Performance comparison of uninsulated and insulated hybrid anaerobic baffled reactor (HABR) operating at warm temperature

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ABSTRACT

In this research, a hybrid anaerobic baffled reactor (HABR) configuration was proposed consisting of a front sedimentation chamber, four regular baffled chambers followed by two floated filter media chambers for the treatment of domestic wastewater. Performance comparison of uninsulated and insulated HABRs was carried out operating at warm temperature (18.6–37.6 °C) under variable HRTs (30 h and 20 h). The study suggests that almost similar COD (91% vs 88%), TSS (90% vs 95%), Turbidity (98% vs 97%), and VSS (90% vs 93%) removal efficiencies for uninsulated and insulated HABRs. Higher nitrogen removal TN of 41%, NH_4^+-N of 44%, and NO_3^--N of 91% were achieved by insulated HABR compare to TN of 37%, NH_4^+-N of 36%, and NO_3^--N of 84% by uninsulated HABR, whereas lower PO_4^{3-} removal efficiency of 17% was found in insulated HABR compare to 24% in uninsulated HABR. This indicated insulation increased nitrogen removal efficiencies by 4% for TN, 8% for NH_4^+-N, 7% for NO_3^--N, but decreased PO_4^{3-}removal efficiency by 7%.

Key words | anaerobic treatment, domestic wastewater, hybrid anaerobic baffled reactor (HABR), insulated HABR, warm temperature

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INTRODUCTION

The world is facing a global sanitation crisis in regards to wastewater management, about 70% of wastewater is treated in high-income countries, 38% in upper-middle-income, 28% in lower-middle-income, and only 8% in low-income countries (Sato *et al.* 2013). On the other hand, most of these low-income and lower-middle-income counties are located either in subtropical or tropical region with warm climate (15–35 °C), which is favourable for biological wastewater treatment. In addition, most of these countries also have electricity deficit, which makes difficult to promote aerobic treatment options (Libhaber 2012).

Over the last few decades, anaerobic technology has become widely adopted owing to its advantages of energy saving, biogas recovery, and lower sludge production (Liew Abdullah *et al.* 2005; Feng *et al.* 2009). One of the most efficient high-rate anaerobic reactor is the Anaerobic Baffled Reactor (ABR) developed by McCarty and co-workers at Stanford University (Bachmann 1985). A traditional ABR consists of a series of vertical baffles which force the wastewater flow under and over them as it passes from the inlet to the outlet (Wang *et al.* 2016). The advantages of this bioreactor include low maintenance requirements, rapid biodegradation, low stable sludge yields, excellent process stability on organic and hydraulic shock loads, simple and inexpensive construction, and stable operation without requirements for pumping and electricity (Chan *et al.* 2009; Reynaud & Buckley 2016).

The major drawback of ABR is that there are very few full-scale ABR applications for wastewater treatment till now. One of the major concerns is reported by researchers (Bwapwa 2012; Zhu *et al.* 2015; Reynaud & Buckley 2016) about sludge/solid washout from the system during

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operation. Sludge washout ultimately affects ABR treatment efficiency, as a consequence, a poor effluent quality. Sludge washout is directly influenced by reactor up-flow velocity. Higher velocity tends more washout and lower velocity tends to overcome this problem. In order to having an optimum reactor volume and minimizing the washout problem, filter media can be used; however, this also increases risk of clogging and/or maintenance. Alternatively, the fluidized bed reactor also has been reported to have higher treatment efficiency with more than 90% (Metcalf & Eddy 2003), which also needs energy for pumping wastewater upward. Most importantly, when comparing with the traditional aerobic process, anaerobic treatment system also processes poor effluent quality, which usually needs post-treatment to meet the discharge limits. Further research on advanced reactor design and control process, ABR could lead to most of its disadvantages being overcome. Perhaps, ABR may be one of the solutions answering the global call for low-maintenance, robust treatment systems (Reynaud & Buckley 2016), which can be easily adopted in those above mentioned countries.

In addition, temperature has a significant effect on the reactor treatment efficiency. Researchers (Nachaiyasit & Stuckey 1997; Feng *et al.* 2008; Wu *et al.* 2016) have shown that treatment efficiencies of the ABR changed with temperature variations. Similar findings have been reported in their studies that there was no or low effect on treatment efficiency when operated at 25–35 °C; but the reactor efficiency deteriorated significantly when the temperature dropped below 15 °C. To overcome temperature effects, deceasing HRT or heating of wastewater could achieve higher removal efficiency (Zhu *et al.* 2015), which also results cost effectiveness of the system.

The construction of a particular reactor is crucial since it has a strong impact on the whole treatment efficiency and capital costs. Selection of proper operating parameters including hydraulic retention time (HRT), organic loading rate (OLR), nutrients ratio, wastewater concentration, temperature, pH and so on are also crucial for the ABR process (Barber & Stuckey 1999; Feng *et al.* 2008). Controlling or modifying of wastewater nutrients, concentration and/or pH will involve process complexity and cost. Therefore, this research work is emphasizing on performance evaluation of an insulated HABR (assuming maximum thermal controlled under insulated condition) within mesophilic range, i.e. 30–35 °C. The overall objectives of this research work are to propose a HABR configuration with improved design concepts and principles; and examine and validate the optimum pollutant removal efficiency of HABR with or without insulation operating at warm temperature (18.6–37.6 °C) condition within the mesophilic ranges (30–35 °C).

MATERIALS AND METHODS

Reactor configuration and operation

The schematic diagram of the proposed HABR is shown in Figure 1, and summarized in Table 1. Two identical HABRs uninsulated (U) and insulated (I) were constructed using acrylic sheet with external dimensions of 90, 20, and 30 cm for length, width, and depth, respectively. The effective volume of uninsulated and insulated reactor were 36.38 L and 36.39 L, respectively. Each HABR consisted of a front sedimentation chamber (U-1 and I-1), four regular chambers (U-2 to U-5, and I-2 to I-5) followed by two floated

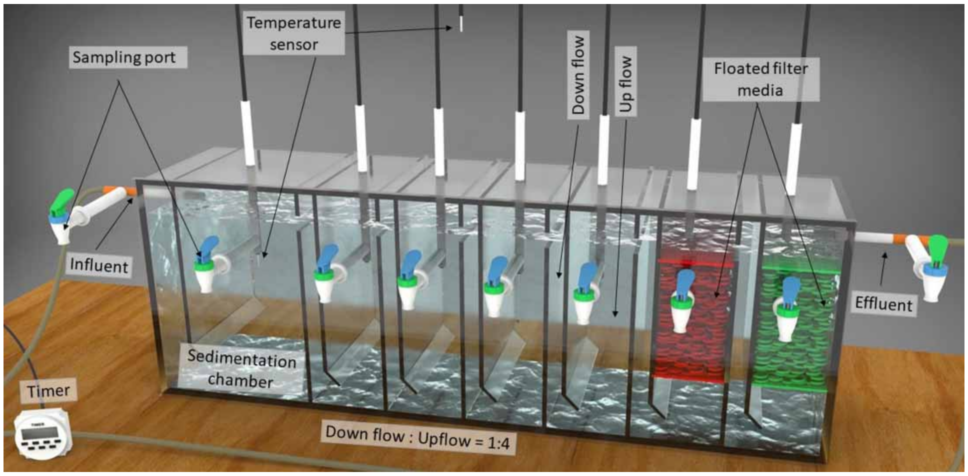


Figure 1 | Schematic of the hybrid anaerobic baffled reactor (HABR).

