

MODEL-BASED OPTIMIZATION OF CARRIER ANAEROBIC BAFFLED REACTOR FOR MUNICIPAL WASTEWATER UNDER VARIABLE TEMPERATURES

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Abstract

Variations in operating temperature can significantly affect the treatment behavior of an anaerobic baffled reactor (ABR), while experimental evaluation at low temperatures is challenging and resource-intensive. This study employed process modeling to assess and optimize the performance of a carrier anaerobic baffled reactor (CABR) across a range of temperatures. The model was calibrated using organics removal data and validated for suspended solids (SS) removal at HRTs of 24 to 6 h, with average absolute relative errors of 11.1% and 13.3%, respectively, within the acceptable 7–15% range. The validated model was then applied to predict the organics and SS removal at temperatures of 35, 32, 28, and 20 °C and HRTs from 24 to 6 h, identifying the optimum HRTs required to meet effluent standards. The results demonstrated that carrier media effectively enhance biomass retention, enabling efficient treatment at reduced HRTs, and provide a cost-effective strategy for compact and reliable decentralized wastewater treatment under variable operational temperatures.

1. INTRODUCTION

Each year, municipal sources contribute close to 400 billion cubic meters of wastewater worldwide (Ungureanu et al., 2020). According to Sato et al. (2013), around 70% of wastewater receives treatment in developed nations, whereas the treatment coverage drops to 38% in upper-middle-income economies and only 8% in developing regions. Poor sanitation causes the death of more than 1.5 million children under the age of 5 and some 180 million disease episodes every year, mainly in developing countries. Lack of sanitation services also has significant economic losses, in

some countries it is more than 5% of national GDP (Reynaud & Buckley, 2016). Disposal of 171.3 billion cubic meter of untreated wastewater annually into the environment causes serious threats to the ecosystem (Jones et al., 2020). UN-Water (2015) suggests that decentralized wastewater treatment, using simple technologies located near the point of generation, can provide a more effective sanitation solution, especially in low-income and peri-urban communities.

The anaerobic baffled reactor presents a potential solution, given its uncomplicated structure, absence of moving parts, and reduced capital,

operating, and energy expenses (Atanasova et al., 2021; Daee et al., 2019; Elreedy et al., 2016; Ozdemir et al., 2013). ABR efficient design is based on retention time of bacterial cells with little loss of microorganisms from the reactor (Sarti et al., 2010). Due to lower metabolic capacity of anaerobes, ABR requires hydraulic longer retention time (HRT) (Stazi & Tomei, 2018). But HRT directly affects the reactor volume and longer HRT demands for comparatively large reactor size which ultimately increases treatment plant capital and construction cost (Su et al., 2019).

The performance of ABRs relies on slow-growing heterotrophic microorganisms, whose growth can be improved by techniques like stimulating granule formation or introducing support materials and mesh systems within the reactor (Lau & Trzcinski, 2024). These strategies promote the decoupling of hydraulic and solids retention times (HRT/SRT), allowing systems to operate effectively at reduced HRTs. Consequently, the required footprint for ABR can be minimized, thereby lowering both capital investment and construction costs associated with wastewater treatment infrastructure (Ullah et al., 2024).

Since its development, the ABR has been the subject of numerous design improvements aimed at optimizing treatment efficiency. Researchers have explored different reactor configurations and support media to enhance microbial proliferation. For example, Feng et al. (2008b) investigated an ABR system that incorporated bamboo as carrier media to enhance biomass retention and reduce the loss of active microorganisms. Although this modification enhanced reactor performance, bamboo carriers present certain limitations, including limited availability in some developing regions, high preparation costs for large-scale application, and their susceptibility to rapid degradation, which restricts their long-term use in full-scale facilities (Saidulu et al., 2022).

In another study, Renuka et al. (2016) examined the performance of a paneled anaerobic baffled-cum-filter reactor (PABFR) for municipal wastewater treatment across six HRTs (40, 24, 12, 8, 6, and 4 hours) under mesophilic conditions (25 - 35 °C).

The system demonstrated maximum removal rates of 90% COD, 91% BOD, and 94% TSS when operated at an 8-hour HRT. Nevertheless, the specific plastic pall rings applied in the PABFR are difficult to source in most developing countries and often must be imported, which increases the overall treatment cost. Moreover, research on nutrient removal using PABFR technology remains scarce, limiting its large-scale adoption.

More recently, Ullah et al. (2023) investigated the treatment behavior of a carrier-based anaerobic baffled reactor (CABR) employing PVC media for municipal wastewater treatment. The reactor was run at six HRTs of 24, 18, 12, 10, 8, and 6 hours under a stable temperature of 35 °C. The CABR demonstrated a COD removal efficiency exceeding 80% even at the shortest HRT of 6 hours, while TSS removal remained between 78% and 83% across all operating conditions. These findings highlight the potential of locally available PVC media to enhance reactor performance while maintaining cost-effectiveness and operational simplicity.

