. Typically, this is a biological treatment process under anaerobic condition, which results in unsatisfactory effluent quality. Effluent or liquid from cesspool system normally seeps into surrounding soil in turn causes groundwater contamination. In this modification, blackwater was treated by a series of upflow sludge tank, photobioreactor and cesspool tank. In the photobioreactor, symbiotic relationship between algae and bacteria was found under aerobic condition, in which the oxygen produced was consumed by bacteria to degrade organics and others. The modified system could achieve much higher removal efficiency than the existing cesspool or the septic tank. In the series of upflow sludge tank and photobioreactor tank of lab-scale experiments with the 2 d of hydraulic retention time, the average effluent chemical oxygen demand concentration was about 120 mg/L, which could possibly meet the effluent standard of Thailand. The flushing effect should be considered for the application in realistic condition. This modification system could be a promising low-cost technology to enhance treatment performance of cesspool system.

Keywords: Blackwater; Cesspool; Photobioreactor; Upflow sludge tank

1. Introduction

In many developing countries, septic tank like on-site sanitation system is commonly applied to treat household's wastewater [1]. Cesspool, one type of septic tank, is a simple wastewater treatment system widely used for treating blackwater from the toilet flushing. Disposed blackwater and fecal sludge in cesspool are later seeped into surrounding soil resulting in severely polluting groundwater as well as spreading of excreta-related pathogens and nitrogen. For the effluent standard of Thailand, chemical oxygen demand (COD), biological oxygen demand (BOD) and suspended solid (SS) concentrations are 120, 20 and 30 mg/L, respectively. Though the final disposal of cesspool system is into soil and the treatment efficiency is quite low, still people use it because of its low-cost (e.g., rowing of cement rings in excavated hole). Previously, many studies toward upgraded or re-designed septic tank for treating domestic wastewater were done, such as filter-based package septic tank [2], upflow septic tank [3] and upflow anaerobic sludge blanket (UASB) septic tank [4]. However, these systems were not that much suitable because of capital cost, cost of installation, configuration and operation. Nowadays, even though modern technologies (such as package septic tank) are available, the perceptions of people about these technologies are not satisfactory. The main reasons behind this are due to high cost and lack of proper drainage network to receive the final effluent from this system. The practice of using cement ring cesspool system is then used for many decades without any

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improvement. In order to improve the treatment performance of cesspool system, this study presents the new idea of retrofitting system by using upflow sludge tank (UST) and photobioreactor (PBR) for treating blackwater and discharging effluent into the existing cesspool system. UST is designed to receive blackwater. The advantages of this technology are as follows: sealed type, light weight, low-cost and easily retrofit to the existing cesspool system. Suspended solid of blackwater is settled in the sedimentation zone and the liquid then flows up through media zone, which promotes microorganism to remove organic substances of wastewater. Then the effluent from UST is further treated in PBR, where treatments are symbiosis processes between algae and bacteria. Using PBR is considerable for the reason that the system is of low-cost and environment-friendly [5]. Photobioreactor has been applied especially in attached form to treat organics and nitrogen of industrial wastewater [6] and to treat nutrient from polluted lake water [7]. Application of microalgal–bacterial biofilm in treating municipal wastewater was also reported in Posadas et al. [5] and Boelee et al. [8]. Therefore, this study was aimed to evaluate the modified cesspool system with UST coupled with low-cost photobioreactor.

2. Materials and methods

2.1. Experimental setup

The experimental setup of this study was conducted in lab-scale (Fig. 1(a)) and pilot-scale units (Fig. 1(b)). The lab-scale experiment was carried out using standalone UST and PBR, while the pilot-scale experiment was undertaken by PBR subsequently connected to UST in field. The individual test of lab-scale PBR was conducted after the test of UST in order to improve the treatment performance. Lab-scale UST and PBR experiments were set up at the ambient laboratory of Asian Institute of Technology (AIT). The configurations of lab-scale UST units were identical cylindrical plastic tanks made by polyethylene (PE) of 40 cm internal diameter and 94 cm height. The effective volume of the reactor was 90 L. The tank had two partitions or zones, that is, bottom zone (sludge storage zone) and media zone (flow stabilization zone). The specific surface area of media in UST was 90 m^2/m^3. In lab-scale PBR, the reactor of 24 L made by transparent acrylic plastic that allows the sunlight to pass through it. This PBR contained attached-growth algal media, low-cost media