Table 1 | Summary of HABR configuration (identical for uninsulated and insulated)

Design Parameter	Specification
ABR dimensions	90 cm (L) × 20 cm (W) × 30 cm (H)
Effective volume	36.4 L
First chamber/settler	2 V (where, V- volume of subsequent chamber)
Deflector angle of hanging baffle	45°
Down-flow/Up-flow	1:4
Type of filter media	Floated filter media (shredded soft drink lid), density – 109 kg/m^3, Specific gravity – 0.93) (grinding of soft drink lid)
Sampling Port	20 cm (from base) at center
In-let/out-let	In-let (27 cm from base); Out-let (25 cm from base)

filter media chambers (U-6 and U-7; and I-6 and I-7). The first chamber volume, designed as settling chamber, was twice than the subsequent chambers. The individual chamber was again divided into two portions by hanging baffle, which separated each chamber in down- and up-flow zone. The ratio between down-flow and up-flow was 1:4, and the bottom portion of the baffle was inclined at 45°. Each chamber had a sampling port located at 20 cm from the base on the front side of each reactor. Approximately, 400 gm of shredded (e.g. making small pieces) soft drink lid were loosely placed as floated filter media in last two chambers of each reactor (Table 1). These locally available materials were used due to their favourable physical properties that won't let the reactor failure for clogging during wastewater treatment. Polyurethane foam (Pu Foam, Boya, Korea) was used for insulating one HABR by applying liquid foam layer (up to 2 inch) and let it dry at room temperature (21–25 °C). Arduino UNIO technology with DS18B20 waterproof digital temperature sensor connected to data logger system was also installed in each compartment for temperature monitoring during operation as presented in Table 2. Each compartment has 3 mm vent pipe (located behind temperature sensors pipe) to exhaust gas (e.g. methane).

Both HABRs, uninsulated and insulated, were operated under the same ambient conditions to evaluate the treatment efficiencies. Domestic wastewater was collected from KUET (Khulna University of Engineering & Technology, Khulna, Bangladesh) campus residential area, and stored in a feed tank equipped with mixture for uniform feed strength. The characteristics of raw wastewater is presented in Table 3. The wastewater was then fed to both HABRs continuously (running system 24/7) using a peristaltic pump (WT600-1F, Longer pump Co., China) which was connected to a Sino-timer (Sino timer, China). The timer was programmed to run the system (feeding reactors) for 10 min/hr (maintaining hourly flow rate 1.213 L in 10 mins for 30 h HRT, and 1.819 L in 10 mins for 20 h HRT) during the entire experiment. The hydraulic retention time (HRT) of both reactors was 30 h for first 40 days and then 20 h for remaining 10 days.

Table 2 | Summary of temperature sensors data for uninsulated and insulated HABR

Uninsulated HABR:	Raw (Up)	U-1	U-2	U-3	U-4	U-5	U-6	U-7	Air Temp
Min	18.6	23.1	22.9	23.4	23.2	23.0	22.9	22.4	19.0
Max	36.2	36.2	35.8	35.9	35.6	35.3	35.2	35.3	37.4
Average	28.5	29.8	29.3	29.7	29.6	29.4	29.3	29.1	28.2
Std. dev.	3.2	2.8	2.7	2.5	2.5	2.4	2.5	2.7	4.1
Insulated HABR	**Raw (Down)**	**I-1**	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**Air Temp**
Min	18.8	22.8	22.7	22.6	22.4	22.6	22.9	22.9	18.6
Max	35.8	34.8	35.4	35.3	34.9	35.3	35.2	35.0	37.6
Average	28.2	28.6	28.6	28.5	28.4	28.6	28.8	28.8	27.9
Std. dev.	3.0	1.6	1.6	1.5	1.5	1.4	1.4	1.4	4.2

Table 3 | Characteristics of influent wastewater

		Influent concentration	
Parameter	**Unit**	**Uninsulated HABR**	**Insulated HABR**
pH	–	8.0 ± 0.2	8.1 ± 0.2
EC	mS/cm	2.7 ± 0.1	2.6 ± 0.3
Turbidity	NTU	556.2 ± 445.5	595.4 ± 430.1
ORP	mV	53.7 ± 19.4	62.7 ± 27.2
DO	mg/L	2.7 ± 1.1	3.0 ± 1.5
TKN	mg/L	68.5 ± 31.3	69.3 ± 31.5
NH_4^+-N	mg/L	57.9 ± 23.4	57.1 ± 23.0
NO_3^--N	mg/L	38.5 ± 68.2	42.3 ± 58.0
NO_2^--N	mg/L	20.5 ± 39.6	19.4 ± 38.3
TN	mg/L	130.7 ± 70.3	135.6 ± 67.8
COD	mg/L	546 ± 136	589 ± 133
TSS	mg/L	325.7 ± 228.2	498.6 ± 327.4
VSS	mg/L	200 ± 136.8	280.0 ± 188.9
PO_4^{3-}	mg/L	26.3 ± 9.5	25.4 ± 18.7

Reactor inoculum

Each HABR was inoculated with septic sludge collected from KUET campus residential area. The septic sludge was sieved using 2.0 mm mesh prior adding into reactor. Approximately 18.2 L (3.2 L for first chamber and 1.5 L for each chamber 2–5) of sludge was added to chamber 1 to 5, the remaining volume being filled with septic tank effluent including chambers 6 and 7. This seeded sludge contributed substantially to the solid requirement in the reactor system after settling. The sieved sludge contained total solids of 8,960 ± 1,824 mg/L and total volatile solids of 6,880 ± 1,137 mg/L. After inoculating, both HABRs were left at ambient temperature for 30 d without further modification.

Sampling and analysis

Wastewater samples were collected from nine sampling points; raw (U-R and I-R), seven sampling ports of each HABR (U-1 to U-7, and I-1 to I-7), and effluent (U-E and I-E). Raw and effluent samples were analyzed for pH, electrical conductivity (EC), turbidity, dissolved oxygen (DO), oxygen redox potential (ORP), total kjeldahl nitrogen (TKN), ammonia-N (NH_4^+-N), nitrate-N (NO_3^--N), nitrite-N (NO_2^--N), total chemical oxygen demand (COD), total suspended solid (TSS), volatile suspended solid (VSS), and Orthophosphate (PO_4^{3-}) according to the standard methods (APHA *et al.* 2005). Samples collected from reactor chambers were also analyzed for selected parameters.

