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Municipal wastewater treatment with corrugated PVC carrier anaerobic baffled reactor

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ABSTRACT

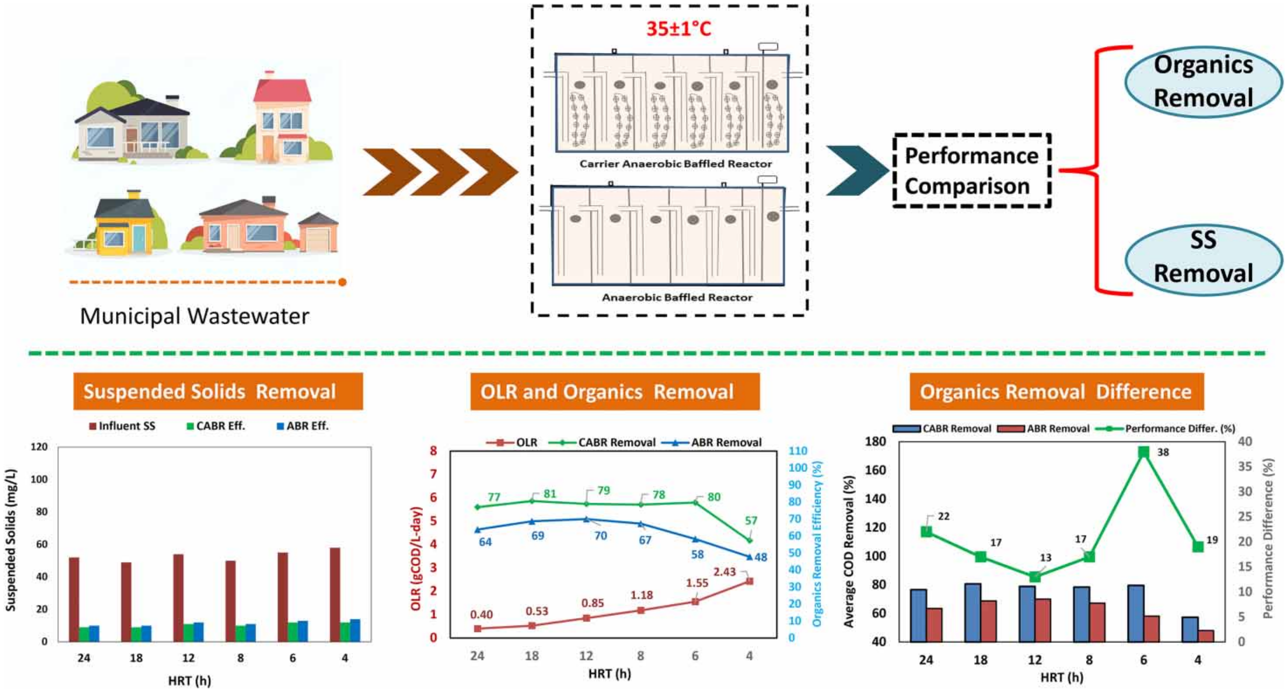
The anaerobic baffled reactor (ABR) is a promising solution for decentralized wastewater treatment due to its low operation cost as compared to the activated sludge process, but it requires comparatively higher hydraulic retention time (HRT). This ultimately increases land requirement, capital and construction cost of treatment plant. This study investigates performance of ABR using polyvinyl chloride (PVC) corrugated pipe as carrier media to improve biomass retention capacity and treatment performance of reactor with the aim to reduce HRT. Comparative performance of two ABRs with and without carrier media was analyzed under mesophilic conditions (35 ± 1 °C) for organics and total suspended solids (TSS) removal at HRTs of 24, 18, 12, 8, 6 and 4 h. Results showed that at HRTs of 24–08 h, the organics removal performance of the carrier anaerobic baffled reactor (CABR) was better than ABR and was in the range of 77–81% for CABR as compared to 64–70% for ABR. However, on further decrease in HRT to 6 h, CABR sustained the treatment with organics removal of 80%, while ABR performance reduced to 58%, creating a performance difference of 38%. Average total suspended solids (TSS) removal was in the range of 76–83% at all HRTs for both reactors. Therefore, this study identified CABR with PVC carrier media as an effective low-HRT reactor for organics and SS removal with less land area requirement.

Key words: biological treatment, carrier anaerobic baffled reactor, corrugated pipe carrier media, hydraulic retention time, municipal wastewater

HIGHLIGHTS

- Novel corrugated poly vinyl chloride (PVC) pipe has been used as carrier media at relatively shorter HRTs of 4–24 h. This kind of media is cheaper and more durable as compared to bamboo carrier media. Also, the preparation of PVC carrier media for large-scale application is easier.
- Mesophilic conditions were maintained.
- Real-time comparison was made for removal efficiency between ABR with and without media.

GRAPHICAL ABSTRACT



INTRODUCTION

More than 1.6 billion people across the globe are facing water shortage, with two-thirds of the world's population having water scarcity in some days of the year (Mekonnen & Hoekstra 2016). Water scarcity can be reduced by treatment and recycling of generated wastewater for various applications including irrigation, ground water recharge, fire-fighting, aquaculture, urban lawn watering and industrial processing (Yang *et al.* 2020). Every year, 400 billion cubic meters of wastewater is generated globally, which causes pollution of 5,500 billion cubic meters of fresh water (Ungureanu *et al.* 2020). People don't have any other option but to use polluted water, causing severe health issues. Diarrhea, hepatitis-A, cholera, and dysentery are some of the diseases caused by using contaminated water. According to the World Health Organization, diarrhea alone causes the death of 842,000 people annually worldwide (Hasan *et al.* 2019).

