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Hydrodynamic behaviour and treatment performance of the hybrid anaerobic baffled reactor

N. Dharsika[a], S. Amal Raj[a,*], S. Mariraj Mohan[b]

[a]*Centre for Environmental Studies, Anna University, Chennai, Tamil Nadu, India, Phone: 9003221411; email: amalrajz@yahoo.com (S. Amal Raj), Phone: 9042212157; email: darskanagul@gmail.com (N. Dharsika)*
[b]*Department of Civil engineering, Alagappa Chettiar Government College of Engineering and Technology, Karaikudi, Tamil Nadu, India, Phone: 9865186845; email: mari_sundar@yahoo.com*

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ABSTRACT

In this study, the hybrid anaerobic baffled reactor (HABR) is designed with four compartments to study the hydrodynamic behaviour and the treatment performance by varying the hydraulic retention time. Residence time distribution analysis investigates the flow pattern and the amount of dead space in HABR by varying the hydraulic retention time (HRT) at 4 h, 8 h, and 12 h. The results obtained from the hydraulic study showed that the flow pattern in HABR fell between a continuous stirred tank reactor and plug-flow for all the runs. It has been observed that the dead-space value in HABR is below 15%, which is comparatively lower than other high-rate reactor designs. The start-up period of HABR is found to be 55 d with maximum chemical oxygen demand (COD) removal efficiency of 87% at an organic loading rate of 0.7 kg COD/m^3/d and 24 h HRT. The COD removal rate of the HABR increases by increasing the HRT (4–12 h) as the flow tends to be more intermediate between the plug-flow and continuously stirred tank reactor. The overall COD removal efficiency of HABR is between 73% and 91%, biochemical oxygen demand is between 80% and 88%, and total suspended solid is 88%–93%.

Keywords: Anaerobic wastewater treatment; Anaerobic baffled reactor; Residence time distribution; Dead space

1. Introduction

The advantage of anaerobic process systems like the minimum energy requirement, minimum sludge production, and minimum operation and maintenance for domestic and industrial wastewater treatment has gained importance over the aerobic processes [1,2]. The septic tank is a widely accepted anaerobic treatment technology due to its economic and functional features, especially in developing countries [3]. The drawbacks associated with the septic tank, like the low treatment efficiency and ineffectiveness in removing nutrients and pathogens, have paved the way for wholly controlled reactors [4,5]. One such novel anaerobic type of technology is the anaerobic baffled reactor. MeCarty [6] at Stanford University initially developed the anaerobic baffled reactor to treat high-strength wastewater. The vertical baffles in the reactor force wastewater to flow under and over as it passes from inlet to outlet [7]. It is well-adopted as a sound decentralized treatment system in the urban and rural areas to treat municipal wastewater, especially in developing countries [8]. The reactor's hydrodynamics and the performance of biomass in the reactor are the two major factors that influence the conversion of organic and inorganic matter in an anaerobic process [1]. An excellent hydraulic pattern inside the reactor leads to good treatment efficiency [9]. The superb flow pattern in the reactor assures the effective

* Corresponding author.

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use of the reactor volume by limiting dead space and the maximum substrate transfer to the microorganisms [10].

In a typical anaerobic treatment system, all stages such as hydrolysis, acetogenesis, and methanogenesis occur due to proper selection of hydraulic retention time (HRT). In addition to this, HRT helps maintain proper mixing inside the reactor; as a result, it ensures sufficient contact time between the substrate and the biomass. In general, an increase in HRT will increase treatment efficiency up to a certain limit, beyond which a reduction in treatment efficiency occurs. Hence, it is necessary to maintain optimal HRT. The organic loading rate (OLR) is a function of influent substrate and HRT. To maintain sufficient active biomass inside the reactor, minimum OLR should be maintained [11]. In a typical anaerobic reactor, OLR plays an important role in the reactor's start-up and reactor's robustness [12]. Anaerobic baffled reactor was effectively used to treat low-strength wastewater for the last two decades. Low strength wastewater has a low chemical oxygen demand (COD) concentration below 1,000 mg/L, including municipal and domestic wastewater. Many research works were carried out in anaerobic baffled reactor (ABR) to treat various low strength wastewater with an organic loading rate of 0.3–3 kg COD/m^3/d and HRT 6–24 h achieving a COD removal efficiency of about 85%–90% [2,13–16]. Anaerobic baffled reactor has a good performance in treating high-strength wastewater. A long hydraulic retention time of about 10 d was required to have good contact between the biomass and substrate and to enhance the settling capacity. The higher organic content increases biogas production, producing turbulent biomass mixing, thus having a higher treatment capacity. The works report the high-strength wastewater treatment with an OLR of 0.33–8 kg COD/m^3/d and HRT 4–20 d, achieving 70%–90% COD removal efficiency [17–20].

The hybrid anaerobic baffled reactor is an anaerobic baffled reactor with improved design concepts and principles to increase the treatment efficiency and the contact between the microorganisms and their substrate. The hybrid anaerobic baffled reactor (HABR) with different media and flow patterns has the advantages like easy biomass attachment, lowering the biomass washout, and increasing the contact area for the biomass and the substrate. The aim of the work is to maximize the treatment efficiency in the reactor by combining both the anaerobic and aerobic processes in the hybrid anaerobic baffled reactor with some modifications in the parent ABR. Very little research work is done combining anaerobic with the aerobic process in a single reactor. These combinations help to eliminate post-treatment to meet effluent quality. In the HABR, the first three compartments act as the anaerobic system and the last compartment as the aerobic to improve effluent quality. The provision of the aerobic process in the last compartment didn't affect the anaerobic process in the previous compartment. Furthermore, the Performance of the hybrid baffle reactor was monitored by varying operational HRTs. In this study, the hydraulic characteristics of HABR are investigated by a series of residence time distribution (RTD) studies to illustrate the effect of HRT and the number of compartments affecting the mixing pattern and dead space in the reactor and the influence of hydraulic characteristics on the treatment efficiency of the reactor.