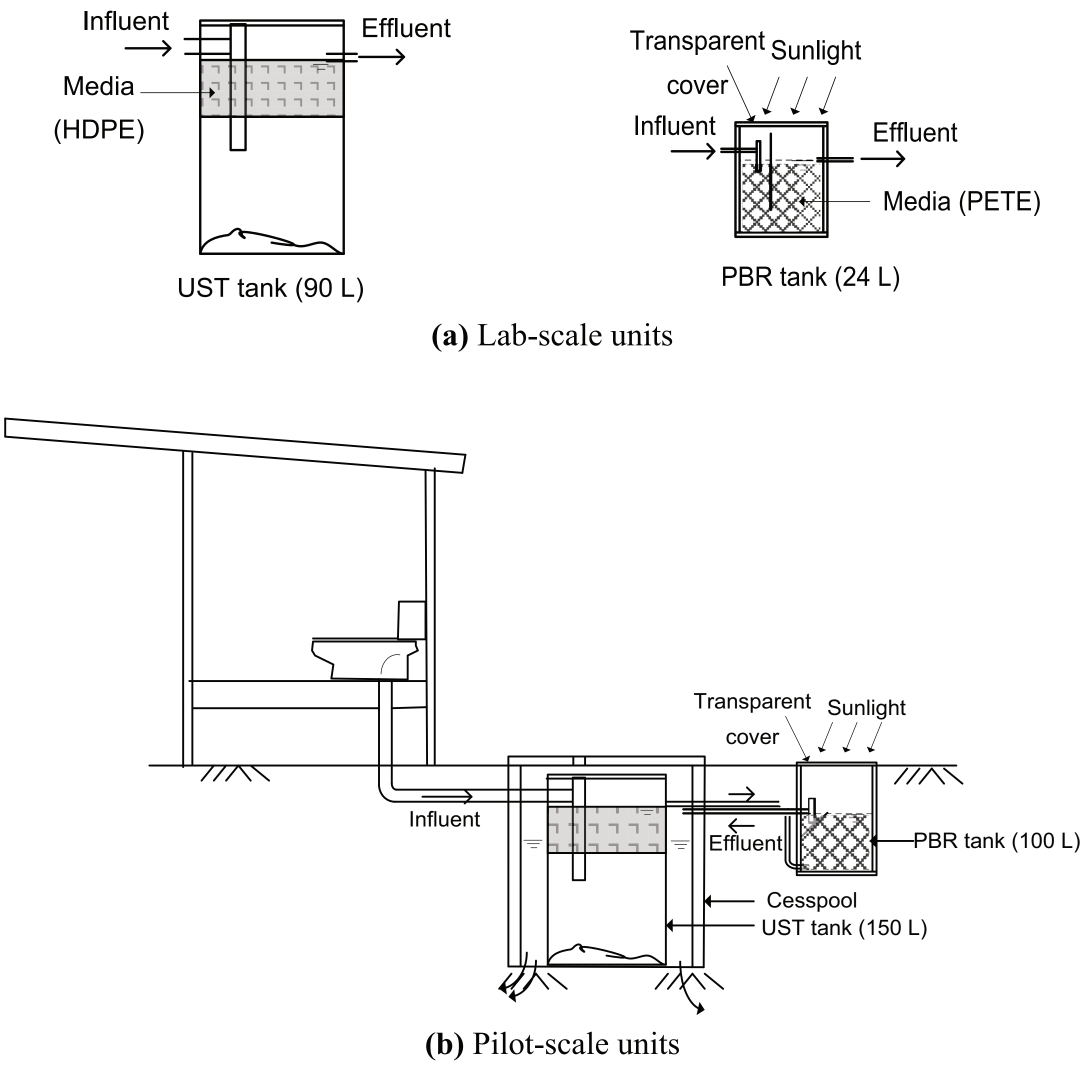

Fig. 1. Setup of (a) lab-scale and (b) pilot-scale experiments.

made by reused plastic bottle, polyethylene terephthalate (PETE). The specific area of this media was 90 m^2/m^3. For the pilot-scale, a general household nearby AIT consisted of five members having cesspool system was selected. Plastic UST of 150 L capacity was installed inside cesspool system. Another plastic PBR tank of capacity 100 L was installed and connected outside cesspool system in a series. Coverlid of the PBR was transparent in order to allow sunlight to expose to media of which specific area of 90 m^2/m^3. In the process operation, blackwater was run through UST, effluent from UST was further treated by PBR and final effluent from PBR was later discharged into the cesspool.