In developed countries, aerobic processes are widely used for municipal wastewater treatment. These processes are time efficient and more effective in organics and nutrients removal, odor control and prevention of greenhouse gases. But aerobic treatment requires high energy, which makes this treatment not practicable in developing countries that are already facing high energy crises (Aqaneghad *et al.* 2018). Realizing the importance of wastewater treatment, developing countries are opting for anaerobic treatment, as this requires less energy consumption, produces less sludge, generates energy, and requires less nutrients for operation (Hahn & Figueroa 2015).

Anaerobic treatment has comparatively less operational cost as compared to aerobic treatment but requires longer hydraulic retention time (HRT) due to low metabolic capacity of anaerobic bacteria. Due to longer HRT, more land area is required for treatment plant construction, which increases its capital cost (Stazi & Tomei 2018).

To reduce HRT and land requirement for anaerobic wastewater treatment plants, biomass retention capacity of the slow-growing anaerobes is enhanced within the reactor. For this purpose, various approaches including biomass immobilization, biomass granulation, biomass retention and biomass recycling are used (Garcia *et al.* 2008; Datta *et al.* 2009; Liu *et al.* 2018). One of the most efficient high-rate anaerobic reactors is the anaerobic baffled reactor (ABR), which was developed by McCarthy and his coworkers at Stanford University in the early 1980s. This is composed of different compartments and chambers having an anaerobic sludge blanket. Wastewater is allowed to move vertically in downward and upward directions in each compartment. This flow pattern facilitates influent to come in contact with the anaerobic sludge blanket in the bottom of each compartment and thus helps to remove organics from wastewater (Schalk *et al.* 2019). Advantages of ABR are its low construction and operational cost, less sludge production, more stable to hydraulic shock loads and no electricity requirement for operation (Reynaud & Buckley 2016). Although ABR has more advantages to use for municipal wastewater treatment, it has low-quality effluent and may not satisfy permissible effluent limits (Aqaneghad & Moussavi 2016).

To improve the performance of ABR, various studies have been conducted. Feng *et al.* (2008) used hollow-sphere bamboo in ABR as carrier media having specific surface area of 2,100 m^2/m^3 for the attachment and growth of biomass. Chemical oxygen demand (COD) removal of the carrier ABR at HRTs of 48, 32, 24 and 18 h was 79, 77, 74 and 69%, respectively. However, no comparison was made with ABR without carrier media for COD removal.

In another study, performance of ABR and hybrid anaerobic baffled reactor (HABR) was evaluated at ambient temperature for removal of total suspended solids (TSS), COD, total nitrogen (TN) and total phosphorus (TP) from municipal wastewater at HRT of 48, 36 and 24 h. HABR met effluent permissible limits at HRT of 36 h, while ABR met the standards at HRT of 48 h in terms of COD removal (COD $\leq$60 mg/L). Moradgholi *et al.* (2019) investigated the performance of ABR integrated with electrochemical system for treatment of municipal wastewater. In electrochemical system ABR (ESABR), two paired steel mesh plate type electrodes were installed in the second and fourth compartments with a DC power supply. This improved ABR had removal performance of 70–80% for organics and TSS at HRT of 14–24 h.

Earlier study on carrier ABR has used bamboo carrier media, but it has certain associated issues, which are as follows: (i) bamboo media is not cheaply available in all developing countries, (ii) preparation of bamboo media for large operation is a challenging job and (iii) these are biodegradable in nature and need to be replaced with the passage of time, which increases the operational cost. Similarly, performance of HABR has not been evaluated at mesophilic conditions and low HRTs to assess its suitability as a high-rate reactor in warm climates for treating municipal wastewater. In ESABR, DC power supply and steel mesh electrodes have been used, which makes it difficult to use in the field.

The objective of this study, therefore, is to evaluate the performance of ABR for removal of organics and TSS from municipal wastewater using corrugated PVC pipe as carrier media under mesophilic conditions (35 $\pm$ 1 °C) at various HRTs. Mesophilic conditions were selected for this study as in most developing countries, particularly in Asia and Africa, ambient temperature is above 30 °C in many months of the year.

MATERIALS AND METHODS

Corrugated PVC pipe was selected as carrier media for this study. Prime focus of using corrugated PVC media for biomass attachment and growth in this study is its low cost and easy availability in developing countries. Even in some developing countries, specifically manufactured media for wastewater treatment is not available, and importing this media increases overall cost of wastewater treatment plant. Also, corrugated PVC pipe is discarded from air conditioners and other appliances, which signifies its importance to be reused.

Reactors and experimental setup

Two identical ABRs made of 8 mm thick acrylic sheet were used in this study. Dimensions of each ABR were **686 mm** $\times$ **344 mm** $\times$ **166 mm** (Length $\times$ Height $\times$ Width) with working volume of 28 L. The ABRs were rectangular in shape, having six compartments of equal size. The width of upflow chamber was 75 mm. Three high density polyethylene (HDPE) pipes having diameter of 25 mm each in parallel were used for downward flow in each compartment. The outlet of each HDPE pipe was kept 75 mm above the bottom of the ABR. Inlet and outlet of the ABRs were kept at the height of 305 and 280 mm, respectively from the bottom. Sampling ports were provided in each compartment, which were 200 mm above the bottom. Two biogas collecting ports were provided in each reactor. To maintain the reactors' internal temperature at 35 °C, water jacketing was provided around the ABRs. Immersion heaters installed in the water jacket were connected with temperature controller and temperature sensor. Temperature sensors were installed within the reactors to collect the reactors' internal temperature data. One small centrifugal water pump was installed in each water jacket for water circulation around the reactor.