Hydrodynamic flow characteristics

The hydraulic characteristics of the proposed HABR (uninsulated) configuration were also determined based on the residence time distribution (RTD) study by tracer stimulus-response technology (Ji *et al.* 2012; Li *et al.* 2015, 2016; Wang *et al.* 2016) prior feeding with wastewater. Nine

Table 4 | Average effluent and final removal efficiency for uninsulated and insulated HABRs

		Effluent concentration		Final removal efficiency (%)	
Parameter	**Unit**	**Uninsulated HABR**	**Insulated HABR**	**Uninsulated HABR**	**Insulated HABR**
pH	–	8.0 ± 0.2	8.0 ± 0.1	–	–
EC	mS/cm	2.6 ± 0.2	2.7 ± 0.2	–	–
Turbidity	NTU	8.5 ± 6.8	11.7 ± 8.1	–	–
ORP	mV	105 ± 18.9	61.7 ± 20.8	–	–
DO	mg/L	4.3 ± 1.5	3.2 ± 0.8	–	–
NH_4^+-N	mg/L	42.9 ± 16.4	53.9 ± 26.8	36 ± 24	44 ± 29
NO_3^--N	mg/L	29.0 ± 34.2	18.7 ± 25.9	84 ± 6	91 ± 5
NO_2^--N	mg/L	21.5 ± 30.2	13.0 ± 26.0	–	–
TN	mg/L	108.8 ± 66.9	93.4 ± 55.1	37 ± 27	41 ± 27
COD	mg/L	45 ± 31	75 ± 51	91 ± 6	88 ± 7
TSS	mg/L	13.3 ± 5.2	16.7 ± 18.6	90 ± 12	95 ± 7
VSS	mg/L	8.3 ± 4.1	10.0 ± 8.9	90 ± 11	93 ± 13
PO_4^{3-}	mg/L	28.5 ± 25.4	42.3 ± 34.2	24 ± 10	17 ± 9

experimental runs A (A1, A2, and A3); B (B1, B2, and B3); and C (C1, C2, and C3) were conducted using a peristaltic pump to investigate the hydraulic behaviour of the HABR at different HRTs (5, 10, and 20 h) under variable influent temperature (10, 25, and 40 °C) using tap water. NUVE BM30 water bath was used to maintained influent temperature. Sodium chloride (NaCl) was used as the tracer due to its various favourable features as described by Li *et al.* (Li *et al.* 2015, 2016). To obtain the RTD curves, 200 mL concentrated NaCl solution (42.5 gm Cl^-/Cl) was instantaneously injected prior to the inlet. The water samples were collected from the sampling port of each

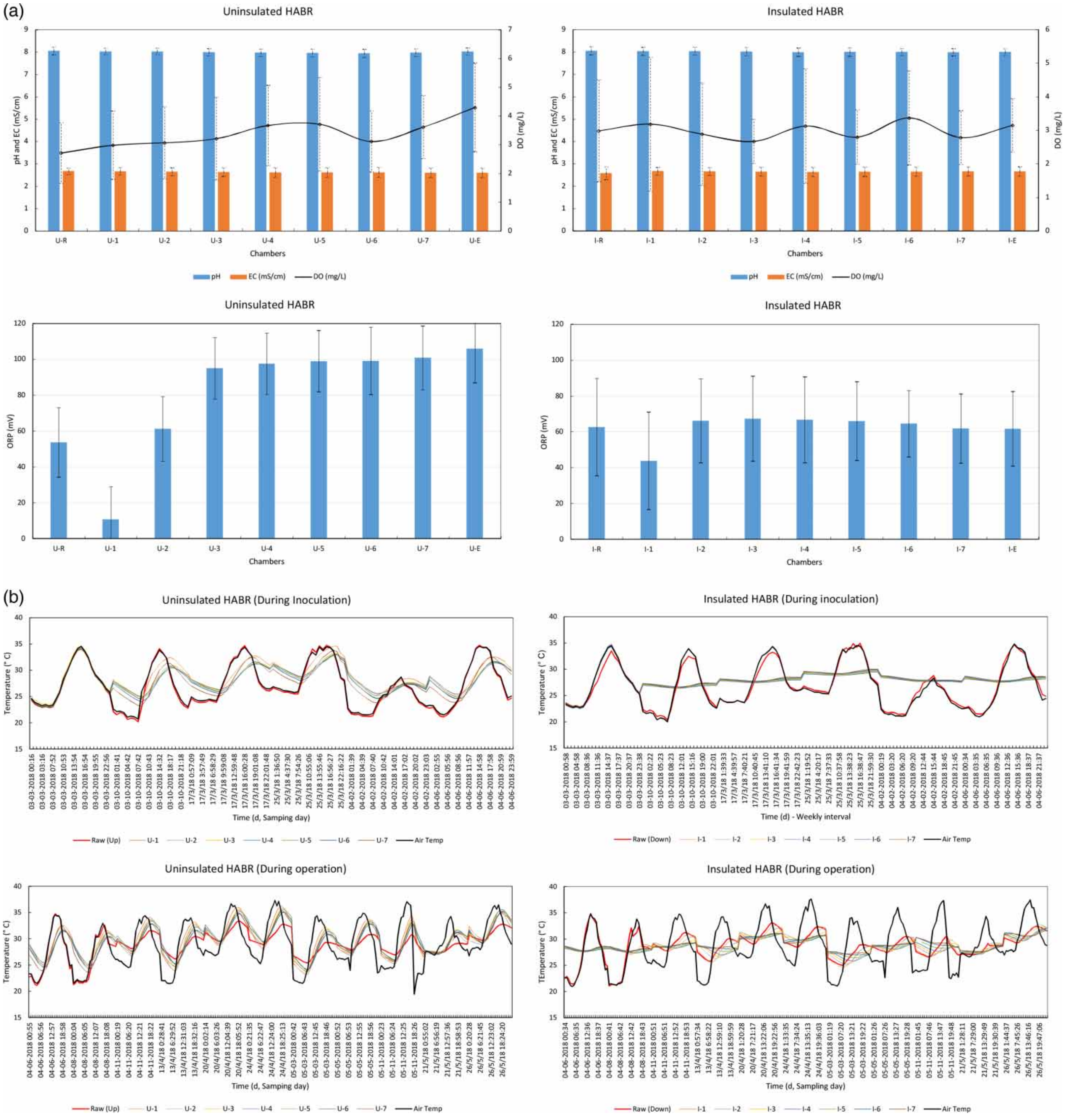


Figure 2 | (a) Average pH, EC, DO, and ORP of raw, seven chambers (1–7), and effluent of uninsulated and insulated HABRs. (b) Temperature data of raw, seven chambers (1–7), and effluent during inoculation and sampling date for both reactors.

chamber and the effluent of the reactor at regularly-spaced intervals from the time of impulse (t = 0), and the total sampling time was 2.5 times the nominal HRT. The chloride ion (Cl^-) concentration was measured using a conductivity meter (Model CD-4302, Lutron, Taiwan) after calibrating with standard conductivity solution (Model CD-14, 1.413 mS) (Levenspiel 1999).

Theoretical interpretation of hydrodynamic study

To compare the mixing patterns of different runs, the unit of time is normalized:

$$\theta = \frac{t}{HRT} \tag{1}$$

where θ is the normalized time (dimensionless), t is the sampling time, and HRT is the theoretical hydraulic retention time.

$$C_\theta = \frac{C(t)}{C_0} \tag{2}$$

where C_θ is the normalized tracer concentration at dimensionless time θ, $C(t)$ is the tracer concentration at time t, and C_0 is the initial tracer concentration.