Method of start-up for both lab- and pilot-scale USTs was modified from previous studies [3,4]. The start-up period of UST was undertaken for 30 d at an average temperature of 30°C. For the start-up of PBR, algal inoculum procedure was modified from the previous study [9]. Hence, a medium of algal inoculums was prepared by the mixture of three parts pond water from AIT pond and seven parts of effluent water from septic tank. Then, reused plastic materials (PETE) shown in Fig. 2(a) were placed in the medium for 20 d for the growth of algae on plastic media (Fig. 2(b)). The obtained algal media was later used in the PBR and the start-up period was 30 d. This PBR system showed the uses of low-cost material, transparent plastic media, for hosting attached growth biofilm of algae and bacteria. The major cost of modified cesspool system was the plastic tank while the reuse of plastic media was very little cost. In which, roughly the estimation at the pilot-scale of this study, the cost of modified cesspool system by the series of UST and PBR was about US$200. This study had applied kinetic model of first-order to UST which described as the completely mixed reactor [10]. Meanwhile, Stover–Kincannon kinetic model was applied to PBR as the biofilm reactor [11].

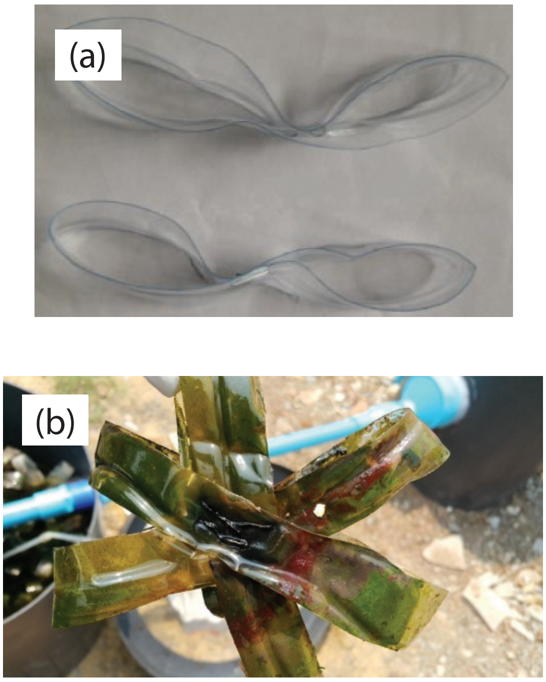

Fig. 2. (a) Reused plastic bottle (PETE) as algal-media strip and (b) algal-media strip after the growth of algae.

2.2. Operational conditions

The synthetic blackwater was obtained by mixing fecal sludge from package septic tank with raw domestic wastewater from AIT campus, which was later used as influent for lab-scale UST. In addition, effluent from package septic tank was used as influent fed to lab-scale PBR. Meanwhile, the real blackwater used for pilot-scale UST was taken from the toilet of selected household and effluent from pilot-scale UST was influent to pilot-scale PBR. Characteristics of blackwater and operational conditions used in UST and PBR for lab-scale and pilot-scale experiments are shown in Table 1. In lab-scale experiments of UST, 90, 45 and 30 L influent per day were fed into the reactor intermittently at hydraulic retention time (HRT) of 1, 2 and 3 d, respectively. Meanwhile, PBR units were operated at HRT of 1, 2 and 3 d in lab-scale experiments. The optimum HRT was later used for pilot-scale experiments. Both lab- and pilot-scale PBRs were illuminated by sunlight with the average light intensity of 860 ± 707 µmol/m^2/s (measured by MQ-200 Apogee® quantum meter, during 06.00 am to 06.00 pm).