Both ABRs were properly sealed to make them airtight. In one ABR, 20% of upflow region in each compartment was filled with cylindrical pieces of corrugated PVC pipe, which served as carrier media. This reactor is termed the carrier anaerobic baffled reactor (CABR). The second reactor had no carrier media and is termed ABR. Length and diameter of each media particle was the same, which was 12 mm. The specific surface area and porosity of the media particles were 615 m^2/m^3 and 77%, respectively. The carrier media was beaded in a string so that media remained fixed in each compartment and did not move along the flow. Synthetic wastewater was supplied to each ABR using peristaltic pumps from a feed tank having storge capacity of 300 liters. These pumps facilitated the controlled flow to both reactors. This lab-scale setup was installed in the backyard of Institute of Environmental Sciences and Engineering (IESE), NUST, Islamabad, Pakistan. Schematic diagram of the setup is shown in Figure 1.

Wastewater characteristics

Synthetic wastewater was prepared simulating the real municipal wastewater samples collected from the inlet of wastewater treatment plant in Sector I-9 Islamabad, Pakistan. Physico-chemical characteristics of synthetic wastewater are given in Table 1.

Inoculum and seeding

For inoculum preparation, sludge was collected from the wetland situated in NUST, H-12 campus, Islamabad. Fresh cow dung was collected from the vicinity of sector H-13, Islamabad. Inoculum was prepared by mixing equal proportions of sludge and fresh cow dung. After proper mixing, 30 percent working volume of each ABR was filled with inoculum. The remaining working volume of both reactors was filled with synthetic wastewater.

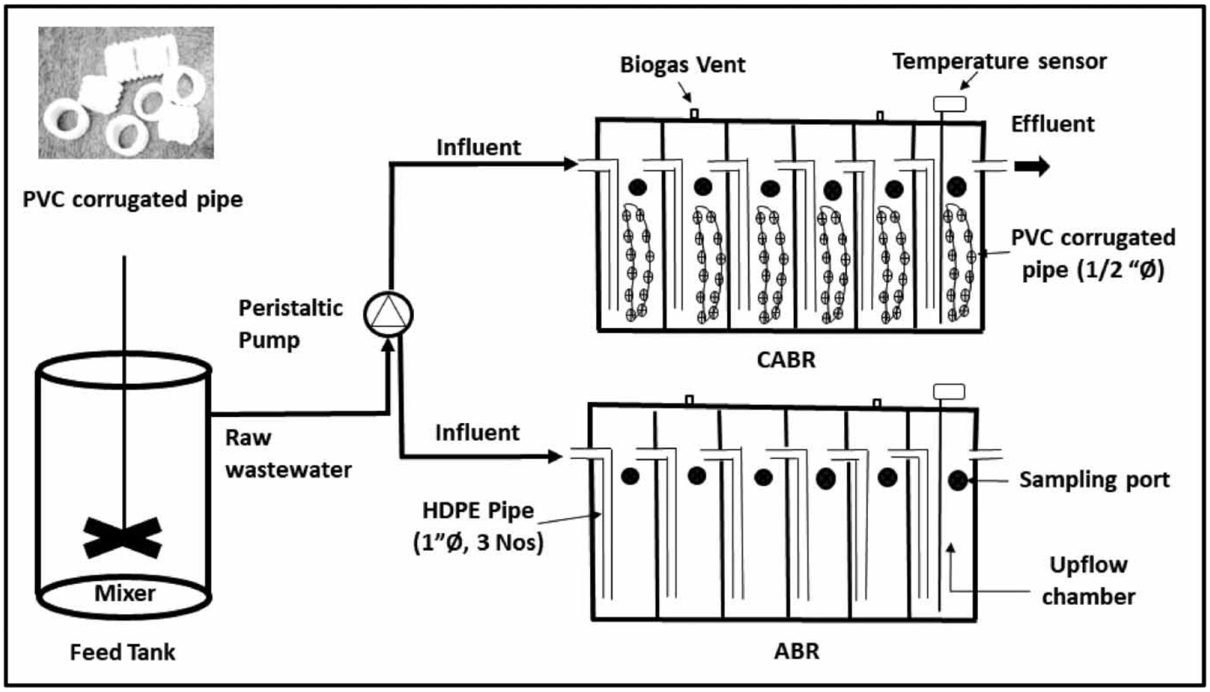


Figure 1 | Schematic diagram of experimental setup.

Table 1 | Physico-chemical characteristics of synthetic municipal wastewater

Parameter	Concentration
SS (mg/L)	53 ± 3.1
COD (mg/L)	400 ± 24
BOD (mg/L)	261 ± 18
pH	7.2 ± 0.2
Total Kjeldahl nitrogen (TKN) (mg/L)	49 ± 16
Total phosphorus (TP) (mg/L)	41 ± 8

Based on the characterization of Islamabad wastewater, synthetic wastewater was prepared with average COD and BOD in the range of 400 ± 24 mg/L and 261 ± 18 mg/L, respectively. pH concentration was in the range of 7.2 ± 0.2, while TKN and TP concentration was in the range of 49 ± 16 mg/L and 41 ± 8 mg/L, respectively. BOD, biochemical oxygen demand; COD, chemical oxygen demand; SS, suspended solids.

Operation of ABRs

The operation of both ABRs has been divided into startup phase and continuous flow mode. The detail of each phase is given separately in the following sections.