2. Materials and methods

2.1. Configuration of hybrid anaerobic baffled reactor

The hybrid anaerobic baffled reactor was made-up of Flexi glass material with a thickness of about 8 mm. The reactor was 100 L capacity with a length of 500 mm, a breadth of 400 mm, a height of 400 mm, and a freeboard of 100 mm. The reactor consisted of four compartments; the first three compartments performed as the anaerobic chambers, and the fourth compartment as an aerobic chamber. In the HABR reactor, the volume of the first three compartments was 20 L (length 100 mm, width 400 mm, and height 500 mm), and the fourth compartment was 40 L (length 200 mm, width 400 mm, and height 500 mm). The baffles were used between the compartments to divide them into up-flow and down-flow chambers in a ratio of 1:4. The sampling port and the sludge drain port were located at a distance of 15 cm from each compartment's top and bottom. The first compartment was provided with the zigzag baffles to speed up the sedimentation process. The up-flow chambers in the first three compartments were packed with media to a height of 300 mm. The second and fourth up-flow chambers were completely packed, while the third compartment up-flow chamber was provided with 40% of media. The media characteristics are presented in Table 1. The gas manifolds were provided on the top of the reactor to collect the biogas generated during the anaerobic process and quantified using the water displacement method. The schematic representation of field scale HABR is presented in Fig. 1.

2.2. Reactor operation

Initially, the reactor was operated in batch mode for 7 d. From the 8th day of operation, the reactor was operated in continuous mode, the hydraulic retention time was maintained at 24 h, and the organic loading rate was at 0.7 kg COD/m^3/d. During the start-up process, the COD removal and pH were analysed. After the steady-state phase in the reactor, the hydraulic retention time was reduced to 4 h, 8 h, and 12 h. The effluent was collected at all four compartments, and the parameters such as COD, biochemical oxygen demand (BOD), total suspended solids, and pH were determined according to the standard methods [21]. The samples were taken in a particular HRT until the reactor achieved the pseudo-steady-state. Pseudo steady state was the insignificant variation in the effluent COD values for successive days.

2.3. Inoculum and feed water characteristics

Anaerobic sludge and aerobic sludge were collected from the anaerobic digester and aeration tank, respectively, at the sewage treatment plant located in Perungudi, Chennai, Tamil Nadu, India. The sludge was passed through a 1.18 mm sieve to remove the debris from the sludge. The first three compartments in the reactor were filled with the anaerobic feed water, and the aerobic sludge was filled in the fourth compartment. The seed sludge was filled up to 50% of the reactor volume. The characteristics of the anaerobic sludge were pH 7.5, COD 40 g/L,

Table 1
Different media characteristics in HABR

Parameters	Media in second compartment	Media in third compartment	Media in fourth compartment
Material	Polypropylene	Polypropylene	Polyethylene
Outer diameter, mm	20	10	60
Inner diameter, mm	18	8	–
Height, mm	14.5	7	–
Density (g/cm^3)	0.97	0.98	0.96
Specific surface area, m^2/m^3	500	680	1,000
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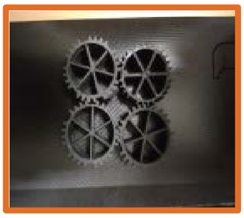
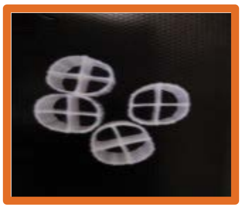
Image			

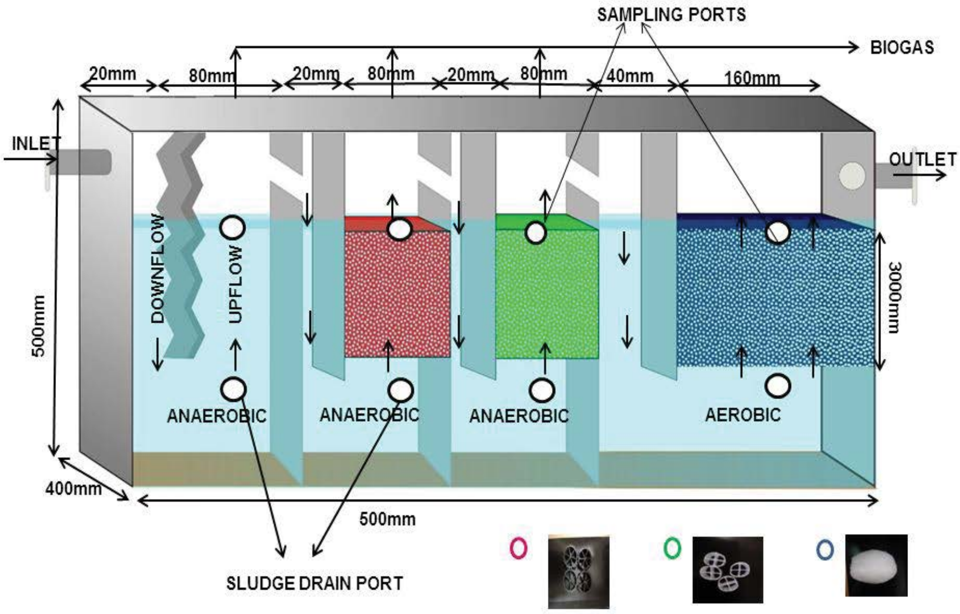


Fig. 1. Diagrammatic representation of HABR.

alkalinity 2350 mg-CaCO$_3$/L, and its biomass concentration was 36.6 g (VSS)/L. The characteristics of the aerobic sludge were pH 7.05, COD 36 g/L, alkalinity 1880 mg-CaCO$_3$/L, and biomass concentration 16.26 g (VSS)/L.

The feed water was the domestic wastewater collected from the Anna University staff quarters and hostels. The characteristics of the feed water are given in Table 2.