The C-curves (C vs θ), determined as a function of the normalized tracer concentration Equation (2) against the normalized time Equation (1). These curves were further analyzed to calculate the mean residence time ($\bar{t}$) by Equation (3) and variance (σ_t^2) by Equation (4). (Wang *et al.* 2016).

$$\bar{t} = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} = \int_0^\infty tE(t)dt \tag{3}$$

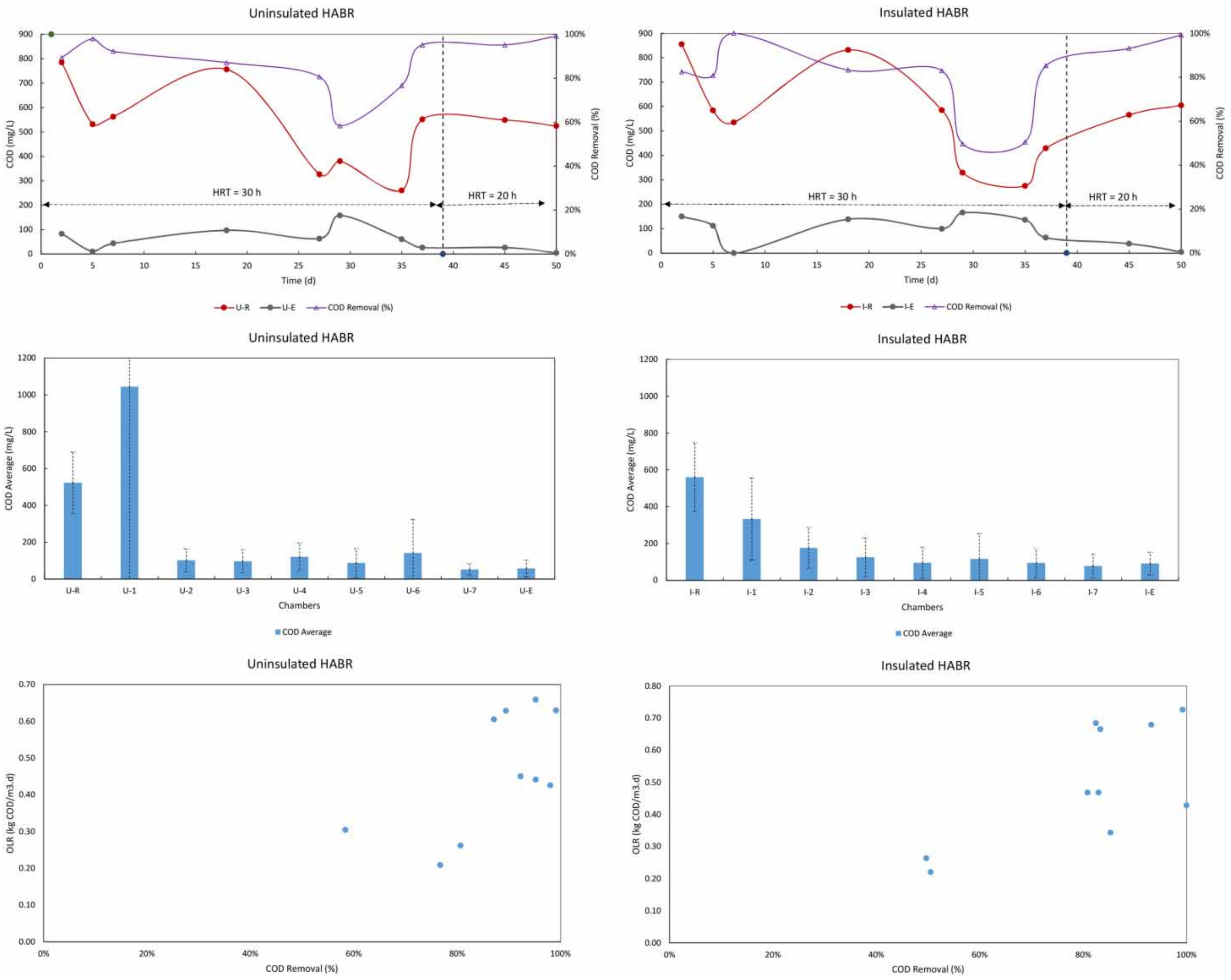


Figure 3 | COD concentration and COD removal, average COD, and OLR of uninsulated and insulated HABRs.

$$\sigma_t^2 = \frac{\int_0^\infty (t-\bar{t})^2 C(t)dt}{\int_0^\infty C(t)dt} = \int_0^\infty t^2 E(t)dt - (\bar{t})^2 \tag{4}$$

The fraction of the dead space (V_d, %) in the reactor is calculated using Equation (5) as explained by Ji *et al.* (2012) and Li *et al.* (2016):

$$V_d = \left(1 - \frac{\bar{t}}{HRT}\right) \times 100\% \tag{5}$$

For a closed-vessel boundary condition, in which only axial mixing is considered, Equation (6) is used to obtain normalized variance as a function of dispersion number (D/uL) (Levenspiel 1999).

$$\sigma_\theta^2 = 2\left(\frac{D}{uL}\right) - 2\left(\frac{D}{uL}\right)^2\left(1 - e^{-\frac{uL}{D}}\right) \tag{6}$$

where, D is the axial dispersion coefficient, u is the average fluid velocity, L is the axial distance of the reactor, and σ_θ^2 is the dimensionless variance of RTD, $\sigma_\theta^2 = \sigma_t^2/(\bar{t})^2$.

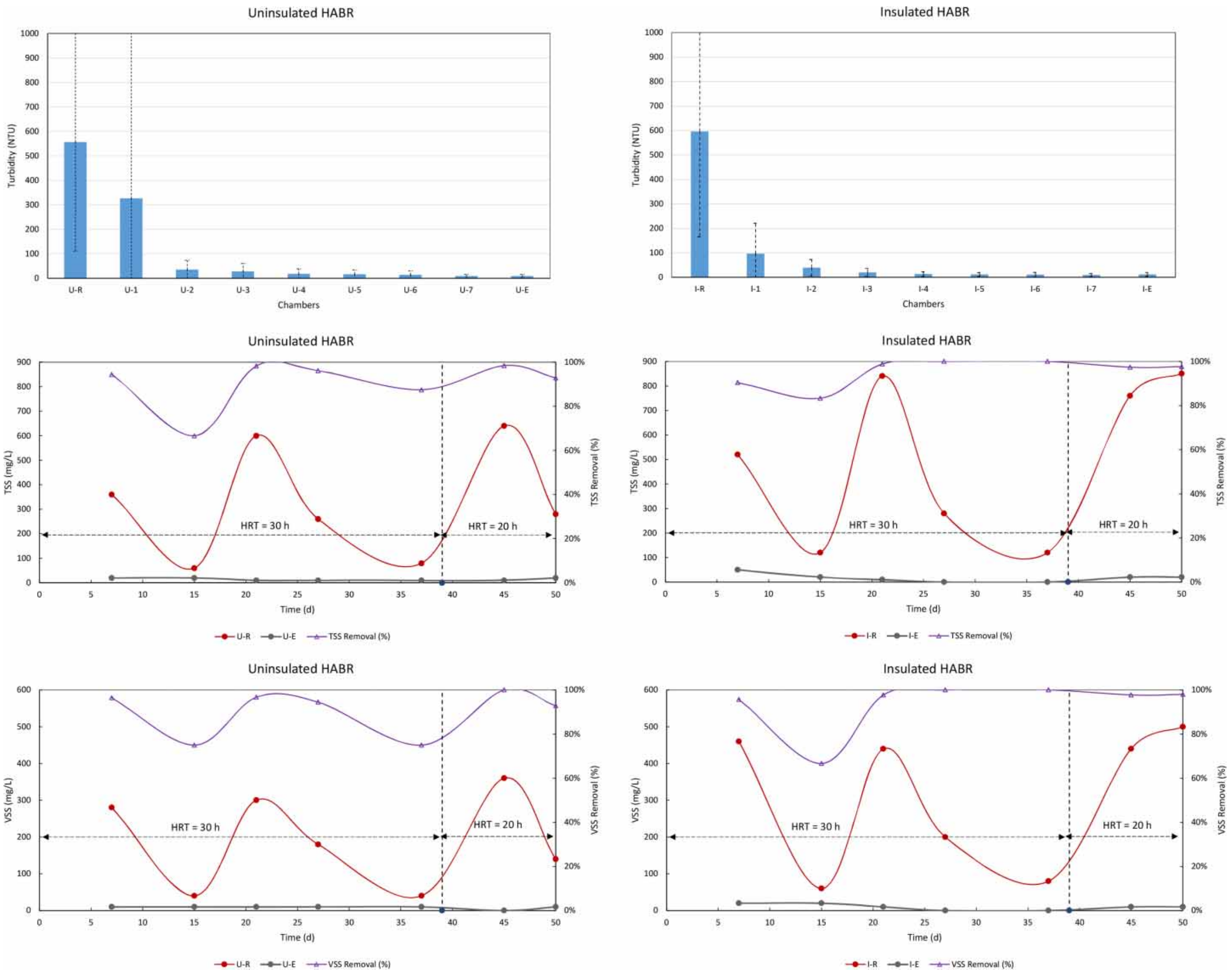
Alternatively, peclet number (*Pe*) is often used to expressed the mixing pattern, which is just the reciprocal of the dispersion number ($Pe = uL/D$).