Startup phase

The startup phase facilitates microorganisms to grow and acclimatize in the reactor and thus develops pollutant-removal conditions in the shortest period of time (Zha *et al.* 2019). Startup phase was conducted in batch mode, which took 90 days. Mesophilic conditions were maintained by keeping hot water in the water jacket. After filling with inoculum and wastewater, both the reactors were left undisturbed for 15 days to facilitate sludge adaptation. Recirculation of reactor content using peristaltic pump equal to one reactor volume was done once a week to maintain pH in permissible limits. COD, pH and oxidation reduction potential (ORP) were regularly monitored.

Continuous flow mode

In order to get the system stability and better performance, continuous flow should be initiated with longer HRT so that the microbes get enough time to adjust to the new environment (Renuka *et al.* 2016). To get better performance, continuous and plug flow process was initiated with HRT of 24 h for both reactors. After running the reactors at 24 h HRT for 46 days, HRT was gradually reduced to 18, 12, 08, 06 and 04 h by increasing organic loading rate (OLR) with the use of a peristaltic pump as shown in Table 2. System HRT was gradually reduced from 24 to 18 h through transitional steps of 22 and 20 h. Similarly, further lower HRTs of 12 and 8 h were achieved through transitional HRTs of 15 and 10 h, respectively. At each transitional HRT, the system was operated for 2 days. For switching to HRTs of 6 and 4 h, there was no transition phase, as the interval was quite low. System performance was analyzed twice a week for each HRT till steady conditions were achieved and then shifted to the next lower HRT gradually.

Sampling and analysis

The system was monitored for pH, COD, SS, total alkalinity (TA) and volatile fatty acids (VFAs) twice a week. Influent and effluent samples from both reactors collected in triplicate were analyzed following the Standard Methods for the Examination of Water and Wastewater (APHA 2017).

RESULTS AND DISCUSSION

System startup phase

As depicted in Table 1, initial COD was 400 mg/L; however, after mixing with inoculum, initial COD of CABR and ABR increased to 1,413 mg/L and 1,129 mg/L, respectively. COD removal performance during startup phase is shown in Figure 2.

Table 2 | Operational conditions of carrier anaerobic baffled reactor and anaerobic baffled reactor for batch flow mode and continuous flow mode

Batch mode for startup of CABR and ABR

	HRT (d)	Initial COD (mg/L)		Operation Time (d)
S No	90	CABR	ABR	90
1		1,413	1,129	

Continuous flow mode for CABR and ABR

S No	HRT (h)	Organic Loading Rate (gCOD/L-day)	Hydraulic Loading Rate (L/day)/L	Operation Time (d)
1	24	0.40	1.0	46
2	18	0.53	1.3	33
3	12	0.85	2.0	32
4	8	1.18	3.0	32
5	6	1.55	4.0	19
6	4	2.43	6.0	12

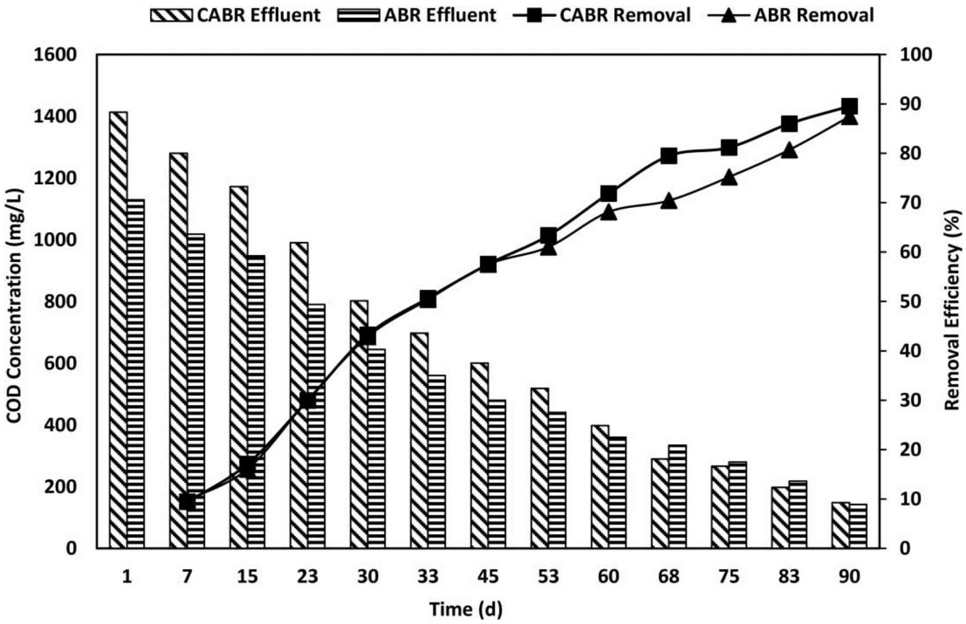


Figure 2 | COD concentration and removal performance during startup phase of carrier anaerobic baffled reactor and anaerobic baffled reactor.

The system showed COD removal of 17 and 16% of the initial COD value on the 15th day of startup for CABR and ABR, which increased to 90 and 87% of initial value on the 90th day, respectively. Feng *et al.* (2015) reported 130 days startup period for treating diluted domestic wastewater using anaerobic baffled reactor with COD removal of 52.3% at temperature below 25 °C. Similarly, Bodkhe (2009) reported 90 days startup period for a self-inoculated nine-chamber anaerobic baffled reactor with a COD reduction of 95%. Another study conducted by Renuka *et al.* (2016) for treating municipal wastewater using panelled anaerobic baffled-cum filter reactor took 90 days startup phase with COD removal of more than 90%. The resulting oxygen reduction potential (ORP) values were −355 mV and −348 mV for CABR and ABR, respectively, at the end of the startup phase. ORP values indicated that anaerobic conditions are achieved in both reactors. For the initial days, pH started to increases which then showed a downward trend. This decrease in pH indicated the start of anaerobic process by micro-organisms. Effluent was recirculated to maintain pH in the range of 7.0–7.3.