2.4. Tracer study

The flow pattern in the reactor was studied using tracer-response studies. The residence time distribution was used to study the hydraulic characteristics inside the reactor. The factors which influenced the tracer analysis were up-flow velocity inside the reactor, mixing, biomass accumulation, and biogas formation. Due to its advantages, the pulse input method was preferred over the step input method. In the pulse input method, a small amount of the tracer was only needed, while in the step input, the tracer was injected until the tracer reached a steady state. The Ponceau 4R was used as the tracer since it will not react or get absorbed in the substances inside the reactor and its maximum absorbance was at 508 nm [22,23]. The samples were collected at constant intervals in all four compartments after the tracer was injected within 10 s into the inlet for a time interval of two times the hydraulic

Table 2
Characteristics of feed water

Parameters	Values
pH	7.04
Alkalinity as $CaCO_3$ (mg/L)	360 ± 10
Biochemical oxygen demand (3 d@27°C) (mg/L)	300 ± 15
Chemical oxygen demand (mg/L)	700 ± 50
Total suspended solids (mg/L)	380 ± 20
Total Kjeldahl nitrogen (mg/L)	60
Total phosphate as P (mg/L)	8
Sulfate as SO_4 (mg/L)	60

retention time. The UV-visible spectrophotometer was used to find the absorbance of samples at 508 nm, and RTD curves were drawn for all four compartments. The above procedure was carried out in the reactor by varying the hydraulic retention time at 4 h, 8 h, and 12 h.

2.5. Theoretical interpretation

The tracer stimulus-response technology was used to carry out residence time distribution studies. The RTD curves were drawn between the normalized time and normalized concentrations at different hydraulic retention times. The mixing patterns in the reactor at different HRTs were studied by normalizing the time and are given in Eq. (1):

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

where θ is the normalized time, t is the sampling time, and HRT is the hydraulic retention time. The normalized tracer concentration is given in Eq. (2):

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

where C_θ is the normalized tracer concentration, $C(t)$ is the tracer concentration at time t, and C_0 is the initial tracer concentration. The mean residence time (τ) is given in Eq. (3):

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

The variance (σ_m^2) is given in Eq. (4):

$$\sigma_m^2 = \frac{\int_0^\infty (t-\bar{t})^2 C(t)dt}{\int_0^\infty C(t)dt} \text{ [24–27]} \tag{4}$$

The axial dispersion model was highly suitable for relatively low back-mixing. The mixing in the radial direction is neglected in the axial dispersion, and it is assumed that the back-mixing occurs only in the radial direction. Only axial mixing was considered for a closed vessel boundary condition, and the normalized variance as a function of dispersion number is given in Eq. (5):

$$\sigma_\theta^2 = 2\left(\frac{D}{uL}\right) - 2\left(\frac{D}{uL}\right)^2 \left(1 - e^{-uL/D}\right) \tag{5}$$

where D is the axial dispersion coefficient, u is the average fluid velocity, L is the axial distance of the reactor, and (D/uL) is the dispersion number (d).

For the condition of strong back-mixing, the tanks-in-series model was applied. N is the number of the continuous stirred tanks-in-series and is given in Eq. (6):

$$N = \frac{1}{\sigma_\theta^2} \tag{6}$$

The dead space (V_d) in the reactor is given in Eq. (7):

$$V_d(\%) = \left(1 - \frac{\tau}{\text{HRT}}\right) \times 100 \tag{7}$$

The hydraulic efficiency of the reactor is given in Eq. (8):

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

where e = τ/HRT is the hydraulic efficiency given by [28], and λ is the hydraulic efficiency given by [29]. The λ value varies from 0 to 1, and it was classified into three groups and is presented in Table 3 [25].

3. Results and discussion

3.1. Residence time distribution studies

The mixing pattern in the reactor was analysed by fitting the variance value into the axial dispersion model and tanks-in-series model [30]. The curve was drawn with normalized time (θ) along the horizontal axis and normalized tracer concentration (C_θ) along the vertical axis to compare the RTD curves. There was only a marginal difference in RTD peaks by varying HRTs, but there was a significant difference in RTD peaks by varying the number of compartments in the reactor. Thus the number of compartments in the reactor was the critical factor in influencing the hydrodynamic behaviour of the reactor. Fig. 2a–c show the RTD curves of HABR at 4 h, 8 h, and 12 h in different compartments.

In the AD model, the mixing pattern was characterized by the dispersion number (D/uL) and Peclet number (Pe). The reactor flow was said to be plug-flow when the (D/uL) was 0, and the flow will be in completely mixed condition if the (D/uL) was ∞. When (D/uL) between 0.02 and 0.2, there will be enormous dispersion, and the flow would be intermediate between plug-flow and completely mixed [30]. For all the runs, the $d = D/uL$ values were between $0.2 > d > 0.002$ in most of the chambers, which leads to large dispersion, and the reactor was said to be intermediate between mixed flow and plug flow conditions.