Although the CABR has shown promising performance under controlled mesophilic conditions (35 °C), its efficiency under variable temperature regimes has not been systematically evaluated. Seasonal temperature fluctuations can markedly influence microbial activity and overall treatment performance (Langenhoff, 2000). In particular, the reactor's response to lower temperatures, such as those encountered during winter, is unclear, limiting understanding of its operational stability and treatment potential. This limits insight into its operational stability and treatment potential under real environmental conditions. Consequently, there is a critical research gap regarding the effect of temperature variation on CABR performance, particularly in terms of optimizing HRT to maintain effective substrate-biomass interaction for improved performance of the reactor (Chen et al., 2007).

Maintaining a controlled low operating temperature in CABR, particularly below room temperature, is often challenging, making experimental evaluation under such conditions difficult. To overcome these practical limitations, process modeling offers a robust and efficient

approach for evaluating and optimizing complex biological, chemical, and physical processes, reducing the need for extensive experimentation, operational costs, and associated risks (Srivastava et al., 2024). Among available platforms, GPS-X is widely recognized for its extensive collection of treatment modules, intuitive interface, and robust simulation features, making it highly effective for forecasting and optimizing wastewater treatment processes (Arif et al., 2020; Jasim, 2020). For instance, Ullah et al. (2025) demonstrated the application of GPS-X in assessing ABR performance under mesophilic conditions, specifically examining the effects of effluent recirculation on municipal wastewater treatment, thereby confirming its potential for process modelling and optimization.

Building on this, the present study employs GPS-X modelling to simulate and optimize CABR performance under low-temperature conditions and varying HRTs. Objectives of the study were as follows: 1) to model CABR performance in GPS-X using experimental data 2) to predict organics and solids removal performance of the reactor at different temperatures and HRTs and 3) to optimize HRTs across various temperature ranges to meet effluent discharge standards.

2. Methodology

2.1 Reactor Setup

A carrier anaerobic baffled reactor (CABR) was constructed from 8 mm thick acrylic sheets and comprised six equal, sequential compartments, providing a total working volume of 24 L. Mesophilic conditions (35 ± 1 °C) were maintained using a water jacket coupled with a temperature control unit installed around the reactor. Each compartment contained cylindrical corrugated PVC pieces occupying 20% of the compartment volume, serving as carrier media to promote biomass attachment. The carrier elements were 12 mm in length and width, offering a specific surface area of $615 \text{ m}^2/\text{m}^3$, and were secured in rings to prevent movement with the flow. Synthetic wastewater was continuously fed into the reactor using a peristaltic pump, and organic loading rates were set to achieve HRTs of 24, 18, 12, 8, and 6 hours (Ullah et al., 2023).

2.2 Wastewater Composition

Wastewater samples were obtained from the influent stream of the treatment facility located in Sector I-9, Islamabad, Pakistan. The composition of the wastewater utilized in this experiment is presented in Table 1.

Table 1 Key physicochemical attributes of the synthetic municipal wastewater

Compound	Formula	Concentration (mg/L)
Dextrose	$\text{C}_6 \text{H}_{12} \text{O}_6$	408.0
Potassium dihydrogen phosphate	$\text{KH}_2 \text{PO}_4$	35.75
Sodium hydrogen carbonate	NaHCO_3	90.0
Ammonium chloride	$\text{NH}_4 \text{Cl}$	190.95
Calcium chloride	CaCl_2	5.0
Magnesium sulphate	MgSO_4	5.0
Cobalt chloride	CoCl_2	0.05
Ferric chloride	FeCl_3	0.5
Nickle chloride	NiCl_2	0.05
Zinc chloride	ZnCl_2	0.05

2.3 Inoculum Preparation and Reactor Startup

The inoculum was prepared by thoroughly mixing sludge and fresh cow dung in equal proportions. The sludge was collected from a constructed wetland located at the NUST main campus in Islamabad, Pakistan (Maryam et al., 2021), while fresh cow dung was sourced from the nearby H-13 sector of Islamabad. During reactor startup, 30% of the working volume was filled with the prepared inoculum, and the remaining volume was supplemented with synthetic wastewater (Ullah et al., 2023).

2.4 Analytical Procedures

Influent and effluent samples were collected twice weekly for laboratory analysis. Chemical oxygen demand (COD), volatile fatty acids (VFA), alkalinity, and suspended solids (SS) were quantified in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). The oxidation-reduction potential (ORP) was measured using a benchtop ORP meter (Hanna Instruments Ltd., HI 83141, UK), and pH was determined with a digital pH meter (Eutech Instruments Pte Ltd., pH 700, Singapore).

2.5 Operation of CABR

The CABR was operated in two stages: a start-up period followed by continuous flow operation. The start-up stage was intended to acclimate the microbial community within the reactor and promote biomass development, enabling the system to establish effective pollutant removal conditions within a short time frame (Zha et al.,

2019). After start-up phase which facilitated acclimatization of microbial community in the reactor, system was brought into continuous flow with OLR corresponding to HRT 24,18,12,08 and 06 h. Operation days at each HRT were as: 24 h,46 days; 18 h,37 days; 12 h,32 days; 08 h,32 days; 06 h,19 days.