In a tank-in-series (TIS) model, the equivalence number of perfectly-mixed TIS (N) can be calculated by Equation (7) below.

$$N = \frac{1}{\sigma_\theta^2} \tag{7}$$

If N tends to 1, the flow pattern of the rector approaches that of continuous stirred tank reactor (CSTR). On the other hand, when N tends to ∞, the flow pattern approached as a plug flow.

The hydraulic efficiency (λ) includes two basic features: (i) the distribution of flow across the reactor and (ii) the


Uninsulated HABR

Insulated HABR

Figure 4 | Turbidity, TSS, and VSS removal of uninsulated and insulated HABRs.

mixing of reaction liquid (Ji *et al.* 2012). It is dependent on the effective volume (e) and the flow pattern as expressed in Equation (8):

$$\lambda = e\left(1 - \frac{1}{N}\right) \tag{8}$$

The effective volume (e) is calculated by subtracting the value of dead space from 1. The hydraulic efficiency of the system can be classified into three categories: (1) excellent hydraulic efficiency with $\lambda > 0.75$, (2) good hydraulic efficiency with $0.5 < \lambda \leq 0.75$, and (3) poor hydraulic efficiency with $\lambda \leq 0.5$.

Statistical analysis

Data analysis was performed with Excel and Design-Expert 10. The one-way ANOVA were used to determine the significance of the analytical results and difference between groups, and $P < 0.05$ was considered as significant.

RESULTS AND DISCUSSION

In the study, pH, EC, OPR, DO were monitored for raw (U-R and I-R), samples from each chamber of both HABRs (U-1 to U-7, and I-1 to I-7), and effluent (U-E and I-E) samples as presented in Tables 3–4, and Figure 2(a). The results show pH 8.0 ± 0.2 and 8.1 ± 0.2, EC 2.7 ± 0.1 and 2.6 ± 0.3, ORP 53.7 ± 19.4 and 62.7 ± 27.2, and DO 2.7 ± 1.1 and 3.0 ± 1.5 of raw wastewater for uninsulated and insulated HABRs, respectively. This indicates a favourable oxic/anoxic condition existed in both reactors for organics biodegradation, nitrification/denitrification/anammox processes. Arduino UNIO temperature data are presented in Table 2

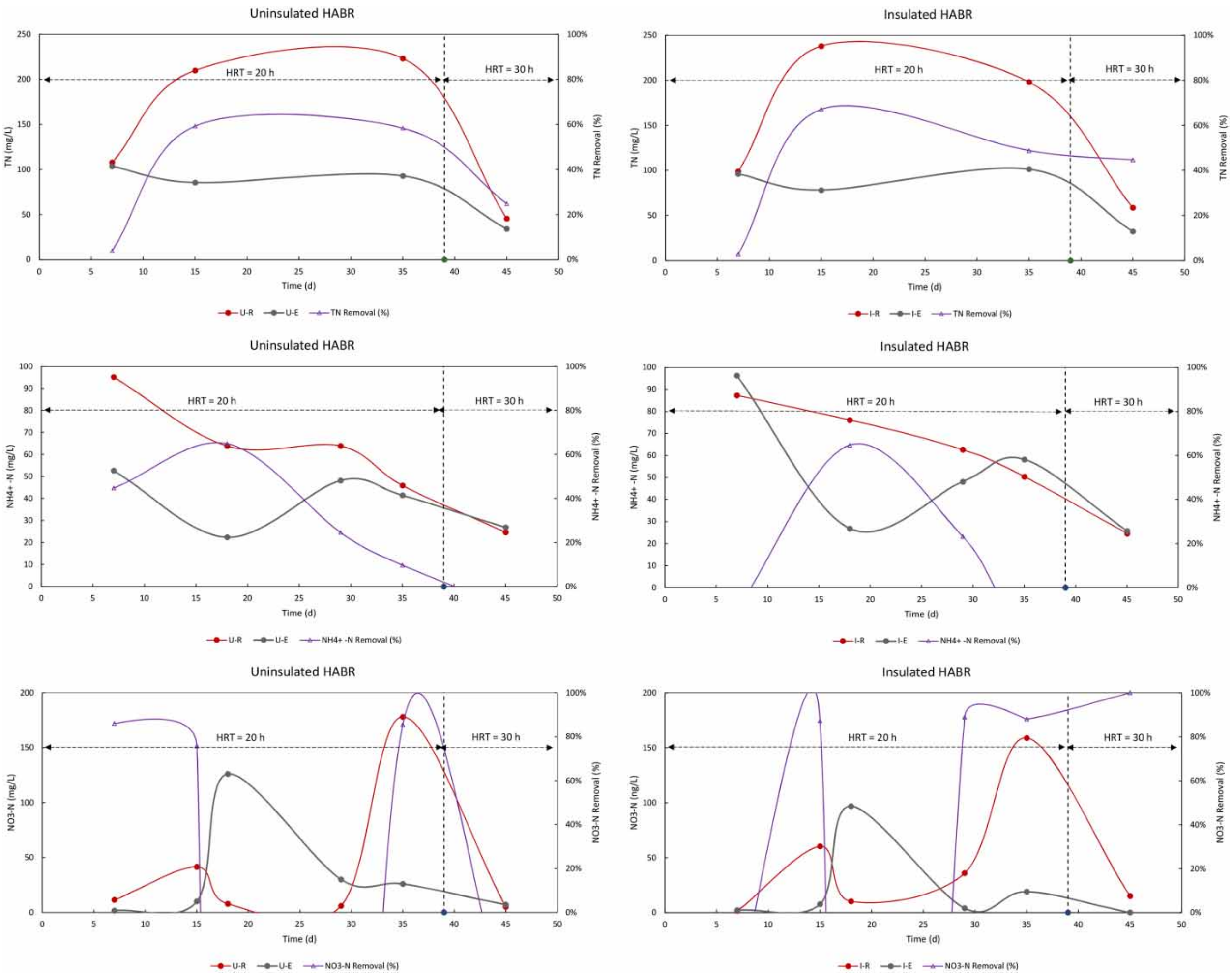


Figure 5 | TN, NH_4^+-N, NO_3^--N removal of uninsulated and insulated HABRs.

and Figure 2(b). It appeared that the insulation provided a better temperature control in insulated HABR during inoculation and operation. Figure 2(b) suggests a significant temperature variation in uninsulated HABR, a minimum variation in insulated HABR. This ultimately affects the HABR treatment efficiency.

