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

Md Khalekuzzaman, Muhammed Alamgir, Mehedi Hasan and Md Nahid Hasan

## ABSTRACT

In this research, a hybrid anaerobic baffled reactor (HABR) configuration was proposed consisting of a front sedimentation chamber and 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 chemical oxygen demand (91% vs 88%), total suspended solids (90% vs 95%), turbidity (98% vs 97%), and volatile suspended solids (90% vs 93%) removal efficiencies were obtained for uninsulated and insulated HABRs. Higher removal of total nitrogen (TN) of 41%, $NH_4^+$-N of 44%, and $NO_3^-$-N of 91% were achieved by the insulated HABR compared to TN of 37%, $NH_4^+$-N of 36%, and $NO_3^-$-N of 84% by the uninsulated HABR, whereas lower $PO_4^{3-}$ removal efficiency of 17% was found in the insulated HABR compared to 24% in the uninsulated HABR. This indicated insulation increased nitrogen removal efficiencies by 4% for TN, 8% for $NH_4^+$-N and 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 regions with warm climate (15–35 °C), which is favorable for biological wastewater treatment. In addition, most of these countries also have electricity deficit, which makes it 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 reactors 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 the ABR is that there are very few full-scale ABR applications for wastewater treatment.

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One of the major concerns reported by researchers (Bwapwa 2012; Zhu *et al.* 2015; Reynaud & Buckley 2016) is sludge/solid washout from the system during operation. Sludge washout ultimately affects ABR treatment efficiency; as a consequence, a poor effluent quality is obtained. Sludge washout is directly influenced by reactor up-flow velocity. Higher velocity tends to produce more washout and lower velocity tends to overcome this problem. In order to have an optimum reactor volume and minimize 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 of more than 90% (Metcalf & Eddy 2003), which also needs energy for pumping wastewater upward. Most importantly, when comparing with the traditional aerobic process, the anaerobic treatment system also processes poor-quality effluent, which usually needs post-treatment to meet the discharge limits. Further research on advanced reactor design and control process could lead to most of the ABR's disadvantages being overcome. Perhaps, the 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, decreasing hydraulic retention time (HRT) or heating of wastewater could achieve higher removal efficiency (Zhu *et al.* 2015), which also improves 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 HRT, organic loading rate (OLR), nutrients ratio, wastewater concentration, temperature and pH is also crucial for the ABR process (Barber & Stuckey 1999; Feng *et al.* 2008). Controlling or modifying of wastewater nutrients and their concentration and/or pH will involve process complexity and cost. Therefore, this research work is focused on performance evaluation of an insulated HABR (assuming maximum thermal control 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 to examine and validate the optimum pollutant removal efficiency of the 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

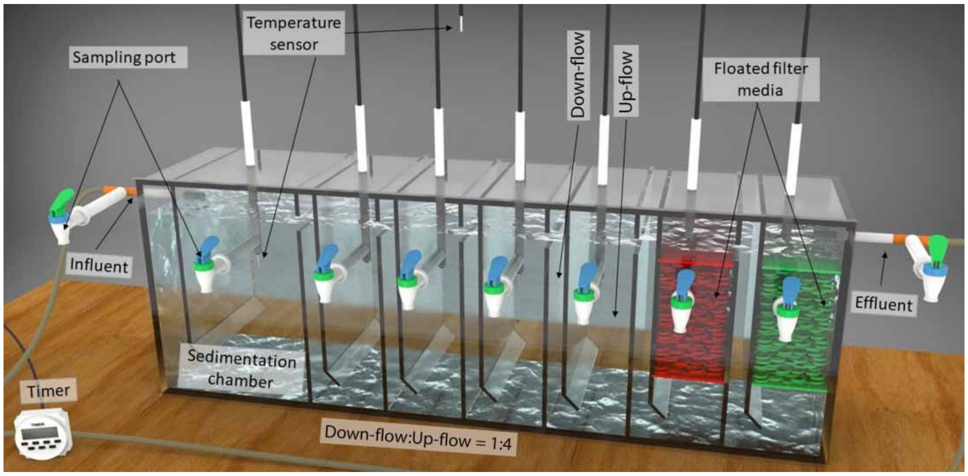

**Figure 1** | Schematic of the hybrid anaerobic baffled reactor.

**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 is 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 |
| Inlet; outlet | Inlet: 27 cm from base; outlet: 25 cm from base |