2.6 Modelling

2.6.1 Model formulation

The CABR performance was simulated in GPS-X (version 8.0, Hydromantis Environmental Software Solutions Inc.) using a model that combined an anaerobic digester with a solids-liquid separator. Each compartment of the reactor was represented by a single digester-separator pair, and the six-compartment system was simulated by linking six such pairs in series (Ullah et al., 2025). The anaerobic digester simulated the biological processes under anaerobic conditions, while the solids - liquid separator represented the physical removal of suspended solids in each compartment. The effect of carrier media was incorporated through calibrated kinetic and stoichiometric parameters to account for enhanced biomass retention and improved substrate degradation in each compartment. Although the carriers were not visually represented in the GPS-X layout, their influence was numerically embedded within the model framework to reflect the actual behaviour of the CABR system. Figure 2 shows the configuration of CABR as represented by GPS-X interface window (Ullah et al., 2025).

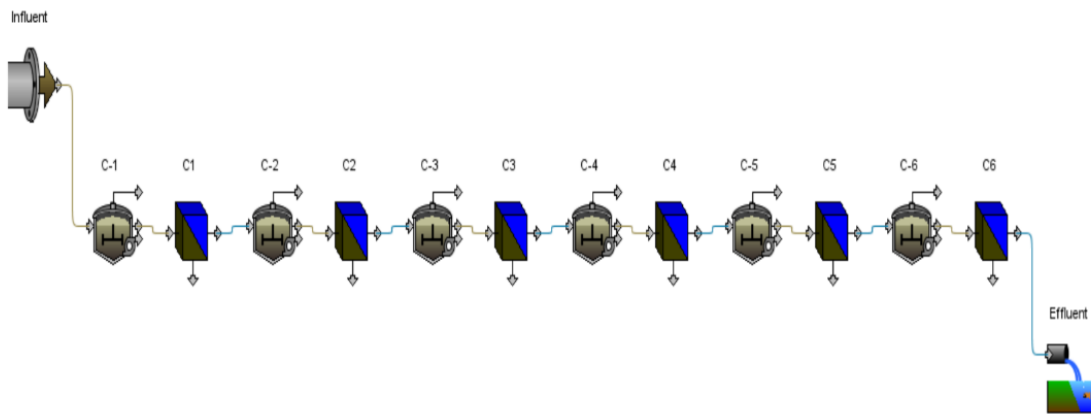


Figure 2. Schematic representation of the CABR modeled in GPS-X

GPS-X simulates anaerobic digestion using a four-group microbial model including heterotrophs, acetogens, acetoclastic, hydrogenotrophic and methanogens (Hydromantis, 2019). The Mantis2lib library was applied for CABR modelling because it includes complete carbon, nitrogen, phosphorus, and pH processes. The model uses 35 stoichiometric and 25 kinetic parameters (Faris et al., 2022), and GPS-X provides validated default values to ensure reliable results. The steady-state mode was selected to evaluate CABR performance under stable operating conditions and to compare temperatures and hydraulic retention times without the effects of short-term fluctuations.

The model was run and simulated effluent COD and SS values were compared with respective experimentally measured values to get better fit of the data for model calibration and validation. Model was then run to predict model organics and SS removal performance at various operating conditions. These model predictions helped to optimize treatment processes for achieving effluent discharge permissible standards.

2.6.2 Wastewater fraction

Influent advisor tool was used to characterize the influent data as influent characterization is the key

to good calibration. It has three columns representing inputs data, state variables and composite variables. These three columns are inter-linked and change in one column causes to make change in other columns. Input data column is as input data source to characterize the influent to be used in the modelling. State variables are the basic variables that are continuously integrated in the model over time and are typically not easily measurable or interpretable (Hydromantis, 2019). Composite variables are calculated from the state variables and are typically measured such as TSS, BOD, COD, TKN, TP etc. Input data effects composite variable data through relevant state variables. Wastewater fraction data was entered into influent advisor to characterize the influent used in experimentation. The wastewater fractions are summarized in Table 2. Although input data, state variables and composite variables had default values. However the input data was carefully adjusted so that the relevant composite variables values were exactly the same to the relevant measured values to better represent the influent composition. GPS-X use composite variables data for modelling and simulation purpose and all these state and composite variables are calculated through mathematical equations.