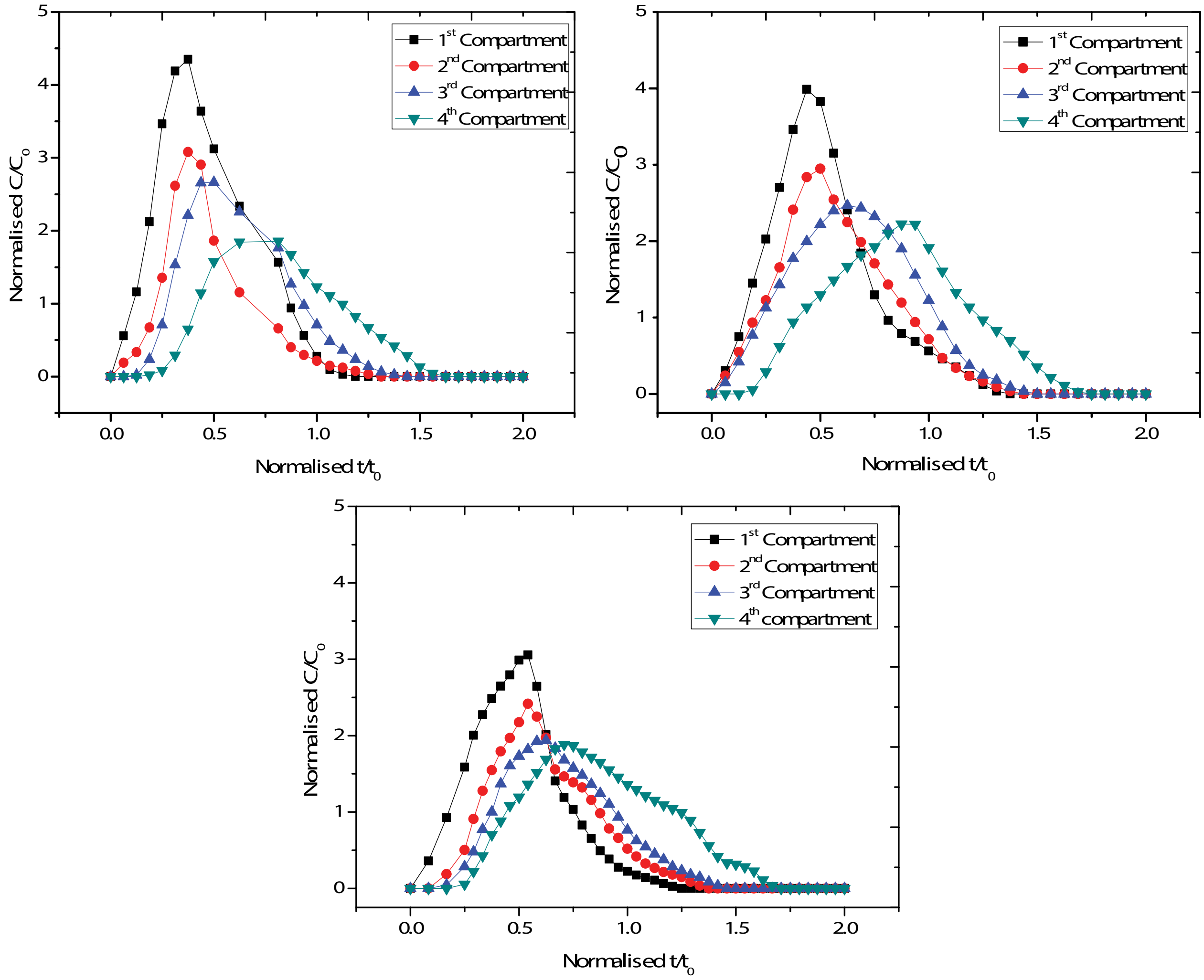


Fig. 2. (a–c) Residence time distribution curves of HABR at 4 h, 8 h, and 12 h.

Table 3
Conditions based on hydraulic efficiency

S. No	λ value	Condition
1	>0.75	Good hydraulic efficiency
2	0.5–0.75	Satisfactory hydraulic efficiency
3	<0.5	Poor hydraulic efficiency

In the tanks-in-series model, if N tends to be 1, the reactor was approximated to be a completely mixed reactor, and if N tends to ∞, the reactor was approximated to be a plug-flow reactor [31–33]. The increase in N value by the increase in hydraulic retention time approaches the reactor towards plug flow condition. For all the HRTs, the N values of the first and second compartments mostly lie between 7 and 4, making the flow pattern intermediate between CSTR and plug flow. The $N > 6$ for the flow in the third and fourth compartments which was closer to the plug flow condition. A similar flow pattern was observed in the hydrodynamic study conducted on an eight-chambered ABR. They found that the flow pattern was intermediate between completely mixed flow and plug-flow. However, as the HRT or number of compartments increased, the reactor behaved well like a plug-flow reactor [30]. The panelled anaerobic baffle-cum filter reactor was designed to investigate the flow pattern. It was also assumed to be intermediate between completely mixed and plug-flow with lesser dead space below 7.4% [9].

The dead zones adversely affected the overall treatment efficiency of the reactor because the dead zone volume was unaccountable to the main flow reducing the mean residence time. Dead zones tend to occur in corners and areas behind. The hydraulic and organic dead spaces constituted the total dead space [32]. The flow rate and the number of compartments in the reactor influenced the hydraulic dead space, whereas biological dead space was a function of biomass and its activity [32]. The hydraulic dead space increased as the HRT decreased, and the higher dead space in the first compartment for 4 h HRT was due to the channelling, which caused stagnant eddies formation under weirs and in corners of the reactor. These eddy acted as reservoirs where the tracer slowly diffuses in and out inside the reactor. The number of compartments was the primary factor in the creation of dead space in comparison to HRT. The variation of dead space concerning the number of compartments was high compared to the variation of dead space concerning HRT. The observation showed that the number of compartments played a vital role in creating dead space compared to HRT.

The dead space decreases by increasing the number of compartments. The HABR with four compartments had the most negligible dead space value. The dead space value increases as the HRT increases since only hydraulic dead space was carried out in the study because the hydraulic dead space contributes to a significant part of the total dead space [33]. The increase in tail area was the reason for the higher value of dead space in the initial compartments, and the dead space value decreased as we increased the number of compartments. From Fig. 2a–c, it was evident that the tail-area decreases as the HRT increases, which was the cause of the decrease in dead space by increasing the HRT. The HABR with four compartments and 4 h HRT had the most negligible dead space value of 13.3%. The dead space value varied between 58.3% and 13.3% throughout the study. A similar work observed a low dead space of about 13% for the ABR with different peak flow factors (1–6) [32]. Khalekuzzaman et al. [30], investigated seven compartment hybrid anaerobic baffled reactors, and the maximum dead volume was 10% approximately by varying the hydraulic retention time (5–20 h). Fig. 3 describes the dead space of HABR at different HRTs in the compartments.