30 cm for length, width, and depth, respectively. The effective volume of uninsulated and insulated reactors was 36.38 L and 36.39 L, respectively. Each HABR consisted of a front sedimentation chamber (U-1 and I-1) and four regular chambers (U-2 to U-5, and I-2 to I-5) followed by two floated filter media chambers (U-6 and U-7; and I-6 and I-7). The first chamber volume, designed as settling chamber, was twice that of the subsequent chambers. The individual chambers were again divided into two portions by a hanging baffle, which separated each chamber into down- and up-flow zones. 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 g of shredded (e.g. making small pieces) soft drink lid were loosely placed as floated filter media in the last two chambers of each reactor (Table 1). These locally available materials were used due to their favorable physical properties that would not cause reactor failure by clogging during wastewater treatment. Polyurethane foam (Pu Foam, Boya, Korea) was used for insulating one HABR by applying a liquid foam layer (up to 2 inch (5 cm)) and letting it dry at room temperature (21–25 °C). Arduino UNIO technology with a DS18B20 waterproof digital temperature sensor connected to a data logger system was also installed in each compartment for temperature monitoring during operation as presented in Table 2. Each compartment has a 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 a mixing device 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/h (maintaining hourly flow rate 1.213 L in 10 mins for 30 h HRT, and

**Table 2** | Summary of temperature sensor 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. |
|---|---|---|---|---|---|---|---|---|---|
| Minimum | 18.6 | 23.1 | 22.9 | 23.4 | 23.2 | 23.0 | 22.9 | 22.4 | 19.0 |
| Maximum | 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 |
| Standard deviation | 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.** |
| Minimum | 18.8 | 22.8 | 22.7 | 22.6 | 22.4 | 22.6 | 22.9 | 22.9 | 18.6 |
| Maximum | 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 |
| Standard deviation | 3.0 | 1.6 | 1.6 | 1.5 | 1.5 | 1.4 | 1.4 | 1.4 | 4.2 |

**Table 3** | Characteristics of influent wastewater

| 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 |

1.819 L in 10 mins for 20 h HRT) during the entire experiment. The HRT of both reactors was 30 h for first 40 days and then 20 h for remaining 10 days.

## 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 to adding into the reactor. Approximately 9.2 L (3.2 L for first chamber and 1.5 L for each of chambers 2–5) of sludge was added to chambers 1 to 5, the remaining volume being filled with septic tank effluent, which was also added to 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 to feeding with wastewater. Nine experimental runs, A1–A3, B1–B3 and C1–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. A NUVE BM30 water bath was used to maintain influent temperature. Sodium chloride (NaCl) was used as the tracer due to its various favorable features as described by Li *et al.* (2015, 2016). To obtain the RTD curves, 200 mL concentrated NaCl solution (42.5 g $Cl^-$/Cl) was instantaneously injected prior to the inlet. The water samples were collected from the sampling port of each 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 $\theta$ 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 $C_\theta$ is the normalized tracer concentration at dimensionless time $\theta$, $C(t)$ is the tracer concentration at time $t$, and $C_0$ is the initial tracer concentration.

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

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

where E(t) is the RTD function

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

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):

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

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).

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

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

Alternatively, Peclet number ($Pe$) is often used to express 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.

$$N = \frac{1}{\sigma_\theta^2} \qquad (7)$$

If $N$ tends to 1, the flow pattern of the reactor approaches that of a continuous stirred tank reactor. On the other hand, when $N$ tends to $\infty$, the flow pattern approaches plug flow.

The hydraulic efficiency ($\lambda$) includes two basic features: (i) the distribution of flow across the reactor; and (ii) the 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):

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

The effective volume 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 $\lambda \leq 0.5$.

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

| | | **Effluent characteristics** | | **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 |

## Statistical analysis

Data analysis was performed with Excel and Design-Expert 10. The one-way analysis of variance (ANOVA) was 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, ORP and DO were monitored in raw wastewater (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 and 4 and Figure 2(a). The results show pH $8.0 \pm 0.2$