Table 2 Wastewater fraction

Parameter	Default value	Adjusted value
total COD (gCOD/m ³)	430	400 ±12
total TKN (gN/m ³)	40	50.0
total phosphorous (gP/m ³)	10	25.0
ammonia nitrogen (gN/m ³)	25	16.0
Ortho-phosphate (gP/m ³)	08	12.0
VSS/TSS ratio (gVSS/gTSS)	0.8	0.2
readily biodegradable fraction of total COD	0.2	0.98
colloidal fraction of total COD	0.15	0.001
soluble inert fraction of total COD	0.05	0.01

2.6.2 Model operating conditions

Model operating conditions are tabulated in Table 3. It has five runs from r-1 to r-5. Each run represented four influent COD and SS concentrations along with respective flow rates and operating temperature at which CABR showed steady state behavior. Operating temperature for all these runs were 35 °C. Steady state behavior was termed as variations in effluent COD concentration was less than 3% in ten consecutive days for each run (Aqanaghad et al., 2018).

In the first run (r-1) system maintained steady state behavior with influent COD concentration of 396, 408, 386 and 405 mg/L and flow rate of 1.0 liter/hour at HRT of 24 h. In the second run (r-2), system showed steady state behavior with four consecutive influent organics concentration of 412, 398, 387, 410 mg/L and flow rate of 1.33 liter/hour keeping an HRT of 18 h. Similarly, in the third run (r-3), system showed steady state flow

behavior with influent organics concentration of 396, 408, 406 and 410 mg/L and flow rate of 2 liter/hour at HRT of 12 h. In the fourth run (r-4), system HRT was 08 h by keeping flow rate of 3 liter/hour with influent COD concentration of 410, 412, 398, 392 mg/L at steady state flow conditions.

In the final run (r-5), system showed steady state behavior at flow rate of 4 liter/hour with influent COD of 386, 400, 398 and 405 mg/L at HRT of 06 h. The influent SS concentration was adjusted at 50 mg/L, matching the SS level in the synthetic wastewater prepared for the study. Synthetic wastewater typically contains low suspended solids because it is formulated from soluble substrates to provide controlled organic loading without the particulate content found in real municipal wastewater. Influent COD and SS concentration, flow rate and reactor internal temperature data were the input data parameters for running the model.

Table 3 Model operating conditions at various runs under steady flow

Reactor Run	Influent COD (mg/L)	Influent SS (mg/L)	Flow rate (liter / hour)	Temperature (°C)
r - 1	396	50	1.0	35
	408	50		
	386	50		
	405	50		

r - 2	412	50	1.33	35
	398	50		
	387	50		
	410	50		
r - 3	396	50	2.0	35
	408	50		
	406	50		
	410	50		
r - 4	410	50	3.0	35
	412	50		
	398	50		
	392	50		
r - 5	386	50	4.0	35
	400	50		
	398	50		
	405	50		

3 Results and Discussion

3.1 Effluent measured COD and SS concentration under steady state flow

Effluent measured COD and SS concentrations against respective organic loading rate and HRT under steady state flow conditions for five runs are tabulated in Table 4. In run (r-1), OLR varied between 0.39 and 0.41 (kg.COD/m³-day) with effluent measured COD concentration was below 60 mg/L. In the second run (r-2), the reactor was operated at OLR between 0.52 and 0.55 kg COD/m³-day, resulting in effluent COD concentrations of around 70 mg/L. Similarly, in

run (r-3), OLR varied between 0.79 and 0.82 (kg.COD/ m³. day). Effluent measured COD concentration varied between 81 and 89 mg/L. In the fourth run (r-4), OLR varied between 1.18 and 1.24 (kg.COD/m³-day) and the effluent measured COD concentration varied between 81 and 90 mg/L. In the final run (r-5), OLR varied between 1.54 and 1.62 (kg.COD/m³-day). Effluent measured COD concentration was in the range of 80 mg/L. Effluent measured SS were in the range of 10 mg/L with little variation for all organic loading rates.

Table 4 Organic loading rates and corresponding effluent measured COD and SS concentration in various runs under steady state flow

Reactor run	HRT (hour)	OLR (kg.COD/m ³ . d)	Eff. measured COD (mg/L)	Eff. measured SS (mg/L)
r -1	24	0.40	59	9.0
		0.41	56	9.5
		0.39	58	9.0
		0.41	56	9.0
		0.55	70	10.0
r - 2	18	0.53	72	10.0
		0.52	64	9.0
		0.55	68	9.5
		0.79	84	10.0

r - 3	12	0.82	89	9.0
		0.81	82	9.0
		0.82	81	9.5
		1.23	90	10.0
r - 4	8	1.24	92	9.5
		1.19	89	10.0
		1.18	81	10.0
		1.54	76	10.0
r - 5	6	1.60	83	9.5
		1.59	81	9.5
		1.62	78	10.0

3.2 Model calibration

Calibration is the adjustment of model parameters to align simulation results with experimental data, minimizing differences between the two datasets (Hellal & Abou-Elela, 2021).

3.2.1 Input parameters adjustment

Using the default stoichiometric and kinetic parameters resulted in discrepancies between measured and simulated data, necessitating model calibration to accurately represent the experimental setup (Liwarska-Bizukojc & Biernacki, 2010). (Liwarska-Bizukojc & Biernacki, 2010). The model was designed by connecting different process units so fine-tuning method was adopted to make adjustments in default input parameter values of each process unit.