Table 1
Characteristics of influent blackwater of UST and PBR and loadings

Experiment	Lab-scale						Pilot-scale	
Reactor	UST	PBR	UST	PBR	UST	PBR	UST	PBR[a]
HRT (d)	1	1	2	2	3	3	1.5	1
COD (mg/L)	2,267 ± 535	203 ± 120	2,247 ± 940	241 ± 108	2,790 ± 785	243 ± 94	1,114 ± 965	301 ± 202
SS (mg/L)	3,224 ± 463	94 ± 28	2,644 ± 788	77 ± 34	3,742 ± 777	94 ± 12	1,050 ± 416	160 ± 61
TN (mg/L)[b]	163 ± 16	125 ± 14	169 ± 10	119 ± 7	176 ± 16	126 ± 16	247 ± 98	143 ± 52
OLR (gCOD/d/L)[c]	2.27	0.20	1.12	0.12	0.93	0.08	0.45	0.30
NLR (gTN/d/L)[c]	0.16	0.13	0.08	0.06	0.06	0.04	0.16	0.14

[a]Effluent from UST pilot-scale unit.
[b]NO_3^-–N and NO_2^-–N concentrations in influent blackwater were less than 1.0 mg/L.
[c]Calculated from average value.

3. Results and discussion

3.1. Removal efficiencies of UST

Results from lab-scale UST experiments are expressed in Table 2. The average concentrations of COD, SS and total nitrogen (TN) in effluents of each experiment were not much different in each HRT. Percentage removals were reported in Fig. 3 while the kinetic models were obtained from graphs in Fig. 4.

Table 2 and Fig. 3(a) reveal results of SS removal efficiencies in lab-scale UST. Maximum SS removal efficiency of 95% was observed at HRT of 3 d, resulting in 187 mg/L of SS concentration at effluent. Meanwhile, SS removal efficiency of UST was 95% and 94% when it was operated at HRT of 2 and 1 d, respectively. Organic removal efficiencies in lab-scale UST units are shown in Fig. 3(b). Average COD concentrations in effluent of UST at HRT of 1, 2 and 3 d were 226, 225 and 223 mg/L, and COD removal efficiencies were 90%, 90% and 92% in UST, respectively. Compared with the effluent of package septic tank, COD of 460 ± 110 mg/L [3], effluent COD concentrations in this study were about the same range. Similar to solid matters, concentrations of COD were related to concentration of SS in the effluent. In which, results of organic removals were corresponded to the suspended solid removals in the upflow at anaerobic treatment system [12]. For nitrogen, removal efficiencies in lab-scale UST are presented in Fig. 3(c). They were slightly increased from 41% to 49% and then 51% operated at HRT of 1, 2 and 3 d, respectively. The removals of organic matters in UST indicated that most of organic matters were settled in this tank. However, the removals due to biodegradable are very low as seen from the reductions of TN about 50%. This is because of the anaerobic condition in this UST tank.

From the mentioned results of the lab-scale UST, the optimum HRT of 1 d was selected for the further step of experiment because there was no significant different results between the HRT of 1, 2 and 3 d in terms of solid and organic removals. However, a sizing of pilot-scale UST at the HRT of 1.5 d was set up in order to cover the fluctuation of actual loads at the household level. SS removal efficiency about 82% was determined in pilot-scale UST. Therefore, the comparatively lower SS removal efficiency in the pilot-scale UST could be due the fluctuation of daily toilet uses during the peak flow, especially in morning and evening times. In which, the upflow velocity might exceed the settling velocity as reported in other studies [3,12]. Meanwhile, only 63% of COD removal efficiency was found in pilot-scale of UST with an effluent concentration 301 mg/L. In addition, 41% of TN removal efficiency was observed. The lower organic removals in pilot-scale experiments could be possible due to the effect of hydraulic loading of real flushing practices as mentioned in the lower SS removals. Moreover, the different characteristics of blackwater could be another factor. In order to prevent the flushing effect, distribution of flow and slowly releasing techniques might be needed in the realistic implementation. Similar to the removal in lab-scale experiments, TN removals in UST of pilot-scale units could be explained by the settling of particulate organic nitrogen accumulated to the bottom sludge. However, accumulated organic nitrogen in sludge bed might not completely altered by hydrolysis and acidification into ammonium nitrogen [4].