The hydraulic efficiency explained the ability to distribute the flow evenly within the reactor and the maximum contact time of pollutants in the reactor with uniform mixing [33]. The flow in the HABR with four compartments had a good hydraulic efficiency with $\lambda > 0.75$. The λ values of HABR with three compartments were between 0.61 and 0.9, which showed the reactor with medium hydraulic efficiency. The HABR with single and two compartments had $\lambda < 0.5$ with poor hydraulic efficiency. The λ value described that the HABR with four compartments had good hydraulic mixing and even flow distribution inside the reactor. Fig. 4 clearly describes the dispersion number and the hydraulic efficiency in the compartments at 4 h, 8 h, and 12 h HRT. The hydrodynamic indices obtained from axial dispersion model and tank in series model, dead space and hydraulic efficiency are given in Table 4.

3.2. Start-up

After seeding, the reactor was operated at a loading rate of 0.7 kg COD/m^3/d with an HRT of about 24 h. The start-up curve showing the various phases in the reactor is shown in Fig. 5a. The curve shows three distinct phases in the start-up process. During the acclimatization phase, the COD removal was 60% which increased to 69%, showing that the active biomass has started to consume the substrates in the feed water. The removal efficiency increased from 69% to 87% during the growth phase, showing rapid biomass growth adapting well to the prevailing reactor condition. In the steady phase, the removal efficiency was more than 87%. After that, there was no significant change

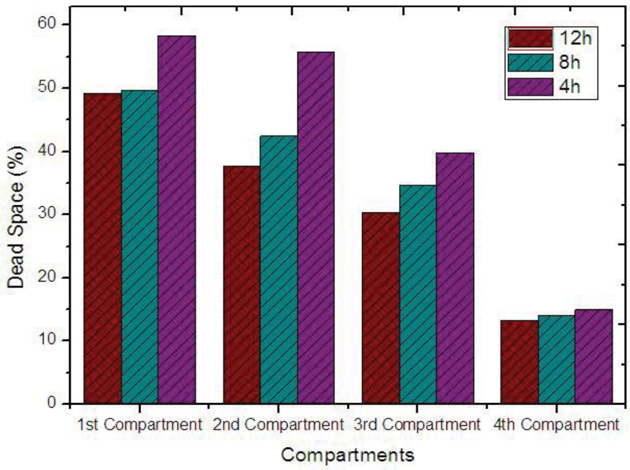


Fig. 3. Dead space of HABR in the compartments at 4 h, 8 h, and 12 h.

in the removal efficiency, stating that the reactor was fully acclimatized at 55 d.

The factors which influenced the start-up process were the temperature, pH, and degree of mixing. In HABR, pH during the start-up phase in all compartments was monitored in all three stages to know the rate of consumption of volatile fatty acid produced by the microorganisms and to know the equilibrium state between the acidogenic and methanogenic bacteria. Due to the low rate consumption of volatile fatty acid during the acclimatization phase (13–34 d) in the start-up process, the pH values were less in the range of 7.06–6.8. The above pH range was due to the non-establishment of equilibrium between the acidogenic and methanogenic bacteria. After the acclimatization phase, there was a rise in the pH value during the growth and steady phases due to the stabilisation of the volatile fatty acid in the compartments. The pH was 7.14–6.99 in the growth phase and 7.35–7.09 in the steady phase. The increase in pH value showed the condition favourable for the methanogenic bacteria, especially in the rear compartments.

3.3. Overall performance of HABR

3.3.1. Removal of organics

The performance study of HABR was consistent after attaining the steady-state due to the change in flow by altering the HRTs. The HRT was increased, and there were initial fluctuations in the performance, but after attaining the steady-state, the performance of the reactor was constant. The overall performance of the HABR was described in terms of the reduction in COD, BOD, and total suspended solid (TSS) removal. The influent COD was averaged between 700 ± 50 mg/L with 73%–91% total COD removal for 4 h, 8 h, and 12 h HRTs. The effluent COD concentration above 8 h HRT was below 60 mg/L with removal efficiency greater than 90%. As the HRT decreased further to 4 h HRT, the performance of the reactor declined, and COD removal efficiency was 73%. When the number of compartments was increased, the overall efficiency of the reactor also increased. The

Table 4
Hydrodynamic indices, dead space, and hydraulic efficiency in HABR

Compartment	HRT (h)	Mean retention time (τ) (h)	Dispersion number (*d*)	Number of tanks-in-series (*N*)	Dead space (%)	Hydraulic efficiency (λ)
1	12	6.10	0.077	7.04	49.2	0.43
2	12	7.48	0.068	7.87	37.7	0.54
3	12	8.35	0.063	8.47	30.4	0.61
4	12	10.40	0.063	8.47	13.3	0.76
1	8	4.10	0.119	5.00	49.7	0.41
2	8	4.61	0.101	5.49	42.4	0.47
3	8	5.23	0.085	6.45	34.6	0.55
4	8	8.20	0.064	8.33	14	0.76
1	4	1.67	0.140	4.17	58.3	0.32
2	4	1.77	0.126	4.54	55.8	0.34
3	4	2.41	0.100	5.55	39.8	0.49
4	4	3.40	0.067	8.06	15	0.75