The CABR compartment wise default and adjusted values of the required input parameters

are tabulated in Table 5. Most of the organics were removed in first three compartments of CABR and the highest microbial activity occurred in first compartment (Reynaud & Buckley, 2016). so, adjustments were made in first three compartments i.e. C₁, C₂ and C₃. Maximum specific growth rate of heterotrophic biomass on substrate in C₁ was adjusted to 15 (1/d) which was higher than default value of 3.2 (1/d). This is justified by the fact that the reactor operating temperature was 35 °C which is the optimum temperature for the microorganisms to grow while GPS-X default temperature is 20 °C. This is also supported by the fact that OLR of the reactor increased from 0.40 to 1.59 (kg.COD/m³-day) by shortening HRT from 24 to 06 h in five runs. The heterotrophic biomass had greater affinity towards substrate which used organics as their food.

Table 5 Default and adjusted values of main parameters affecting the performance of anaerobic digesters for model calibration and validation

Parameter	Unit	Compartment	Default value	Adjusted value
maximum specific growth rate of heterotrophic biomass on substrate	1/d	C - 1	3.2	15.0
		C - 1		0.67
anoxic heterotrophic yield on soluble substrate	gCOD/gCOD	C - 2	0.533	1.61
		C - 3		1.0
		C - 1		

yield of fermentative biomass	gCOD/gCOD	C - 2	0.18	0.01
		C - 3		
		C - 1	3.0	14.5
maximum fermentation rate	1/d	C - 2		14.0

Increase in OLR supplied more organics which might have facilitated heterotrophic biomass to grow and remove organics. Similarly, anoxic heterotrophic yield on soluble substrate is closely related to biomass which used organics in substrate as their food and the yield value was adjusted as 0.67, 1.61 and 1.0 in compartments C₁, C₂ and C₃ respectively against default value of 0.533 (gCOD/gCOD) respective

Maximum fermentation rate (1/d) in first two compartments was adjusted to 14.5 and 14.0 respectively against default value of 3.0 (1/d). The fermentative bacteria were dominant in first two compartments for hydrolysis, acidogenesis and acetogenesis. Although yield of fermentative

biomass was reduced to 0.01 in these three compartments against default value of 0.18 (gCOD/gCOD). Keeping the default value resulted in more organics removal which was not supported by literature and experimentation.

For SS removal in each compartment, solid-liquid separation units were applied, and the solids removal efficiencies were adjusted at 35% for C₁, 78% for C₂, 40% for C₃-C₄, 30% for C₅, and 3% for C₆. In each unit SS were allowed to settle at the bottom but not removed from the system to represent the actual experimental setup as no desludging was done. SS removal efficiency of each unit was adjusted to align organics and SS removal with corresponding measured values.

3.2.2 Calibration results

To access the agreement between measured and simulated values, average absolute relative error (ARE) was employed (Liwarska-Bizukojc et al., 2011). ARE was calculated by the following equation. (1)

$$ARE = \frac{1}{N} \times \sum_{i=1}^N \frac{|(m_i - p_i)|}{m_i} \times 100\% \quad \text{Eq.(1)}$$

Where m_i is the measured value of output variable, p_i is the simulated value of output variable and N

is the total no of variation. An ARE value of 7-15% is sufficient for model calibration (Liwarska-Bizukojc et al., 2011).

The model calibration results for effluent COD concentration are presented in Figure 3. The simulated COD concentrations obtained from runs r-1 to r-5 were compared with corresponding measured concentrations at HRT ranges from 24 to 6 h. The respective ARE value was 11.1%. Li et al (2016) reported an ARE of 9.2% while calibrating effluent COD concentration in modelling modified anaerobic baffled reactor.