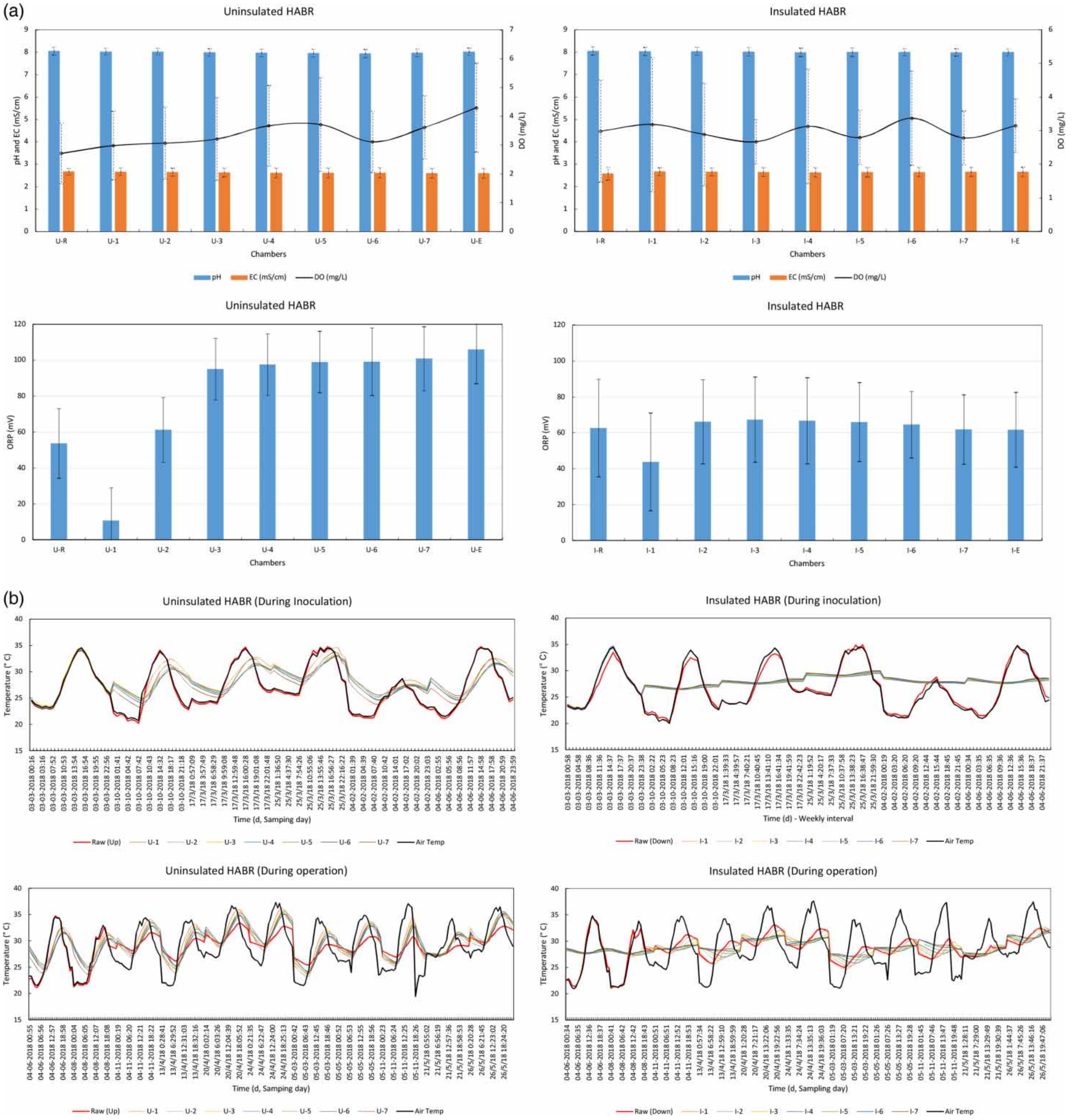

**Figure 2** | (a) Average pH, EC, DO, and ORP of raw, seven chambers (1–7), and effluent of uninsulated and insulated HABRs. (b) Temperature data of raw, seven chambers (1–7), and effluent during inoculation and sampling date for both reactors.

and 8.1 ± 0.2, EC 2.7 ± 0.1 and 2.6 ± 0.3 mS/cm, ORP 53.7 ± 19.4 and 62.7 ± 27.2 mV, and DO 2.7 ± 1.1 and 3.0 ± 1.5 mg/L in raw wastewater for uninsulated and insulated HABRs, respectively. This indicates a favorable oxic/anoxic condition existed in both reactors for organics biodegradation and nitrification/denitrification/anammox (anaerobic ammonium oxidation) processes. Arduino UNIO temperature data are presented in Table 2 and Figure 2(b). It appeared that the insulation provided a better temperature control in the insulated HABR during inoculation and operation. Figure 2(b) suggests a significant temperature variation in the uninsulated HABR and a minimum variation in the 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 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 the uninsulated and insulated HABR, respectively. It appeared that the COD removal efficiencies for both reactors fluctuated during this experiment; 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 was 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