COD removal

COD removal efficiencies for both uninsulated and insulated HABRs are shown in Figure 3. As the actual domestic wastewater was used for the experiments, the influent COD concentrations were observed to be varying (Bodkhe 2009). Influent wastewater COD ranges were 261–785 mg/L and 275–855 mg/L for uninsulated and insulated HABR, respectively. It appeared that the COD removal efficiencies for both reactors fluctuated during this experiments, it actually followed the pattern of the influent COD. The COD removal efficiencies were 58%–99% for uninsulated, and 50%–100% for insulated HABR, respectively. The OLR were 0.21–0.66 kgCOD/m^3.d for uninsulated, and 0.22–0.73 kgCOD/m^3.d for insulated HABR, respectively. The results indicate the COD removal is directly influenced by OLR (Bodkhe 2009; Lu *et al.* 2011). No significant influence on COD removal efficiency was observed because of insulation of the HABR. Figure 3 also shows that average COD

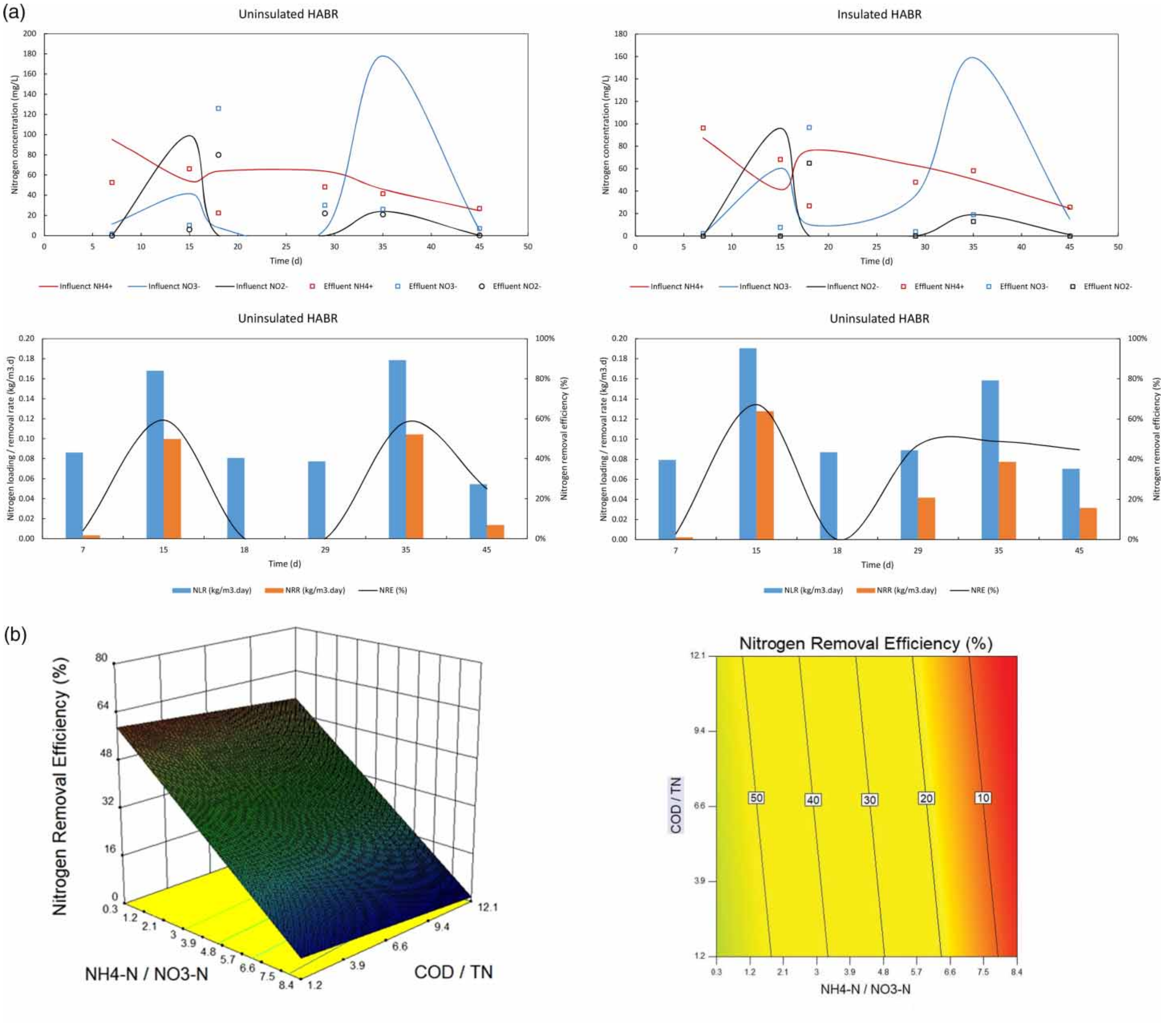


Figure 6 | (a) Influent and effluent N (NH_4^+-N, NO_3^--N, NO_2^--N), and NLR, NRR, and NRE of uninsulated and insulated HABRs. (b) Nitrogen removal efficiency 3D and contour repose for COD/TN and NH_4^+-N/ NO_3^--N.

concentration in each chamber for both reactors. It appeared that COD concentration decreased along the chambers of the reactor for both HABRs except there were an increase of COD in chamber 1 and 6 for uninsulated HABRs. During the experiments, it was also observed that more suspended particles coming in chamber 1 samples at 20 h HRT. This was due to more turbulence and mixing in chamber 1 at lower 20 h HRT resulting particles suspension and migration on subsequence chambers. The higher COD concentration in chamber 6 was perhaps due to biomass washout from floated filter media in chamber sample. The average effluent COD was 45 ± 31 mg/L for uninsulated, and 75 ± 51 mg/ for insulated HABRs. The influent ORP was 53.7 ± 19.4 and 62.7 ± 27.2 for uninsulated and insulated HABRs. This indicated favourable oxic/anoxic condition existed in both HABRs for biological organic matter degradation in presence of free molecular oxygen (DO = 2.7 ± 1.1 for uninsulated, DO = 3.0 ± 1.5 for insulated) (Saby *et al.* 2003).