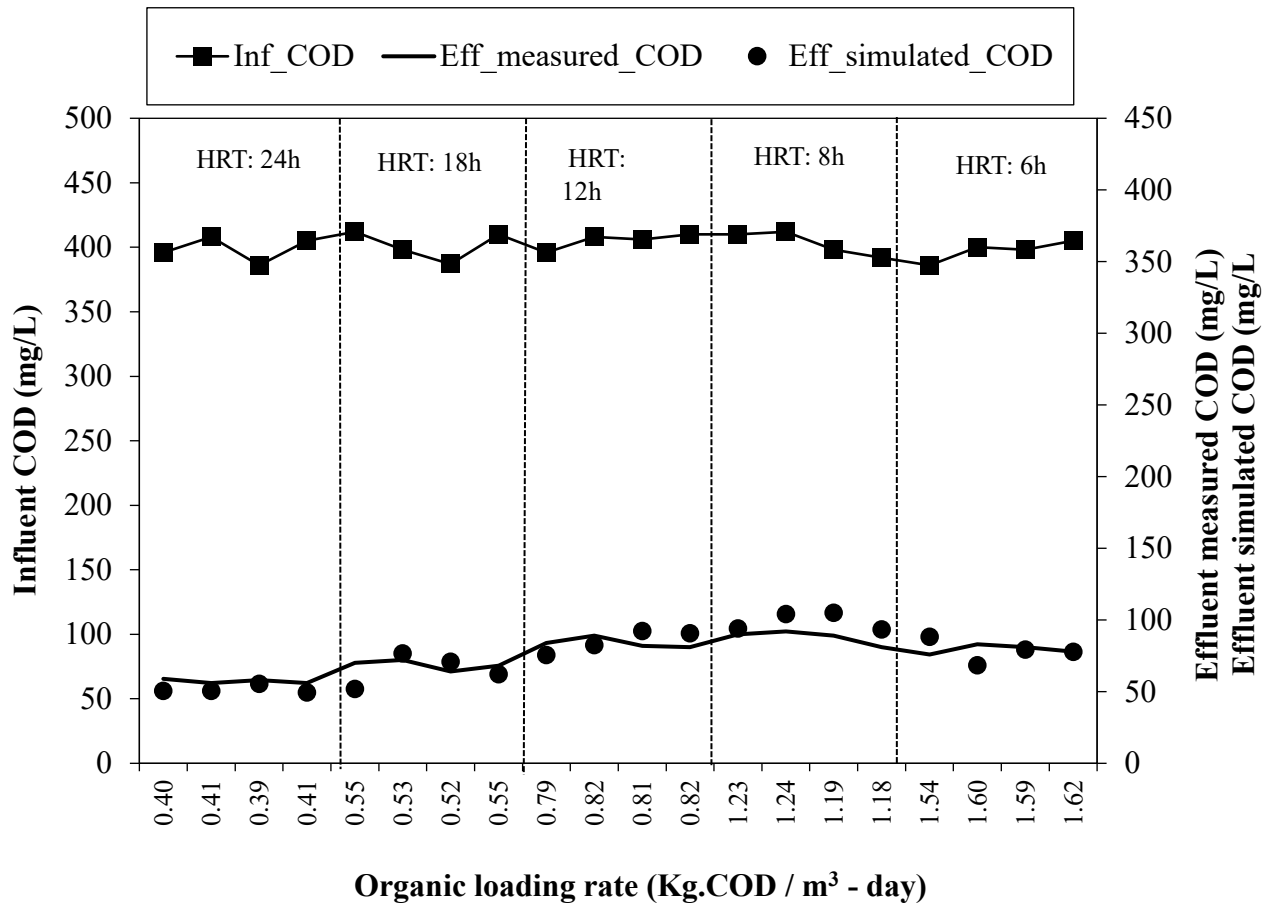


Figure 3. Influent COD, effluent measured COD and simulated COD at various OLRs for model calibration

3.3 Model validation

Model validation is essential for assessing the reliability of a model and demonstrating its accuracy and applicability (Donoso-Bravo et al., 2011). For validation, the effluent measured SS

values were correlated with respective simulated SS values for model runs of r-1 to r-5 as shown in Figure 4. The corresponding ARE being 13.3% which falls in the acceptable range of 7 - 15%.