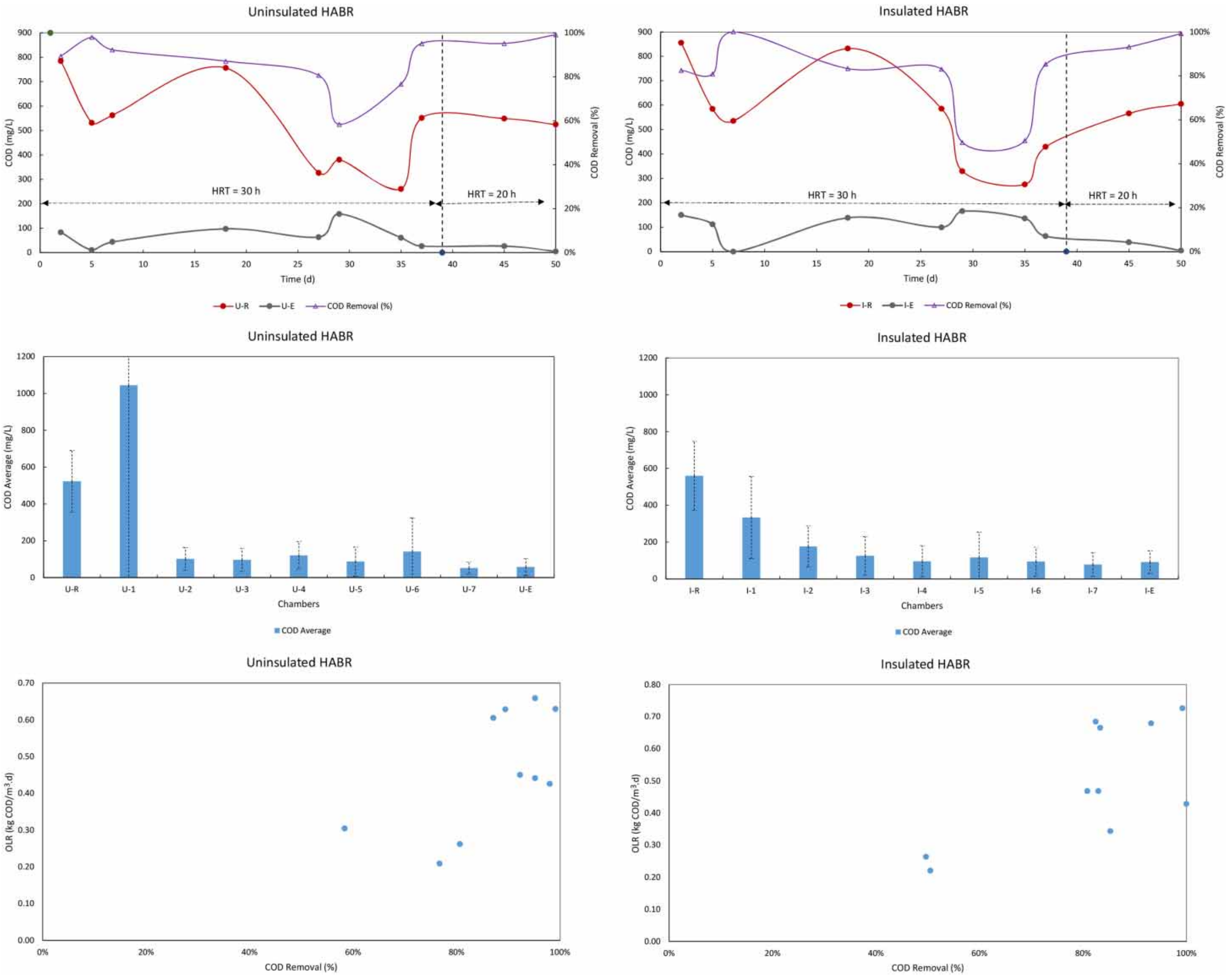

**Figure 3** | COD concentration and COD removal, average COD, and OLR of uninsulated and insulated HABRs.

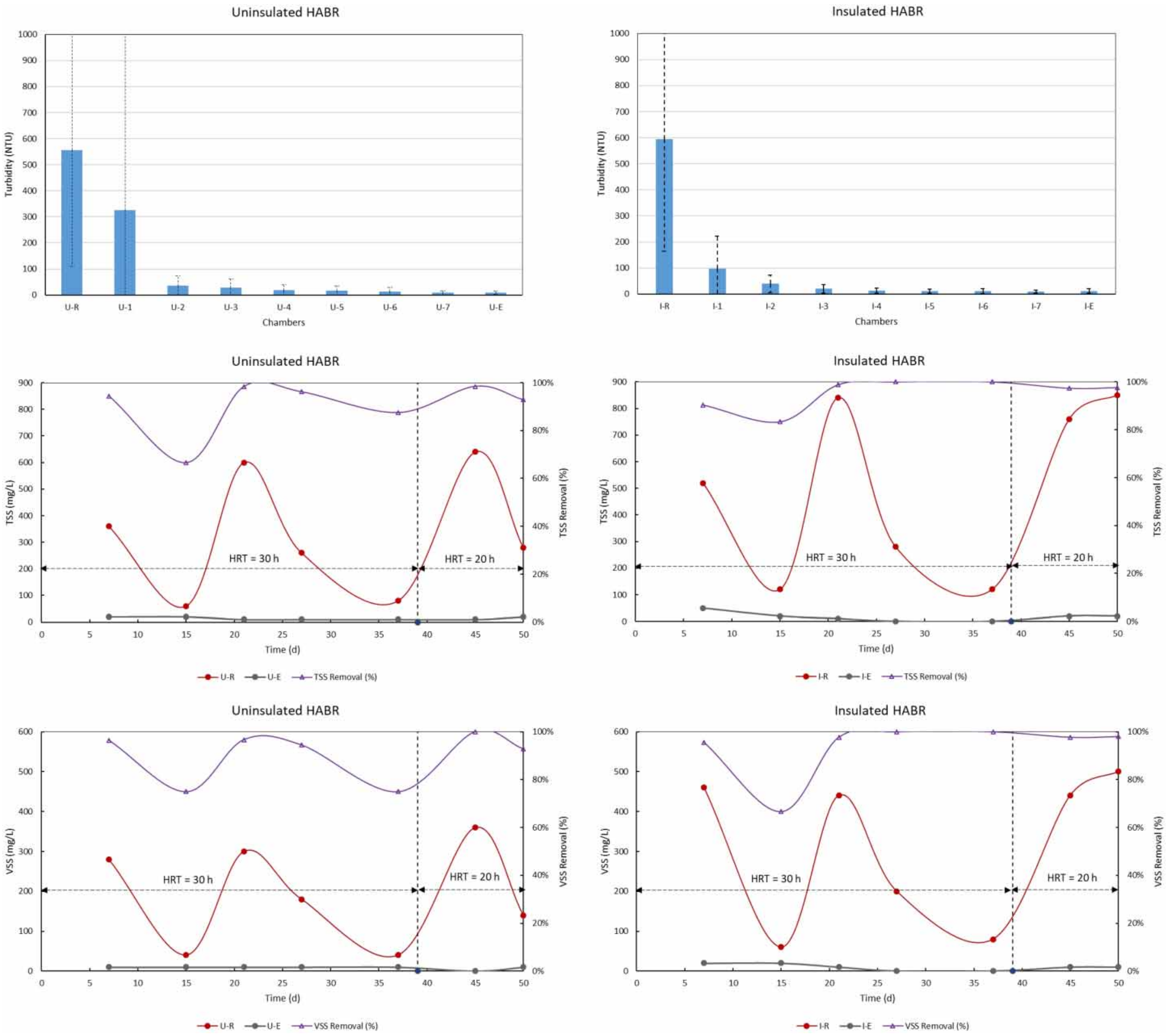

**Figure 4** | Turbidity, TSS, and VSS removal of uninsulated and insulated HABRs.

the COD removal is directly influenced by OLR (Bodkhe 2009; Lu *et al.* 2011). Insulation of the HABR had no significant influence on COD removal efficiency. Figure 3 also shows the average COD concentration in each chamber for both reactors. It appeared that COD concentration decreased along the chambers of the reactor for both HABRs except for an increase of COD in chamber 1 and 6 for the uninsulated HABR. During the experiments, it was also observed that more suspended particles were 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 in particles suspension and migration in subsequent chambers. The higher COD concentration in chamber 6 was perhaps due to biomass washout from floated filter media in the chamber sample. The average effluent COD was 45 ± 31 mg/L for uninsulated, and 75 ± 51 mg/L for insulated HABRs. The influent ORP was 53.7 ± 19.4 and 62.7 ± 27.2 mV for uninsulated and insulated HABRs. This indicated favorable oxic/anoxic condition existed in both HABRs for biological organic matter degradation in presence of free molecular oxygen (DO = 2.7 ± 1.1 mg/L for uninsulated, DO = 3.0 ± 1.5 mg/L 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 the uninsulated HABR, and from 595 ± 430 NTU to 11.7 ± 8.1 NTU in the insulated HABR. This represents 98 ± 1% and 97 ± 2% turbidity reduction in the uninsulated and insulated HABR, respectively. Superior performance of both HABRs in terms of TSS removal was observed as shown in Figure 4. The average TSS removal efficiency was 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) 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 was 0.50–0.78 for the uninsulated HABR and 0.50–0.88 for insulated HABR, suggesting a high VSS/TSS ratio which was favorable for successfully anaerobic digestion (Henze *et al.* 2015). The average VSS removal was 90 ± 11% in the uninsulated and 90 ± 13% in the insulated HABR, respectively. Insulation of the HABR had no significant effects either on TSS or VSS removal.