Solid removal

During the experiments, turbidity was measured for samples collected from each chamber for both reactors (Figure 4). The turbidity reduced significantly from 556 ± 446 NTU of raw wastewater to 8.5 ± 6.8 NTU of effluent sample in uninsulated HABR, and from 595 ± 430 NTU to 11.7 ± 8.1 NTU in insulated HABR. This represents 98 ± 1% and 97 ± 2% turbidity reduction in uninsulated and insulated HABR, respectively. Superior performance of the both HABRs in term of TSS removal were observed as shown in Figure 4. The average TSS removal efficiency were 90 ± 12% (effluent 13.3 ± 5.2 mg TSS/L) and 95 ± 7% (effluent 16.7 ± 18.6 mg TSS/L) in uninsulated and insulated HABRs, respectively. Feng *et al.* (2008) has been studied a bamboo carrier ABR and reported TSS removal of 81.92 ± 3.53% (effluent TSS 14.35 ± 3.01 mg/L) when operating at 48 h HRT at constant temperature 28 ± 1 °C. The proposed HABR configuration suggested higher TSS removal efficiency in comparison with their study. The VSS/TSS ratio of raw wastewater were 0.50–0.78 for uninsulated HABR and 0.50–0.88 for insulated HABR suggested high VSS/TSS ratio which was favourable for successfully anaerobic digestion (Henze *et al.* 2015). The average VSS removal were 90 ± 11% in uninsulated and 90 ± 13% in insulated HABR, respectively. There were not significant effects either on TSS or VSS removal observed because of insulation of the HABR.

Nitrogen removal

Figure 5 shows the nitrogen (TN, NH_4^+-N, NO_3^--N) concentration of influent and effluent samples, and their removal

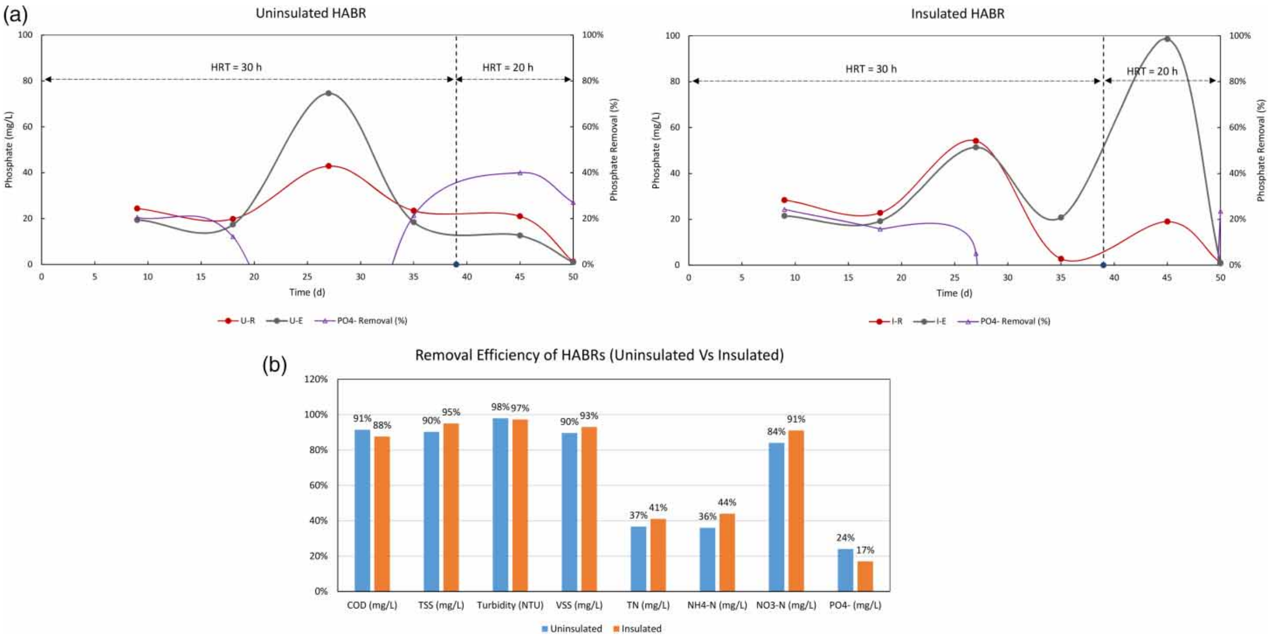


Figure 7 | (a) PO_4^{3-} removal of uninsulated and insulated HABRs. (b) Overall treatment efficiencies of uninsulated and insulated HABRs.

Table 5 | Results of residence time distribution (RTD) studies

Run	Chamber	$\bar{t}$/hr	Vd/(%)	D/uL	N	λ	Run	Chamber	$\bar{t}$/hr	Vd/(%)	D/uL	N	λ	Run	Chamber	$\bar{t}$/hr	Vd/(%)	D/uL	N	λ
A1	ch-1	1.9	61.6	1.33	1.3	0.08	**A2**	ch-1	2.3	54.1	∞	0.9	0.00	**A3**	ch-1	2.4	52.3	∞	0.9	0.00
	ch-2	2.8	44.8	0.28	2.5	0.33		ch-2	3.4	31.2	0.50	1.8	0.30		ch-2	3.3	33.0	0.52	1.7	0.28
	ch-3	3.3	34.4	0.19	3.2	0.45		ch-3	3.8	23.5	0.31	2.3	0.43		ch-3	3.7	25.1	0.33	2.2	0.41
	ch-4	4.0	19.5	0.13	4.4	0.62		ch-4	4.6	8.3	0.17	3.5	0.66		ch-4	4.4	11.6	0.18	3.4	0.62
	ch-5	4.8	4.1	0.09	5.9	0.80		ch-5	5.0	–	0.12	4.7	0.79		ch-5	5.0	0.7	0.13	4.5	0.77
	ch-6	5.0	–	0.07	7.3	0.86		ch-6	5.0	–	0.09	6.2	0.84		ch-6	5.0	–	0.09	6.3	0.84
	ch-7	5.0	–	0.06	9.6	0.90		ch-7	5.0	–	0.07	8.1	0.88		ch-7	5.0	–	0.07	8.1	0.88
	Effluent	5.0	–	0.05	10.5	0.91		Effluent	5.0	–	0.07	8.2	0.88		Effluent	5.0	–	0.07	8.1	0.88
B1	ch-1	2.4	76.2	0.43	1.9	0.11	**B2**	ch-1	3.4	65.6	∞	1.0	0.00	**B3**	ch-1	4.2	58.4	∞	0.9	0.00
	ch-2	4.7	53.1	0.32	2.3	0.26		ch-2	5.8	41.5	0.30	2.3	0.33		ch-2	6.2	38.2	0.40	2.0	0.31
	ch-3	6.5	34.9	0.24	2.7	0.41		ch-3	6.7	33.2	0.19	3.2	0.46		ch-3	7.4	26.4	0.27	2.5	0.44
	ch-4	8.4	15.7	0.17	3.5	0.60		ch-4	8.3	17.0	0.11	5.2	0.67		ch-4	9.0	9.6	0.15	4.0	0.68
	ch-5	9.8	1.6	0.12	4.8	0.78		ch-5	9.7	2.6	0.08	6.7	0.83		ch-5	10.0	–	0.10	5.6	0.82
	ch-6	10.0	–	0.09	6.2	0.84		ch-6	10.0	–	0.07	8.0	0.88		ch-6	10.0	–	0.08	7.1	0.86
	ch-7	10.0	–	0.07	8.2	0.88		ch-7	10.0	–	0.05	11.2	0.91		ch-7	10.0	–	0.05	10.3	0.90
	Effluent	10.0	–	0.06	8.3	0.88		Effluent	10.0	–	0.05	10.6	0.91		Effluent	10.0	–	0.06	9.5	0.89
C1	ch-1	7.6	61.8	4.30	1.1	0.03	**C2**	ch-1	7.6	62.0	0.74	1.5	0.13	**C3**	ch-1	11.1	44.6	2.77	1.1	0.06
	ch-2	12.8	35.9	0.30	2.3	0.37		ch-2	11.8	40.8	0.18	3.4	0.42		ch-2	15.5	22.5	0.33	2.2	0.42
	ch-3	15.4	23.1	0.19	3.2	0.53		ch-3	14.9	25.6	0.13	4.4	0.57		ch-3	17.9	10.4	0.21	3.0	0.60
	ch-4	18.7	6.7	0.13	4.3	0.72		ch-4	17.4	12.8	0.09	5.9	0.72		ch-4	20.0	–	0.14	4.2	0.76
	ch-5	20.0	–	0.10	5.6	0.82		ch-5	20.0	–	0.07	7.4	0.87		ch-5	20.0	–	0.10	5.4	0.81
	ch-6	20.0	–	0.08	7.1	0.86		ch-6	20.0	–	0.06	8.9	0.89		ch-6	20.0	–	0.08	6.8	0.85
	ch-7	20.0	–	0.06	8.8	0.89		ch-7	20.0	–	0.05	11.3	0.91		ch-7	20.0	–	0.06	9.0	0.89
	Effluent	20.0	–	0.06	8.9	0.89		Effluent	20.0	–	0.04	11.9	0.92		Effluent	20.0	–	0.06	9.0	0.89