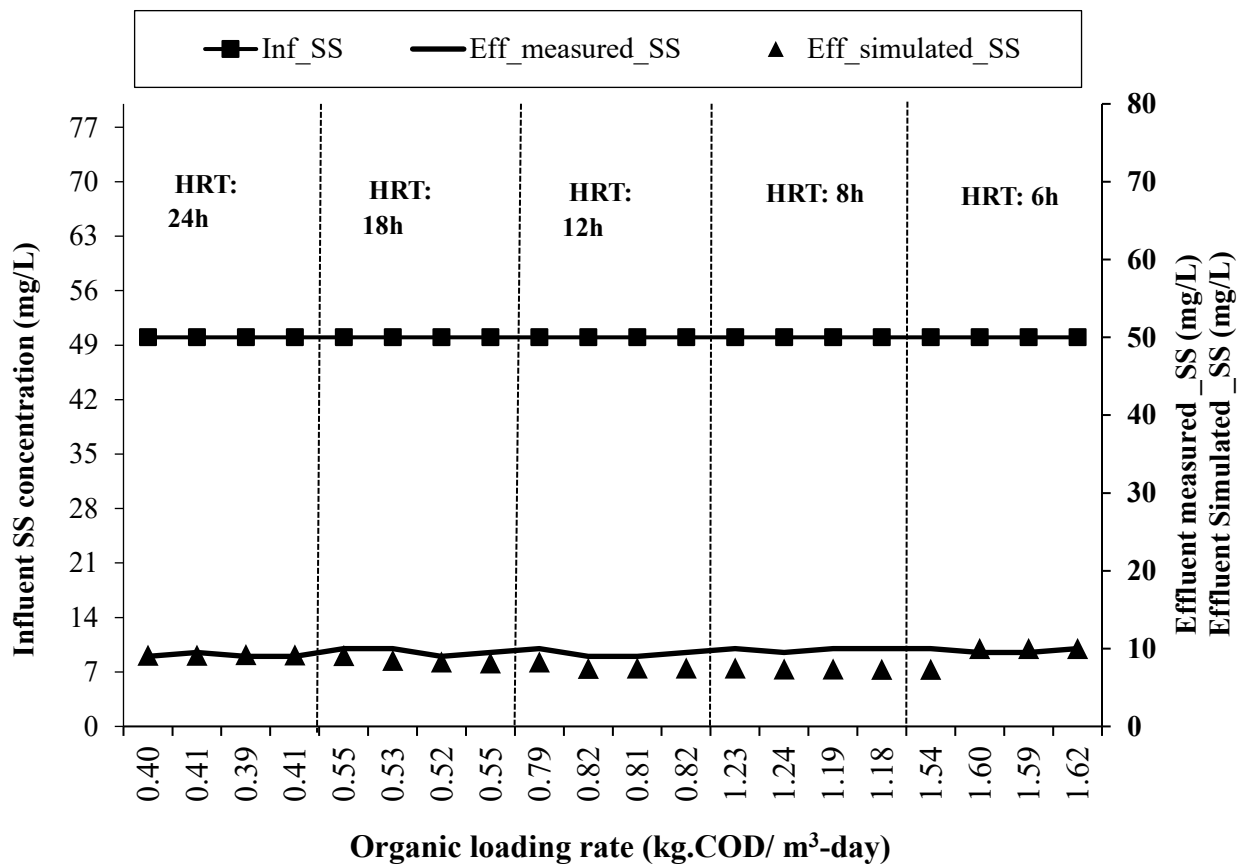


Figure 4. Influent SS, effluent measured and simulated SS at various OLRs for model validation

3.4 Measured organic removal rate and simulated organic removal rate

To evaluate model organics removal performance, measured organic removal rates (MORR) and simulated organic removal rates (SORR) were compared as shown in Figure 6. MORR were obtained through experimental work and SORR

were obtained from running the model. MORR values ranged from 0.34 to 1.27 (kg.COD/m³-day) while SORR values ranged from 0.35 and 1.28 (kg.COD/m³-day). At HRT 24 h, MORR and SORR values were 0.34 and 0.35 (kg.COD/m³-day) respectively which showed a better fit of the model with the measured data.

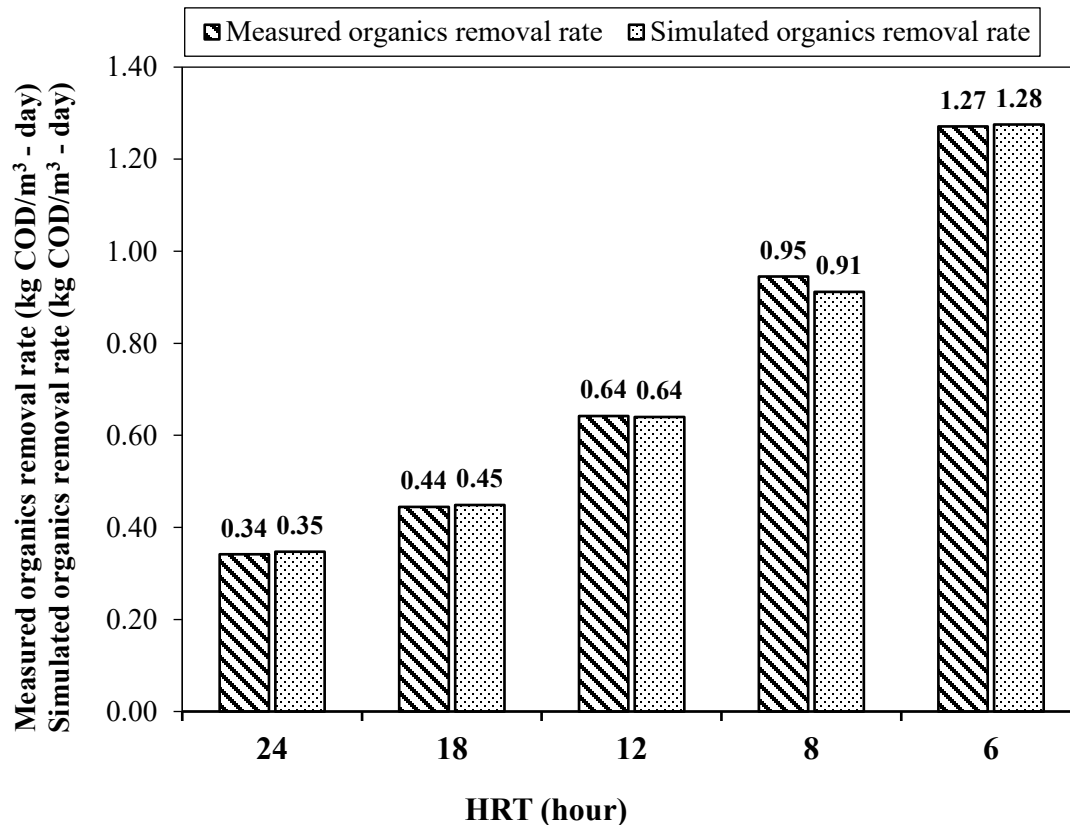


Figure 5. Measured organic removal rates and simulated organic removal rates at various HRTs

At HRT 18 h, MORR and SORR values were 0.44 and 0.45 (kg.COD/m³-day) respectively. Shortening HRT to 12, 08 and 06 h indicated that both respective MORR and SORR values were accurately matched and gave a better fit. These results reflected that the model is precisely representative of MABR and the model can be used to predict reactor performance at various operating conditions.