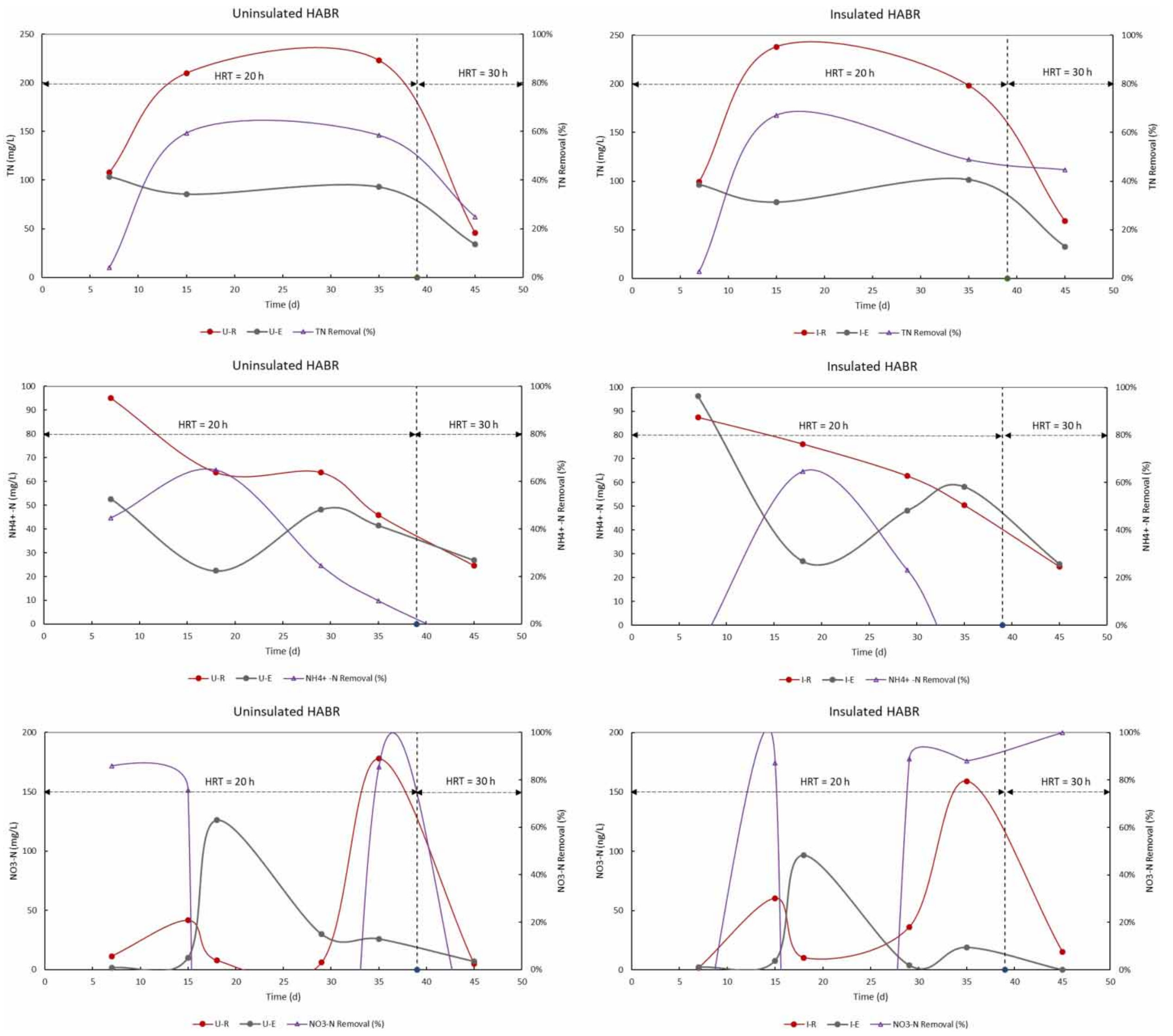

**Figure 5** | TN, $NH_4^+$-N and $NO_3^-$-N removal of uninsulated and insulated HABRs.

## Nitrogen removal

Figure 5 shows the nitrogen (TN, $NH_4^+$-N, $NO_3^-$-N) concentration of influent and effluent samples, and their removal percentages for both reactors. The results showed that TN removal (%) in both reactors followed the influent TN concentration. However, $NH_4^+$-N removal due to nitrification was observed to be high on day 18 and then gradually decreased afterward. $NO_3^-$-N removal due to denitrification was also high (more than 80%) before day 15 and after day 35. The influent ORP was 53.7 ± 19.4 and 62.7 ± 27.2 mV for uninsulated and insulated HABRs, which suggested that oxic/anoxic favorable 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