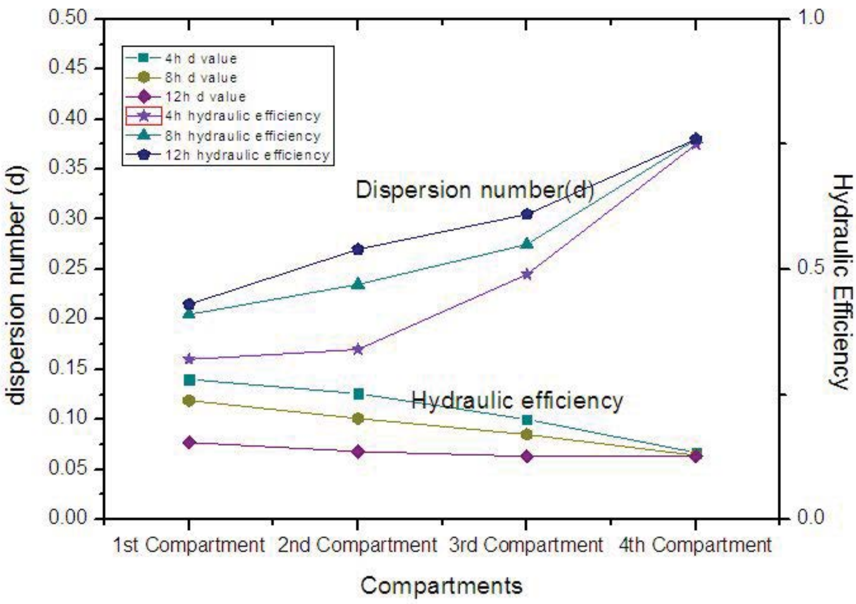


Fig. 4. Dispersion number (d) and hydraulic efficiency in the compartments at 4 h, 8 h, and 12 h.

overall efficiency of HABR with three compartments ranged between 87% and 61% for different HRTs, and for HABR with two compartments, it was 79% to 53%, and for HABR with a single compartment, it was 55% to 38%. There was also a limitation that there was no significant increase in removal efficiency by further increasing the number of compartments.

From Fig. 6b we can observe that on the 55th day, the HABR had attained steady-state, and the COD removal was about 87% at OLR of about 0.7 kg COD/m^3/d. Hence the HABR has acclimatized within 55 d. After 90 d of operation, the reactor was operated at the OLR of about 4.12 ± 0.19 kg COD/m^3/d and 4h HRT. From Fig. 6b it is also evident that there was a slight fluctuation in the performance after every change in HRT. Once it attained a steady-state, the performance was constant. At 4 h HRT, the COD removal percentage was about 73%, and the effluent COD was averaged at 170 mg/L. From the 145th day, the HRT was increased to 8 h, and the OLR was about 2.05 ± 0.05 kg COD/m^3/d. After a few days of operation and attainment of steady-state, the COD removal was about 91%, with effluent COD value below 60 mg/L. From the 210th day, the HRT increased to 12 h, and OLR was about 0.97 ± 0.05 kg COD/m^3/d. After attaining the steady-state, the COD removal was about 92%, and the effluent concentration was about 57 mg/L. Fig. 6c shows the biogas yield for 4 h, 8 h, and 12 h HRTs. The average biogas yield of HABR at 4 h operation was 0.204 m^3/kg COD. By increasing the HRT value to 8 h and 12 h, the average biogas yield was about 0.377 and 0.381 m^3/kg COD.

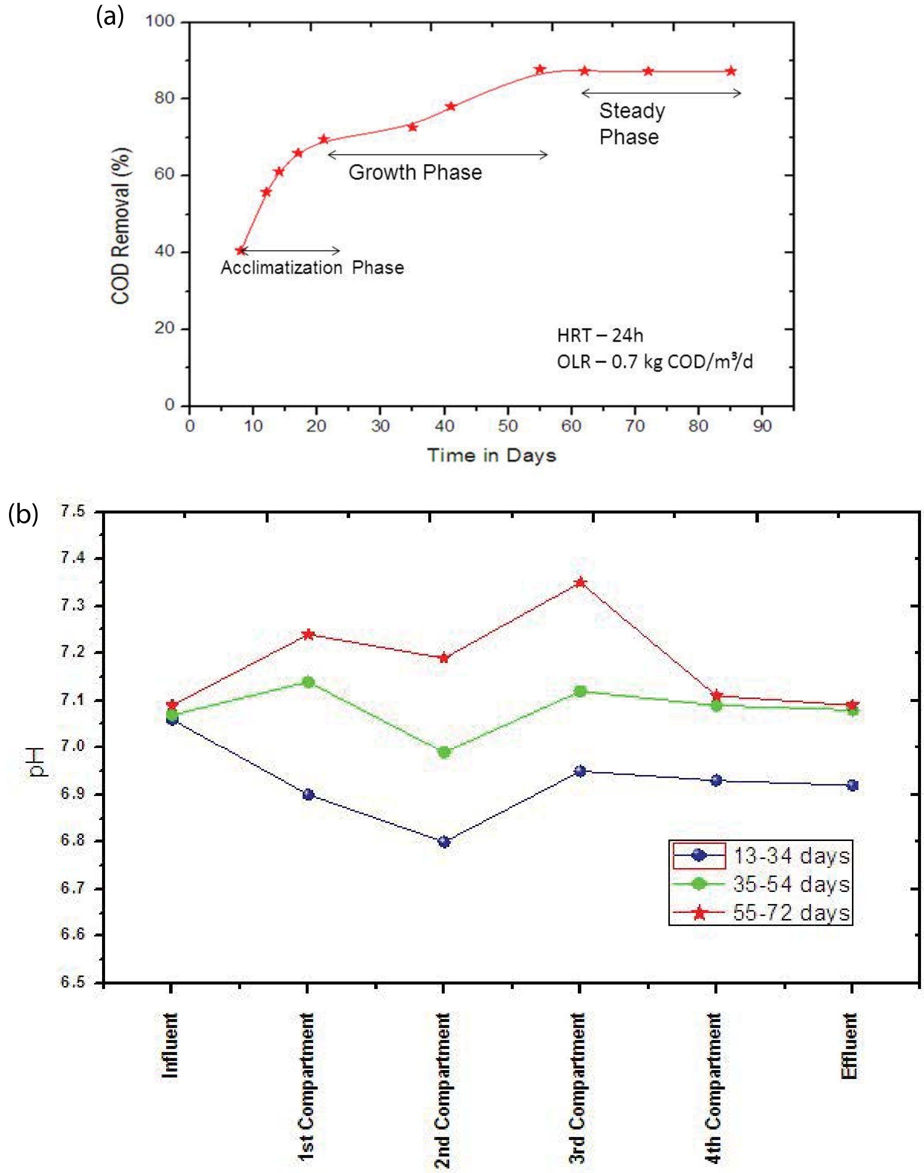


Fig. 5. (a) Various start-up phases in HABR and (b) pH values at various phases during the start-up process in HABR.