percentages for both reactors. The results showed that TN removal (%) in both rectors followed the influent TN concentration. However, NH_4^+-N removal due to nitrification was observed high on day 18 and then gradually decrease afterward. NO_3^--N removal due to denitrification was also observed high (more than 80%) before day 15 and after day 35. The influent ORP was 53.7 ± 19.4 and 62.7 ± 27.2 for uninsulated and insulated HABRs suggested that oxic/anoxic favourable condition existed in both HABRs for nitrification and denitrification (Kishida *et al.* 2006). However, these process were not stable because of significant variation of NH_4^+-N and NO_3^--N concentration in the raw wastewater. The nitrification/denitrification process responded based on influent concentration.

Figure 6(a) shows NH_4^+-N, NO_3^--N, and NO_2^--N concentration of both influent and effluent; along with nitrogen loading rate (NLR), nitrogen removal rate (NRR), and nitrogen removal efficiency (NRE) for both uninsulated and insulated HABRs. It appeared that influent NH_4^+-N, NO_3^--N, and NO_2^--N concentration varied due to raw wastewater storage in feed tank during the experiments. The results showed NRE was influenced by NLR for both reactors; however, it was better in insulated HABR after day 30 even in higher HRT 20 day (after 40 d). NRE was primarily affected by NLR and HRT.

Chen *et al.* (2016) have examined effect of COD load on nitrogen removal in a anammox ABR. Their finding suggested that nitrogen removal enhanced at low COD (99.7 mg/L) and inhibited at high COD (284 mg/L) concentration. In addition, higher nitrogen removal was achieved when COD/TN ratio dropped from 2.33 and 1.25. In present study, a statistical analysis was conducted using ANOVA and response surface methodology (RSM) on effect of COD/TN and/or NH_4^+-N/NO_3^--N on NRE. The results suggest that NRE is primarily affected by NH_4^+-N/NO_3^--N (significant, $p = 0.002 < 0.05$) than COD/TN (not significant, $p = 0.59 > 0.05$). This is perhaps because of minor anammox activity occurred in both uninsulated and insulated HABRs. The nitrogen removal primary occurred by denitrification than nitrification rather than anammox activity. Figure 6(b) suggests higher NRE (>50%) was achieved at lower NH_4^+-N/NO_3^--N (<2.1) either at low (1.2) or high (12.1) COD/TN.

Phosphate removal

Phosphate (as Orthophosphate, PO_4^{3-}) was analyzed for influent and effluent samples collected from both HABRs (Figure 7(a)). The results showed unstable phosphate removal in both reactors, similar findings has been reported by Kishida *et al.* (2006). However, an average phosphate removal of $24 \pm 10\%$ was achieved in uninsulated HABR than $17 \pm 9\%$ in insulated HABR. After 20 d of operation, phosphate removal was ceased in uninsulated HABR because of biological phosphorus release by fermentative bacteria by producing fatty acids in the reactor resulting higher phosphate concentration in the effluent. However, removal efficiency recovered once these bacteria absorbed fatty acid after day 35. On the other hand, this scenario took late (after 35 d) to happen in case of insulated HABR resulting less phosphate removal ($17 \pm 9\%$).

Hydrodynamics behavior

The hydrodynamics study of the proposed HABR (uninsulated) was conducted at different HRTs (5, 10, and 20 h) under variable influent temperature (10, 25, and 40 °C) using tap water prior to operation (Table 5). The study suggests that the hydrodynamic performance is greatly influenced by the number of chambers in the reactor rather than HRT and influent temperature. The influence of HRT and feed temperature were mainly observed on the front chambers (1–4) than rear chambers (5–7). The optimum reactor performance; low dead space (<10%), excellent hydraulic efficiency ($\lambda > 0.75$), and intermediate mixing pattern ($Pe > 10$), were achieved using the proposed HABR with more than 5 chambers.

Overall performance of uninsulated and insulated HABR

Figure 7(b) shows the overall treatment efficiencies of COD, TSS, VSS, TN, NH_4^+-N, NO_3^--N, PO_4^{3-} of uninsulated and insulated HABRs. The results show almost similar COD (91% vs 88%), TSS (90% vs 95%), Turbidity (98% vs 97%), VSS (90% vs 93%) removal efficiencies for uninsulated and insulated HABR when operating at warm temperature (18.6–37.6 °C) condition. In addition, higher nitrogen removal TN of 41%, NH_4^+-N of 44%, and NO_3^--N of 91% were achieved by insulated HABR compare to TN of 37%, NH_4^+-N of 36%, NO_3^--N of 84% by uninsulated HABR. However, lower PO_4^{3-} removal efficiency of 17% were found in insulated HABR compare to 24% in uninsulated HABR.

CONCLUSION

A HABR configuration was proposed with improved design principles; consisting of a front sedimentation chamber, four regular baffled chambers followed by two floated filter media chambers. The treatment efficiency of both uninsulated and insulated HABRs were conducted and compared when operating at warm temperature (18.6–37.6 °C) conditions. The study suggests similar removal efficiencies for COD (91% vs 88%), TSS (90% vs 95%), Turbidity (98% vs 97%), VSS (90% vs 93%) in uninsulated and insulated HABRs. However, insulation increased nitrogen removal efficiencies by 4% for TN, 8% for NH_4^+-N, 7% for NO_3^--N, but decreased PO_4^{3-}removal efficiency by 7%.

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