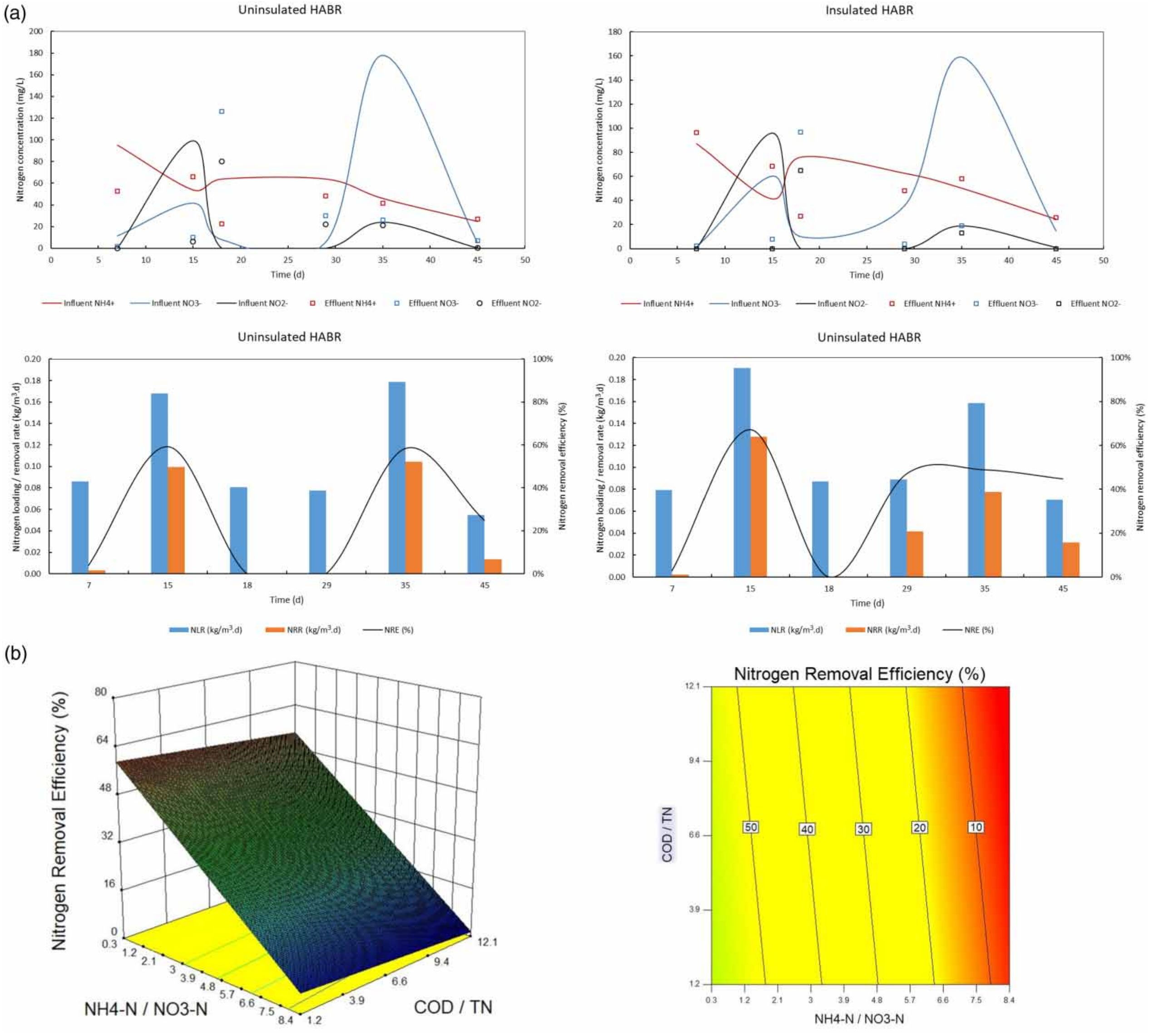

**Figure 6** | (a) Influent and effluent N ($NH_4^+$-N, $NO_3^-$-N, $NO_2^-$-N), and NLR, NRR, and NRE of uninsulated and insulated HABRs. (b) Nitrogen removal efficiency 3D and contour response for COD/TN and $NH_4^+$-N/ $NO_3^-$-N.

$NH_4^+$-N, $NO_3^-$-N, and $NO_2^-$-N concentration varied due to raw wastewater storage in the feed tank during the experiments. The results showed NRE was influenced by NLR for both reactors; however, it was better in the insulated HABR after day 30 even at higher HRT of 20 days (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 an anammox ABR. Their finding suggested that nitrogen removal was 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 to 1.25. In the present study, a statistical analysis was conducted using ANOVA and response surface methodology 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 minor anammox activity occurred in both uninsulated and insulated HABRs. The nitrogen removal primarily occurred by denitrification than by nitrification, but there was minimum 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) was analyzed for influent and effluent samples collected from both HABRs (Figure 7(a)). The results showed unstable phosphate removal in both reactors, similar to findings reported by Kishida *et al.* (2006). However, an average phosphate removal of 24 ± 10% was achieved in the uninsulated HABR and 17 ± 9% in the insulated HABR. After 20 d of operation, phosphate removal ceased in the uninsulated HABR because of biological phosphorus release by fermentative bacteria producing fatty acids in the reactor, resulting in 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 longer (after 35 d) to happen in the insulated HABR resulting in less phosphate removal (17 ± 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