System continuous flow performance

System continuous flow performance was evaluated for six different HRTs. The system was evaluated for COD, TSS, pH, Alkalinity and VFAs. After completion of the startup phase, the system was operated in continuous flow mode during an operational period of 91–272 days to evaluate performance of both reactors at HRTs of 24, 18, 12, 08, 06 and 04 h. Under each run, the effect of HRT was evaluated on the performance of both reactors in terms of COD and TSS removal efficiency.

COD removal in continuous flow mode at various HRTs by carrier anaerobic baffled reactor and anaerobic baffled reactor

Feeding of wastewater to the system was initiated at an HRT of 24 h by keeping low organic loading rate (OLR) of 0.41 ± 0.06 g COD/L-day. COD removal and performance efficiency of the system are shown in Figure 3. The system was operated under continuous flow until steady-state conditions were achieved and the system did not show variation of more than 3% in 10 consecutive days (Aqaneghad *et al.* 2018). At HRT of 24 h, CABR and ABR gave maximum COD removal performance of 89 and 74%, respectively. High COD removal for CABR may be attributed to the growth of biomass on carrier media, which utilized more organics for metabolism. Feng *et al.* (2008) reported COD removal efficiency of more than 75% using bamboo carrier media in ABR treating municipal wastewater at 28 ± 1 °C at HRT of 24 h. Similarly, another study conducted by Zha *et al.* (2019) reported COD removal efficiency of 75.06 ± 3.56% using modified ABR for pretreatment of black water at 36 ± 1 °C. So, our study results are consistent with the previous studies using modified ABR for treating municipal wastewater.

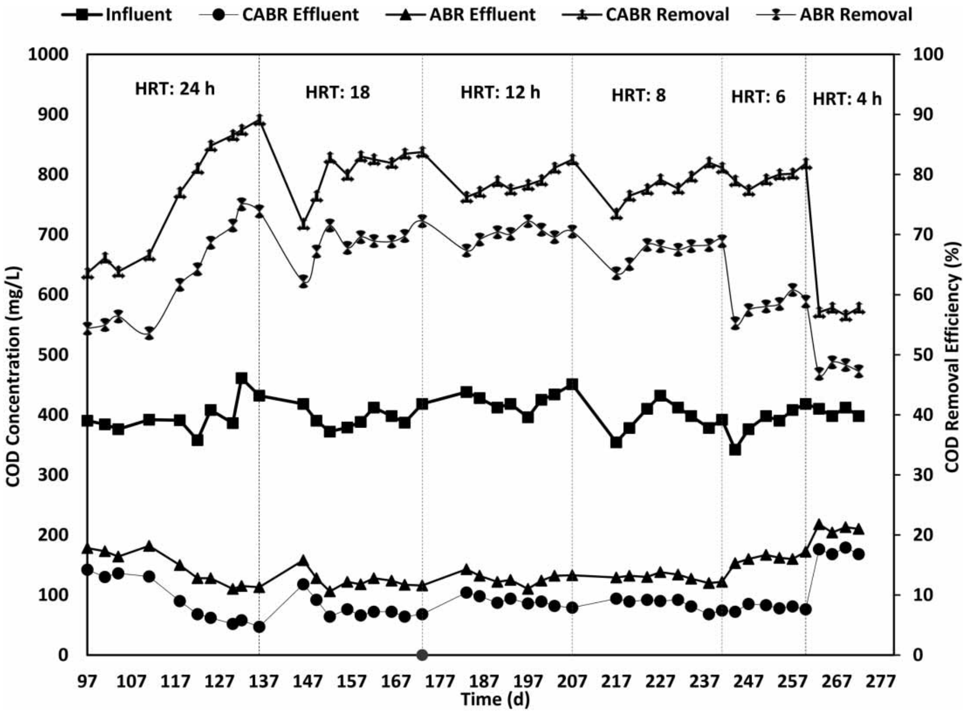


Figure 3 | COD removal of carrier anaerobic baffled reactor and anaerobic baffled reactor during continuous flow mode at various HRTs.

In the second run, system HRT was gradually reduced to 18 h by increasing the OLR to 0.53 $\pm$ 0.03 g COD/L-day. At the start, the system showed a decrease in COD removal, but it recovered as soon as the microbial process properly developed in the system. Maximum COD removal efficiency of 84 and 72% was noted for CABR and ABR, respectively. Bodkhe (2009), using modified ABR for treating municipal wastewater, reported more than 85% COD removal efficiency at OLR of 0.53 g COD/L-day.

In order to further evaluate the system performance, HRT was gradually reduced to 12 h. OLR was further increased to 0.85 $\pm$ 0.05 g COD/L-day. The system was operated for 8 days before taking samples for COD removal. CABR maximum COD removal was 82%, while ABR showed maximum performance of 71%.