The nine-chambered modified anaerobic baffled reactor attained a COD removal efficiency of about 84% at 6h HRT [2]. A five-compartment panelled anaerobic baffled cum filter reactor (PABFR) with OLR of 0.37–6.96 kg $COD/m^3/d$ for 2–40 h HRT achieved the COD removal efficiency in the range of 57%–92% [34]. The low strength complex wastewater of OLR 0.6–2 kg $COD/m^3/d$ at 6–20 h HRT achieved COD removal efficiency of 88%–92% [14]. This study's hybrid anaerobic baffled reactor provides maximum COD removal efficiency of 91% at 8 h HRT compared to other anaerobic baffled reactors. The higher COD removal efficiency was due to the suspended growth microorganisms in the first compartment, attached growth microorganisms in the last three compartments, and the combination of anaerobic and oxic processes in the HABR.

The removal of BOD followed a similar trend as the COD removal. The BOD concentration of the influent was averaged at 300 ± 15 mg/L, and the effluent BOD concentration above 8h HRT was averaged below 35 mg/L, with the removal efficiency greater than 88%. The HRT was decreased to 4 h, and the BOD removal efficiency was also reduced to 80%, with the decline in reactor performance. The BOD removal of HABR with three compartments ranged between 64% and 84%, and with two compartments, it ranged between 46% and 69%. The BOD removal with a single compartment was in the range of 48%–58%. Thus HABR with four compartments gave satisfactory BOD removal efficiency.

The increase in suspended solids concentration in the effluent might occur due to the disturbance in the sludge bed by high-strength feed water because of the higher biogas production. Since only low-strength feed water was used, this study did not notice such a problem. The TSS influent concentration was averaged at 376 ± 20 mg/L,

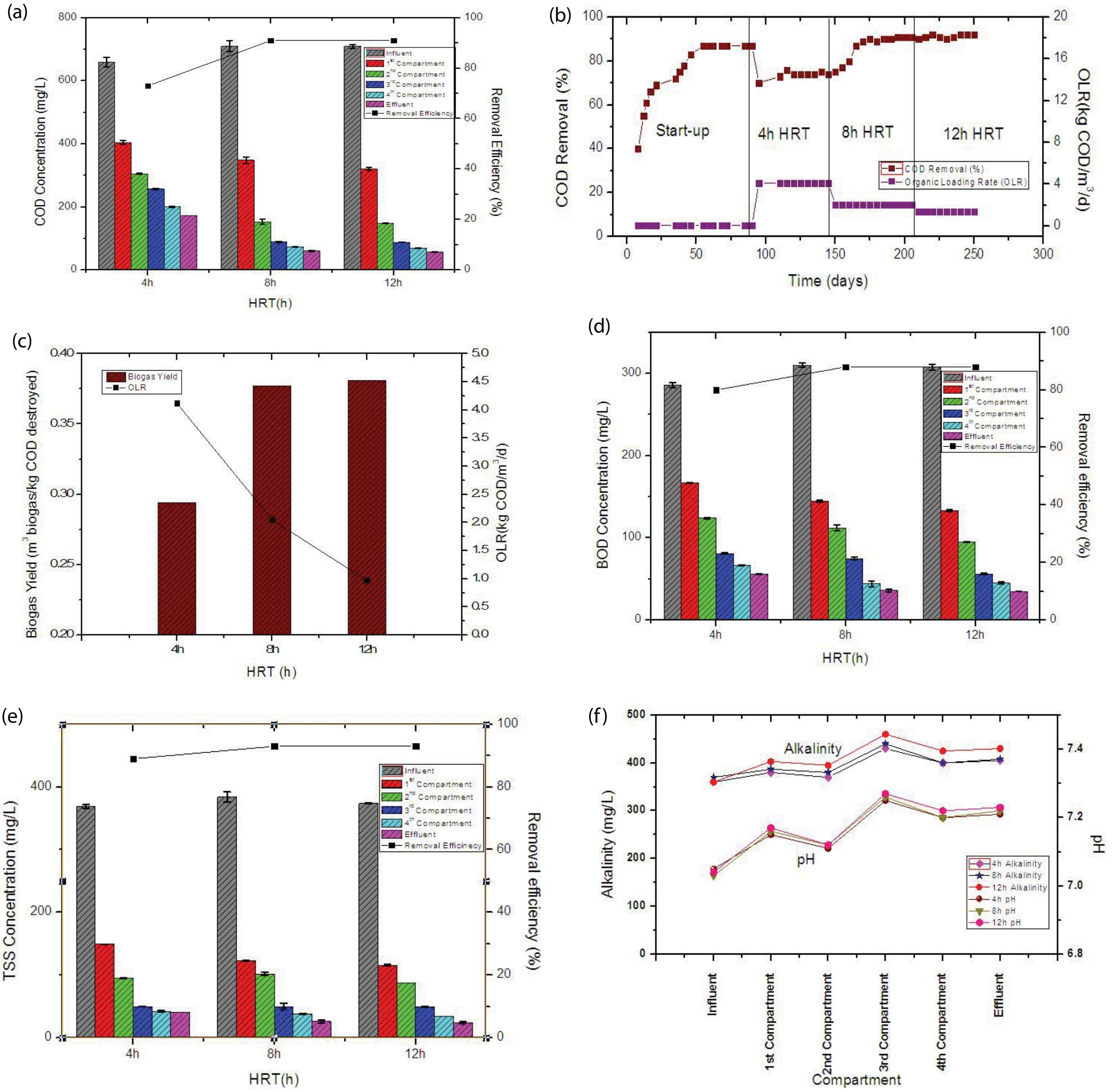


Fig. 6. (a) COD concentration and COD removal efficiency at 4 h, 8 h, and 12 h. (b) COD removal efficiency concerning OLR during the entire operation period. (c) Biogas yield at 4 h, 8 h, and 12 h HRT. (d) BOD concentration and removal efficiency at 4 h, 8 h, and 12 h HRTs. (e) TSS concentration and removal efficiency at 4 h, 8 h, and 12 h HRTs. (f) Alkalinity and pH profile at 4 h, 8 h, and 12 h HRTs.