Table 2
Effluent concentrations from lab-scale and pilot-scale UST experiments

HRT (d)	Lab-scale			Pilot-scale
	1	2	3	1.5
COD (mg/L)	226 ± 43	225 ± 13	223 ± 57	301 ± 202
SS (mg/L)	193 ± 25	132 ± 16	187 ± 38	189 ± 38
TN (mg/L)	96 ± 9	86 ± 9	86 ± 7	146 ± 48

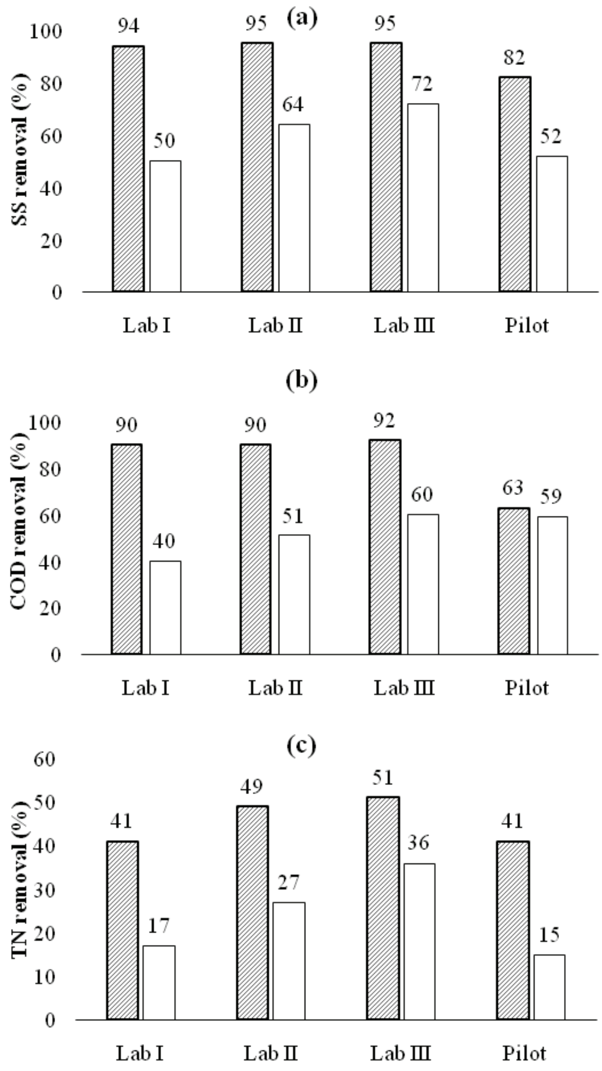

Fig. 3. Percentage of (a) SS, (b) COD and (c) TN removal efficiencies by UST (▨) and PBR (☐).

3.2. Removal efficiencies of PBR

Similar to UST experiments, results of PBR in lab-scale and pilot-scale are shown in Table 3. At HRT of 1, 2 and 3 d in lab-scale PBR, SS removal efficiencies were 50%, 64% and 72%,

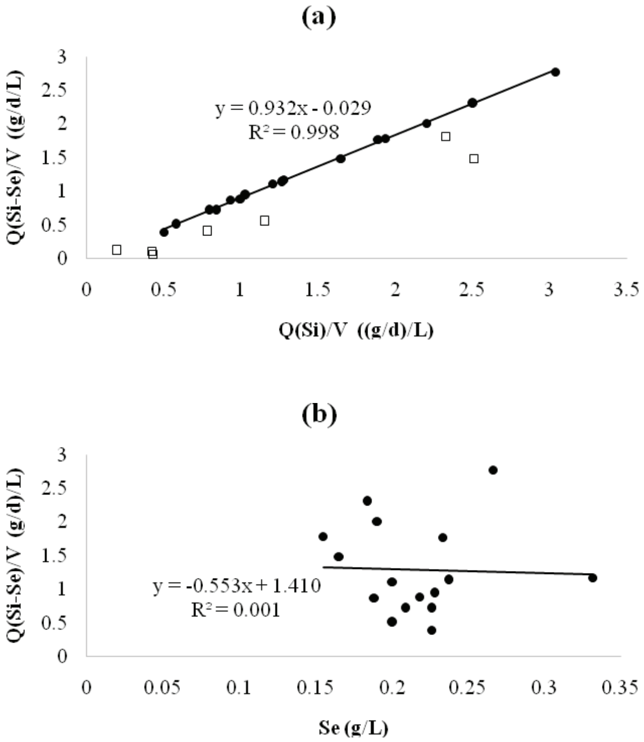

Fig. 4. Relationship between (a) organic removal rate (ORR) vs. organic loading rate (OLR) and (b) first-order rate for organic removal in lab-scale (●) and pilot-scale (□) of UST.