In the fourth run, system performance was evaluated for HRT 8 h by increasing OLR to 1.18 $\pm$ 0.12 g COD/L-day. Maximum performance of 81 and 69% was observed for CABR and ABR, respectively, in terms of organics removal . In the fifth run, system HRT was further reduced to 6 h by increasing OLR to 1.55 $\pm$ 0.13 g COD/L-day. CABR retained its maximum COD removal performance at 82% while ABR removal efficiency reduced to 59%. The reason for this increased difference in the performance of CABR and ABR might be attributed to the development of sufficient microbial community in CABR, which consumed high organics for their energy consumption. Su *et al.* (2019) observed the same downward trend in organics removal for changing HRT from 24 to 12 h.

In the final run, the system was evaluated at an HRT of 4 h by increasing OLR to 2.43 $\pm$ 0.04 g COD/L-day. In this case, a drastic decrease in removal performance was noticed for both reactors. COD removal performance of 58 and 47% was observed for CABR and ABR, respectively, which did not satisfy effluent standard permissible limits. At HRT of 4 h, velocity in the upflow chamber significantly increased, which caused reduced contact time of organics with biomass and thus resulted in reduced performance of both reactors. The same downward trend in organics removal was observed by Thanwised *et al.* (2012) with COD removal performance reduced to 21.97 $\pm$ 0.94% from 29.30 $\pm$ 0.84% by shortening HRT from 6 to 3 h treating tapioca wastewater using an ABR.

Average COD removal efficiency for CABR was 77, 81, 79 and 78%, while for ABR these values were 64, 69, 70 and 67% at HRT of 24, 18, 12 and 8 h, respectively, as shown in Figure 4. CABR performed 22, 17, 13 and 17% better than ABR at HRT of 24, 18, 12 and 8 h, respectively. Beyond this point, a major difference in performance of both reactors was observed. CABR

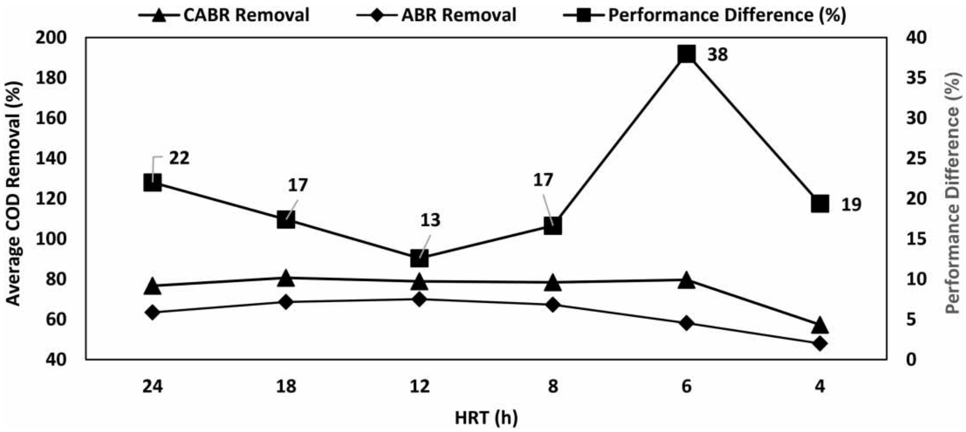


Figure 4 | Average COD removal efficiency and performance difference at various HRTs for carrier anaerobic baffled reactor and anaerobic baffled reactor.

sustained its removal performance at 80%, while ABR performance drastically dropped to 58%, CABR performance was 38% better than ABR at HRT of 6 h.

Biomass developed in the system and adapted to the changing environment, and thus, gradual reduction in HRT from 24 to 8 h did not cause significant reduction in its removal performance. At each HRT after achieving steady-state conditions, biomass growth rate on carrier media might have been equal to biomass decaying and detachment rate, and thus, no improvement in COD removal was observed beyond this point.

Effect of organic loading rate on organics removal

Average OLR and organics removal efficiency for different HRTs of the system are shown in Figure 5. For CABR, organics removal efficiency varied between 77 and 81%, while ABR showed removal efficiency between 64 and 67% in changing OLR from 0.40 to 1.18 (gCOD/L-day). However, further increase in OLR to 1.55 (gCOD/L-day) organics removal of CABR was sustained at 80%, while it dropped to 58% for ABR. These results showed that the biomass retention capacity of CABR has substantially improved, which caused reduced wash out of anaerobes as compared to ABR. So, increase in OLR did not affect CABR performance, as sufficient biomass had been accumulated capable of using high organics as food, while ABR did not

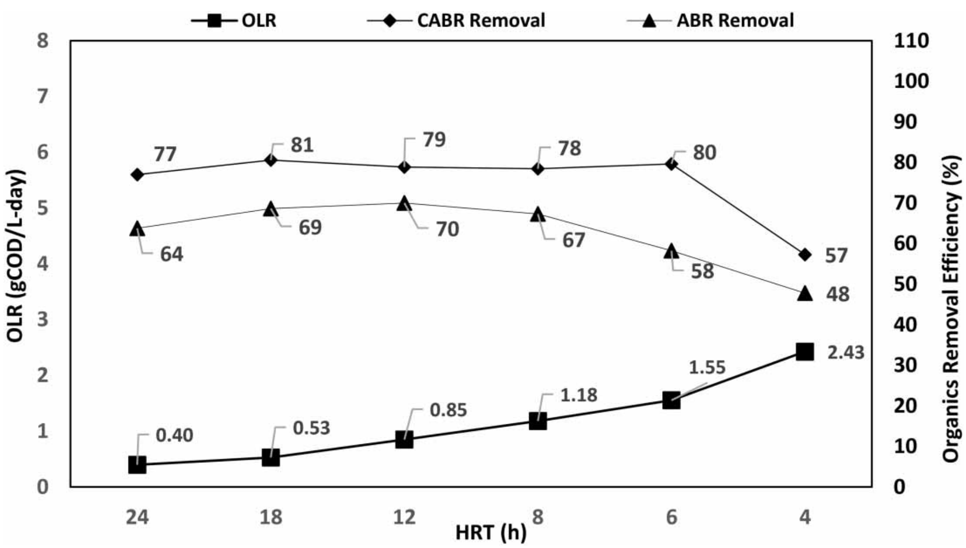


Figure 5 | Average organic loading rate and organic removal efficiency at various HRTs for carrier anaerobic baffled reactor and anaerobic baffled reactor.

have sufficient biomass to use the increased organics as food, and thus, its removal performance was reduced significantly. Further increase in OLR caused reduction in organics removal efficiency of both reactors.