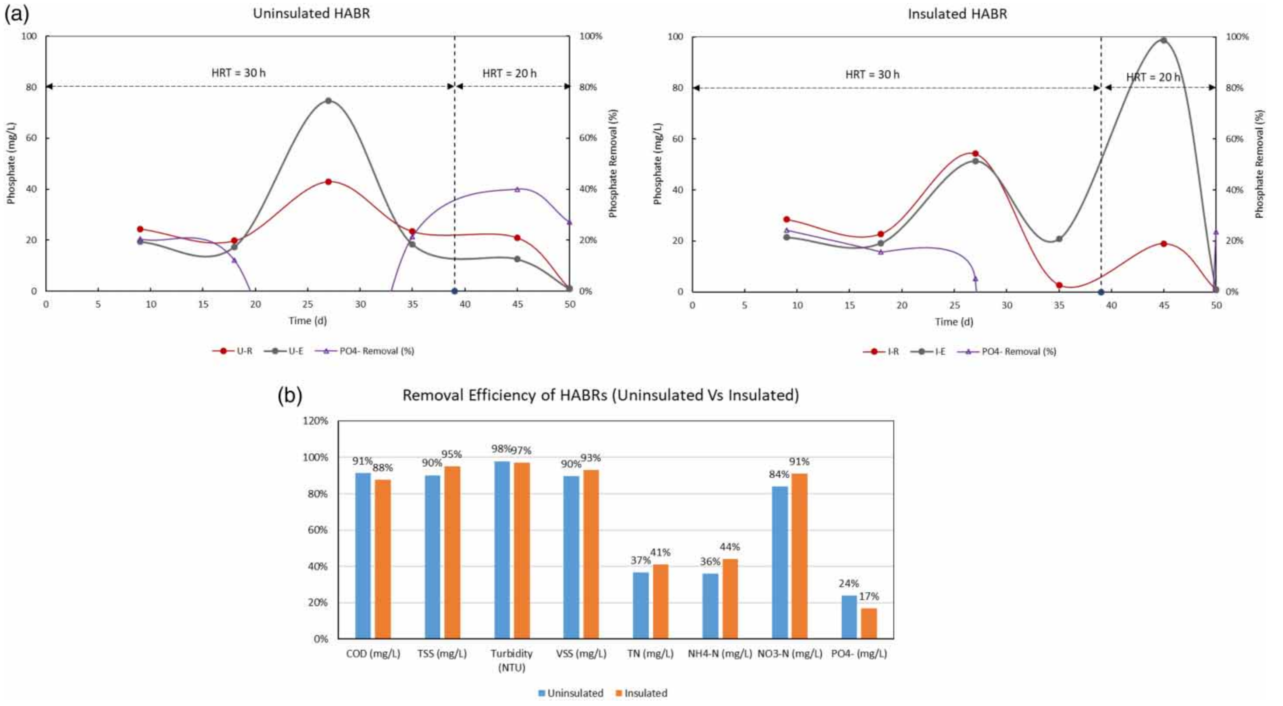

**Figure 7** | (a) $PO_4^{3-}$ removal of uninsulated and insulated HABRs. (b) Overall treatment efficiencies of uninsulated and insulated HABRs.

**Table 5** | Results of residence time distribution studies

| Run | Chamber | $\bar{t}$ (h) | $V_d$ (%) | D/uL | N | $\lambda$ | Run | Chamber | $\bar{t}$ (h) | $V_d$ (%) | D/uL | N | $\lambda$ | Run | Chamber | $\bar{t}$ (h) | $V_d$ (%) | D/uL | N | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

rather than HRT and influent temperature. The influence of HRT and feed temperature was mainly observed in 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 ($Pe > 10$) – was achieved using the proposed HABR with more than five 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%) and VSS (90% vs 93%) removal efficiencies for uninsulated and insulated HABRs when operating at warm temperature (18.6–37.6 °C) condition. In addition, higher nitrogen removal of TN of 41%, $NH_4^+$-N of 44%, and $NO_3^-$-N of 91% was achieved by the insulated HABR compared to TN of 37%, $NH_4^+$-N of 36% and $NO_3^-$-N of 84% by the uninsulated HABR. However, lower $PO_4^{3-}$ removal efficiency of 17% was found in the insulated HABR compared to 24% in the uninsulated HABR.

## CONCLUSION

A HABR configuration was proposed with improved design principles, consisting of a front sedimentation chamber and four regular baffled chambers followed by two floated filter media chambers. The treatment efficiency of both uninsulated and insulated HABRs was 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%) and VSS (90% vs 93%) in uninsulated and insulated HABRs. However, insulation increased nitrogen removal efficiencies by 4% for TN, 8% for $NH_4^+$-N and 7% for $NO_3^-$-N, but decreased $PO_4^{3-}$removal efficiency by 7%.

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