showing the final concentrations as 47, 33 and 26 mg/L, respectively (Fig. 3(a)). The COD removal efficiencies were increased with increasing HRT from 41% to 55% and 61%, respectively (Fig. 3(b)). Meanwhile, the final effluent of lab-scale showed the COD concentrations between 94 and 120 mg/L. Dissolved oxygen (DO) concentrations were observed within range of 2–13 mg/L in lab-scale units. This could indicate that organics were degradable by aerobic heterotrophs in PBR. The relation of two processes of algae and aerobic bacteria in the same reactor was called as a symbiosis system to achieve organic removals in PBR [8]. In another study, it was also found that COD could achieve 70% reduction by algal–bacterial system in PBR treating synthetic urine wastewater [13], and 50%–60% of COD reduction in PBR treating swine slurry [14]. Results of nitrogen removal efficiencies of PBR are demonstrated in Fig. 3(c). Lab-scale PBR performed 19%, 27% and 36% of TN removal efficiencies at HRT of 1, 2 and 3 d, respectively. The results of effluents indicated that at least 40% reduction of organics could be achieved and the effluent concentration could meet the effluent standard. Therefore, the HRT of 1 d was selected as the optimum condition according to qualified COD concentration with the effluent standard.

In pilot-scale PBR, 52% of SS removal efficiency representing the concentration as 77 mg/L was found at the average HRT of 1 d. Meanwhile, 38% of COD removal efficiency was found with the effluent COD concentration of higher than 120 mg/L. The result was higher than results from lab-scale experiment and the limit of effluent standard. This might result from the effect of hydraulic load to UST and continually affected the PBR. However, the observed DO concentrations were within range of 2–6.5 mg/L. Therefore,

Table 3
Effluent concentrations from lab-scale and pilot-scale PBR experiments

HRT (d)	Lab-scale			Pilot-scale
	1	2	3	1
COD (mg/L)	120 ± 13	108 ± 13	94 ± 23	186 ± 131
SS (mg/L)	47 ± 9	33 ± 6	26 ± 4	77 ± 10
TN (mg/L)	101 ± 13	87 ± 7	81 ± 11	122 ± 63

15% of TN removal efficiency was found in pilot-scale PBR at HRT of 1 d. The removal efficiencies in pilot-scale experiment were closed to the results in lab-scale experiments. It was mentioned that removed nitrogen was mainly assimilated into algae cell in PBR as majority of nitrogen form in the wastewater was inorganic nitrogen [15]. In contrast, although even DO concentrations were more than 2 mg/L in both lab- and pilot-scale of PBR, the NO_3^-–N concentrations resulted from nitrification process were lower than 1 mg/L. It could be explained by the inhibition by light as mentioned by Sinha and Annachhatre [16] and Vanzella et al. [17]. Even though the COD concentration of treated backwater from the modified series of UST and PBR in the pilot-scale could not meet the effluent standard of Thailand as higher than 120 mg/L, there was the possibility to improvement. Therefore, flow distribution and reducing the flushing effects as mentioned earlier would be the challenges.

3.3. Organic removal rates in UST

Based on lab-scale UST experiments, organic removal rates (ORR) and organic loading rates (OLR) were observed as significantly relation to linear correlation (R^2 = 0.99) as shown in Fig. 4(a). Relationship between ORR and OLR in lab-scale of UST indicated that ORR increased with increasing of OLR, for example, obtaining ORR of 2.23 g COD/L/d from OLR of 2.31 COD/L/d. The removal rate was similar to the previous study [2]. Relationship between ORR and OLR in the pilot-scale UST also has similar trend to the lab-scale. In addition, when applied the ORRs with modified first-order model in completely mixed flow reactor (CMFR), the organic removals were not related to the first-order (R^2 = 0.001) as presented in Fig. 4(b). This could be ascribed by the sedimentation process that plays an important role as found in SS and COD removals. Thus, the improvement of flow distribution as mentioned earlier will be the key successes for the organic removals in this tank.