Change in OLR from 0.40 to 1.55 (gCOD/L-day) did not reduce removal performance of CABR, which indicates that CABR can be used as a high-rate organic load reactor with improved organics removal performance, thus reducing wastewater treatment cost.

TSS removal by carrier anaerobic baffled reactor and anaerobic baffled reactor

Influent SS concentration varied from 49 to 58 mg/L. Variation in SS removal efficiency along with variation in HRT is illustrated in Figure 6. Reduction in HRT from 24 to 4 h did not cause any significant reduction in SS removal performance and varied between 83 and 76% for both reactors. Moradgholi *et al.* (2019) reported SS removal performance of 79% and 78.5% at HRT 24 and 18 h, respectively, using electrical simulated ABR for treating low-strength municipal wastewater.

SS concentration in both reactors' effluent varied from 9 to 14 mg/L. It was observed that when the system was brought to continuous flow mode, SS removal efficiency was too low, which gradually improved with the passage of time. Similarly, minute reduction in SS removal was observed when HRT was reduced at various intervals. This reduction in removal efficiency was caused due to disturbance occurring due to detachment of loosely attached biomass as flow rate was increased. The disturbance ended with wash-away of loosely attached biomass and solids; thus, an improvement in SS removal was observed with the passage of time for each HRT.

pH of ABRs during continuous flow mode

pH plays a significant role in anaerobic treatment of wastewater. pH value did not show any significant variation among various HRTs, and it varied between 7.0 and 7.1. These values fall in the optimum pH range (6.8–7.5) for the growth of anaerobes (Pirsaheb *et al.* 2021). It was observed that variation in influent pH does not cause significant change in effluent pH for both reactors. This is because of the fact that the VFAs produced were effectively consumed by methanogens. Effluent pH values indicated more favorable conditions in the system for microbes, thus causing no inhibition.

Alkalinity and volatile fatty acids (VFAs) of ABRs

Alkalinity determines the ability of the anaerobic process to resist changes in pH, which directly affects system performance (Pirsaheb *et al.* 2015). Total alkalinity (TA) and VFA/TA ratio in the reactors of the present study are illustrated in Figure 7. TA for CABR and ABR varied between 810 and 515 and between 750 and 500 (mg/L as $CaCO_3$), respectively. Alkalinity of CABR and ABR was 780 and 740 (mg/L as $CaCO_3$), respectively, at HRT 24 h. It was observed that shifting of HRT to 18 h caused TA to increase to 810 and 750 mg/L for CABR and ABR, respectively, which remained unchanged while reducing

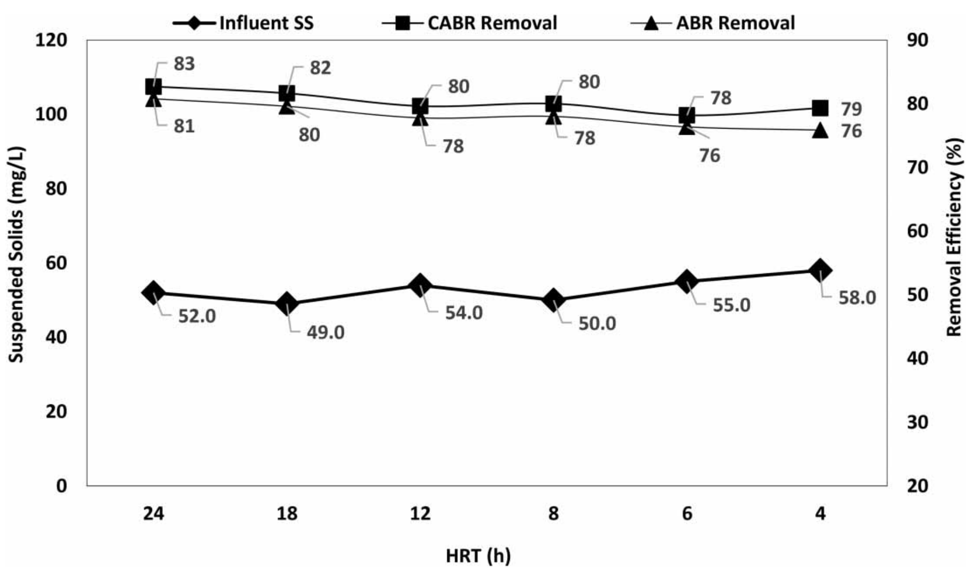


Figure 6 | Average suspended solids removal of carrier anaerobic baffled reactor and anaerobic baffled reactor at various HRTs.