and the effluent concentration was 25–40 mg/L with the removal efficiency of 88%–93% at 4 h, 8 h, and 12 h HRTs. The HABR with four compartments gave effective TSS removal compared to HABR with one, two, or three compartments. The HABR with three compartments gave the averaged effluent concentration of about 50 mg/L with the removal efficiency of 86% at 4 h, 8 h, and 12 h HRTs. The HABR with two compartments gave the effluent concentration of about 85–95 mg/L with 73%–76% removal efficiency at 4 h, 8 h, and 12 h HRTs. The HABR with a single compartment gave the effluent concentration of 135–150 mg/L with 63%–58% removal efficiency at 4 h, 8 h, and 12 h. Singh et al. studied the performance of an anaerobic baffled reactor and hybrid constructed wetland treating high-strength wastewater, achieving about 78% of BOD_5 removal efficiency and 91% of TSS removal efficiency [35]. The anaerobic baffled reactor treating the natural rubber processing wastewater achieved the total suspended solids removal efficiency of 90% with an OLR of 1.4 ± 0.3 kg COD/m^3/d [36]. The modified anaerobic baffled reactor for the municipal wastewater treatment achieved 87% BOD removal efficiency and about 86%

suspended solids removal efficiency with an HRT of 6 h [2]. The authors have compared the other works with the performance of hybrid anaerobic baffled reactor in the BOD and TSS removal. A good BOD removal efficiency of more than 88% and TSS removal of more than 93% were achieved in HABR. The last chamber filter media reduces the washout of biomass in the effluent, thus reducing the total suspended solids concentration in the effluent.

3.3.2. Reactor monitoring

The pH in the reactor indicated the effective functioning of an anaerobic system concerning alkalinity and volatile fatty acid [37]. The pH in the earlier compartments was low compared to the latter compartments. There was a decrease in pH in the 1st (7.17–7.15) and 2nd compartment (7.12–7.1) and an increase in pH in the 3rd compartments (7.27–7.25). Similar findings were observed in [14,15,38] that the lower value of pH in the 1st and 2nd compartments were due to the predominance of acidogens. The increase in pH and alkalinity in the third compartment was due to methanogenesis. There was a decrease in pH in the last compartment due to alkalinity consumption (7.2–7.22) during the aerobic nitrification process since ammonia (NH_4) was present in the feed wastewater. It was also observed that the alkalinity values were low in the 1st and 2nd compartments, similar to pH (in the range of 370–400 mg/L) due to the non-consumption of volatile fatty acids (VFA) by the acidogens in the initial compartments. In the 3rd compartment, there was an increase in alkalinity up to 460 mg/L, indicating the degradation of VFA by the methanogens. The above statement clearly explains the compartment-wise distribution of acidogens and methanogens in HABR. The effluent alkalinity values were approximately 20% more than the influent alkalinity. A similar observation in [2,13] showed an increase in the effluent alkalinity value of about 25% to 35%. The increase in alkalinity was due to carbonates and bicarbonates in the reactor. The VFA accumulation was also monitored since it was considered the typical reactor response [2]. The VFA/alkalinity ratio should be less than 0.3 to 0.4, and it was used as the process efficiency indicator [39]. The VFA/alkalinity was in the range of 0.03 to 0.06, which was less than 0.3, and it describes a perfect process condition in HABR. The hydrolysis of the substrate to catabolic intermediates (VFA) was incomplete during acidogenesis, and VFA was not consumed quickly by methanogens at low HRTs. By increasing the HRT to 12 h, there was a decrease in VFA by the consumption of VFA by methanogens. We can observe VFA of 15.8 mg/L at 12 h HRT and VFA of 18 mg/L at 4 h noticing a decrease in VFA when there was an increase in HRT.

4. Conclusion

In this work, the anaerobic baffled reactor with improved design concepts and principles provides a better hydrodynamic behaviour and treatment performance. The mixing pattern in HABR for all runs has an intermediate state between plug-flow and completely mixed, and we can observe the reactor closer to plug flow when there is an increase in HRT. The dead space of HABR with four compartments did not exceed 15%, which is less than other high rate anaerobic systems. The HABR with 8h HRT provides good hydraulic efficiency and achieves more than 91% COD removal and 93% TSS removal. Hence, the hybrid anaerobic baffled reactor with four compartments is a possible option as a decentralised wastewater treatment system in terms of hydrodynamic and treatment performance.

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Symbols

θ	—	Normalised time
t	—	Sampling time
HRT	—	Hydraulic retention time
C_θ	—	Normalised tracer concentration
$C(t)$	—	Tracer concentration at time t
C_0	—	Initial tracer concentration
τ	—	Mean retention time
σ_m^2	—	Variance
D	—	Axial dispersion coefficient
u	—	Average fluid velocity
L	—	Axial distance of the reactor
d	—	Dispersion number
N	—	Number of the continuous stirred tank-in-series
λ	—	Hydraulic efficiency
V_d	—	Dead volume
e	—	Reactor effective volume
RTD	—	Residence time distribution

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