3.4. Organic removal rates in PBR

In PBR, ORR had significantly related to OLR (R^2 = 0.81) and ORR increased with the increasing of OLR (Fig. 5(a)). ORRs within the range of 0.04–0.10 g COD/d/$L_{reactor}$ (0.44–1.11 g COD/d/m^2_{media}) were achieved in lab-scale PBR. The results were lower than the previous study, which was reported 1.3 g COD/d/$L_{reactor}$ of ORR in PBR biofilm treating urine wastewater [13]. It was stated that increasing of OLR in algal–bacterial biofilm system could enhance capacity of ORR [8]. However, feeding more than 3.09 g COD/d/m^2_{media}

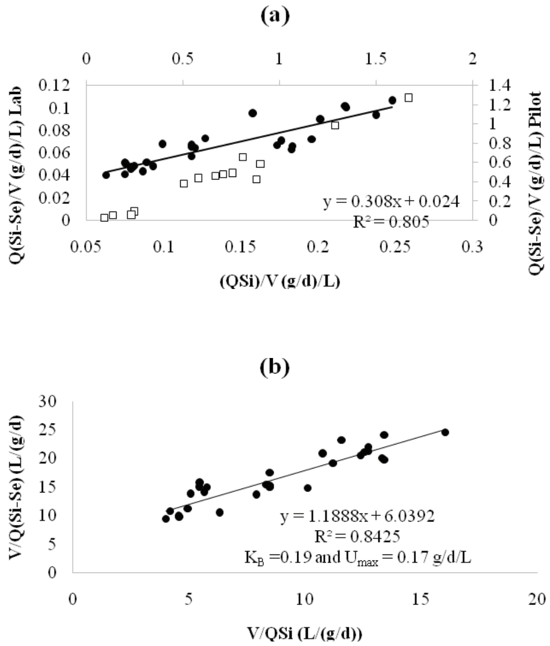

Fig. 5. Relationship between (a) organic removal rate vs. organic loading rate and (b) Stover–Kincannon kinetic model in lab-scale (●) and pilot-scale (□) of PBR.

of OLR to algal–bacterial system could result in heterotrophs overgrowing autotrophic organism such as nitrifying bacteria and algal–biofilm on support media in PBR [18]. According to Yu et al. [19], Stover–Kincannon kinetic model was originally applied for substrate removal by biofilm in rotating biological contactor system in which suspended biomass was negligible. Moreover, applications of this model were also conducted in anaerobic hybrid reactor [20], anaerobic filter reactor [21], anaerobic packed column reactor [22], an integrated rotating biological contactor-activated sludge system (RBC-AS) [23] and UASB reactor [24]. For algal–bacterial biofilm in this study, Stover–Kincannon kinetic model was then applied and results are shown in Fig. 5(b). Linear plotting between V/Q(Si-Se) or 1/ORR and V/QSi or 1/OLR shows the applicable model for organic removal prediction (R^2=0.84) which Stover-Kincannon kinetics; saturation value constant (K_B) and maximum removal rate constant (U_{max}) were 0.19 and 0.17 g/d/$L_{reactor}$, respectively. Comparing with the Stover–Kincannon kinetics of biofilm system as RBC-AS, the K_B and U_{max} of 15.2 and 14.8 g/d/$L_{reactor}$ [23], the kinetics of PBR was very low. This might be due to the low OLR fed to the PBR in this study. Moreover, amount of heterotrophic organisms on the supported media might be less. The correlation between amount of microorganisms and the enhancing number of microorganism in PBR system are recommended to investigate for the further research. However, obtained ORRs in series of UST and PBR from this study could be possibly used to modify the cesspool system in order to achieve the effluent standard.

4. Conclusion

Symbiotic relationship between algae and bacteria was found in PBR under aerobic condition in which bacteria consumed produced oxygen to degrade organics and others. DO concentrations in PBR were higher than 2 mg/L. Modified cesspool by the series of UST and PBR could improve the treatment performance of existing cesspool system to meet the qualified level of COD concentration in lab-scale experiment at the total HRT of 2 d. Obtained ORR was in between range of 0.40–2.77 gCOD/L/d in UST and 0.04–0.10 gCOD/L/d in PBR. In realistic application, the improvement or further study on hydraulic loading of flushing and real blackwater application are needed to considerations.

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