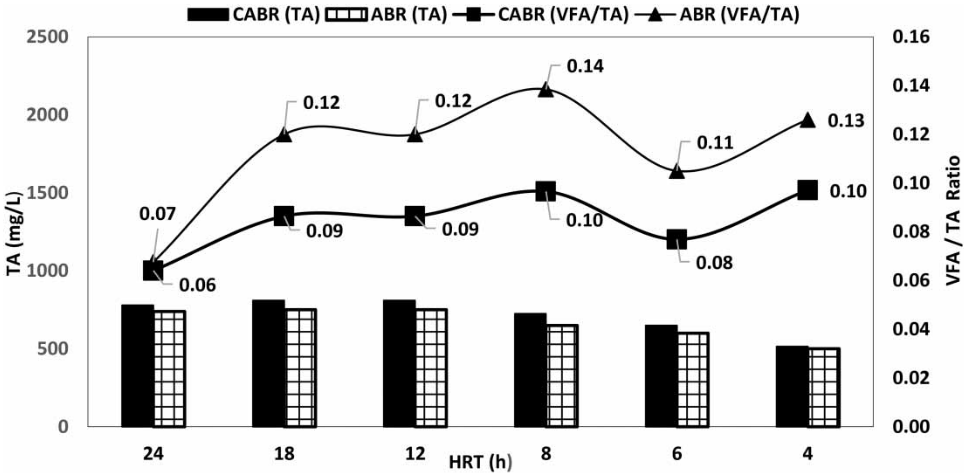


Figure 7 | Total alkalinity and VFA/alkalinity ratio at various HRTs for carrier anaerobic baffled reactor and anaerobic baffled reactor.

HRT to 12. Reduction in TA was observed for both reactors when HRT was reduced to 6 and 4 h. Shortening the HRT was accompanied by increase in OLR, which caused acidification in both reactors after a certain time. To neutralize the VFAs, available alkalinity was utilized, which caused a decrease in total alkalinity (Rajesh Banu *et al.* 2008).

The ratio of VFA to TA determines the stability of the anaerobic process, and it should be below 0.25 for proper working of the anaerobic process (Sayedin *et al.* 2019). It was observed that the VFA/TA ratio was 0.07 and 0.06 for CABR and ABR, respectively, which indicates the stability of the system for HRT of 24 h. It was also observed that for HRT 18, 12, 8, 6 and 4 h, the VFA/TA ratio was in the range of 0.1–0.14, which signified good performance of both reactors. A VFA/TA ratio beyond 0.4 causes system instability, and corrective action needs to be taken (Khanal 2008).

SELECTION OF PROPER HRT

HRT plays a key role in cost effectiveness, because it affects the reactor volume required for anaerobic treatment of wastewater; however, it also affects the treatment efficiency. Proper HRT should be ensured to reduce capital and operation cost while ensuring permissible effluent limits. It was observed that an HRT as low as 6 h for CABR gave optimum performance for organics and SS removal. Moreover, HRT longer than 6 h had no significant effect on removal performance, whereas HRT less than 6 h had a negative effect on organics and SS removal. Table 3 describes the comparative performance of this study with other previous studies related to ABRs and modified ABRs in treating municipal or low-strength wastewater. According to this review table, different ABRs and modified ABRs performed differently in organics and SS removal. Reactor performance is greatly affected by HRT, operating temperature, wastewater characteristics and reactor configuration.

Table 3 | Performance comparison of various anaerobic baffled reactors, modified anaerobic baffled reactors and carrier anaerobic baffled reactors in treating municipal/low-strength wastewater

ABR System Type	HRT (h)	COD (%)	TSS (%)	Reference
ABR	12	43	83	Hahn & Figueroa (2015)
ABR	24	75	79	Moradgholi *et al.* (2019)
ABR	12	70	78	This study
ABR Modified (nine chambers of equal size arranged in three parallel sets)	6	84	86	Bodkhe (2009)
Panelled anaerobic baffle-cum-filter reactor	6	83	92	Renuka *et al.* (2016)
CABR (Bamboo carrier)	48	79	81.9	Feng *et al.* (2008)
CABR (PVC corrugated pipe)	6	80	78	This study
CABR (PVC corrugated pipe)	18	81	82	This study

The present study gave better performance results, which are in line with the results of previous studies. Most importantly, PVC corrugated media will improve ABR performance at any HRT down to as low as 6 h. Furthermore, the existing ABRs can be upgraded to a high organic load reactor by introducing PVC corrugated media, which will give optimum results at HRT of 6 h. Most importantly, CABR can easily be implemented at field level in a cost-effective manner for new treatment plants as well as for the upgradation of the existing ABRs.

Reduction in HRT ultimately results in less land area requirement for plant construction, as a lower reactor volume would be required based on the formula $V = Q \times HRT$. This will reduce the capital and construction cost of the plant. Ultimately, the cost of wastewater treatment will be reduced and will result in improving water quality and public health by reducing water pollution, safer reuse of treated wastewater, and increasing sanitation coverage all contributing towards SDG – 6.

CONCLUSION

Performance evaluation of CABR was conducted in a long-term operation of 272 days, and its comparison with simple ABR was made at HRTs of 24, 18, 12, 8, 6 and 4 h. The CABR achieved COD and SS removal of 80 and 78%, respectively, in treating municipal wastewater at an HRT of 6 h. In comparison, ABR showed COD removal performance of 58% at the same HRT, which indicates that carrier media in CABR is helpful in sustaining the treatment performance at HRT as low as 6 h and CABR can be used as a high-rate, low HRT reactor. Better performance of CABR at low HRT is attributed to the fact that PVC carrier media provided a suitable surface area for biomass immobilization, retention and growth. Further studies are suggested to evaluate ABR performance using various cheaply available carrier media for removal of organics, nutrients, and suspended solids.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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