3.5 Model simulation for compartment wise COD reduction

The model was simulated to get compartment wise COD removal as shown in Figure 6. Influent

COD concentration was in the range of 400 mg/L. Most of the COD removal occurred in first two compartments (Krishna et al., 2009). Percentage COD removal reduced from C₁ to C₃ and no significant COD removal occurred beyond compartments C₃ to C₆ (Yenji et al., 2021). First compartment showed 48% COD removal while second and third compartment removed 24% and 3% respectively. Manariotis & Grigoropoulos, (2002) reported COD removal of 56.1, 22.4 and 5.3% in first three compartments respectively of anaerobic baffled reactor treating low strength wastewater. So, the model simulated results were consistent with the pervious experimental studies.

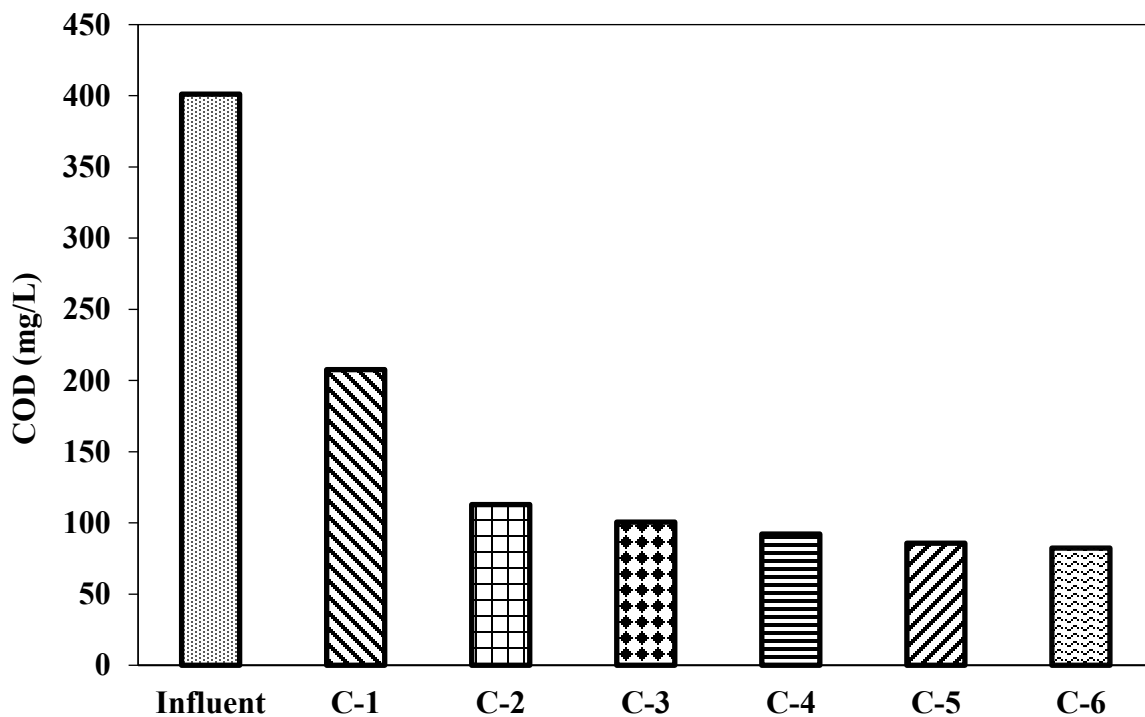


Figure 6. Influent COD and simulated compartment wise effluent COD concentration

3.6 Model prediction

3.6.2 Organics removal prediction

CABR predicted organics removal efficiencies at operating temperature of 32, 28 and 20 °C plotted against HRTs of 24, 18, 15, 12, and 06 h are presented in Figure 7. At operating temperature of 35 °C, reactor's organics removal efficiency varied between 86 and 76% while shortening HRT from 24 to 6 h by increasing OLR from 0.40 to 1.60

(kg.COD/m³-day). Bodkhe (2009) reported an organics removal efficiency of 80% while changing OLR from 0.53 to 1.36 (kg.COD/m³-day) in treating municipal wastewater using modified anaerobic baffled reactor at operating temperature of 35 °C. Similarly, Zha et al., (2019) reported COD removal of 75+3.56% using modified ABR for pretreatment of black water at 36 ±1°C at 24 h hydraulic retention time.

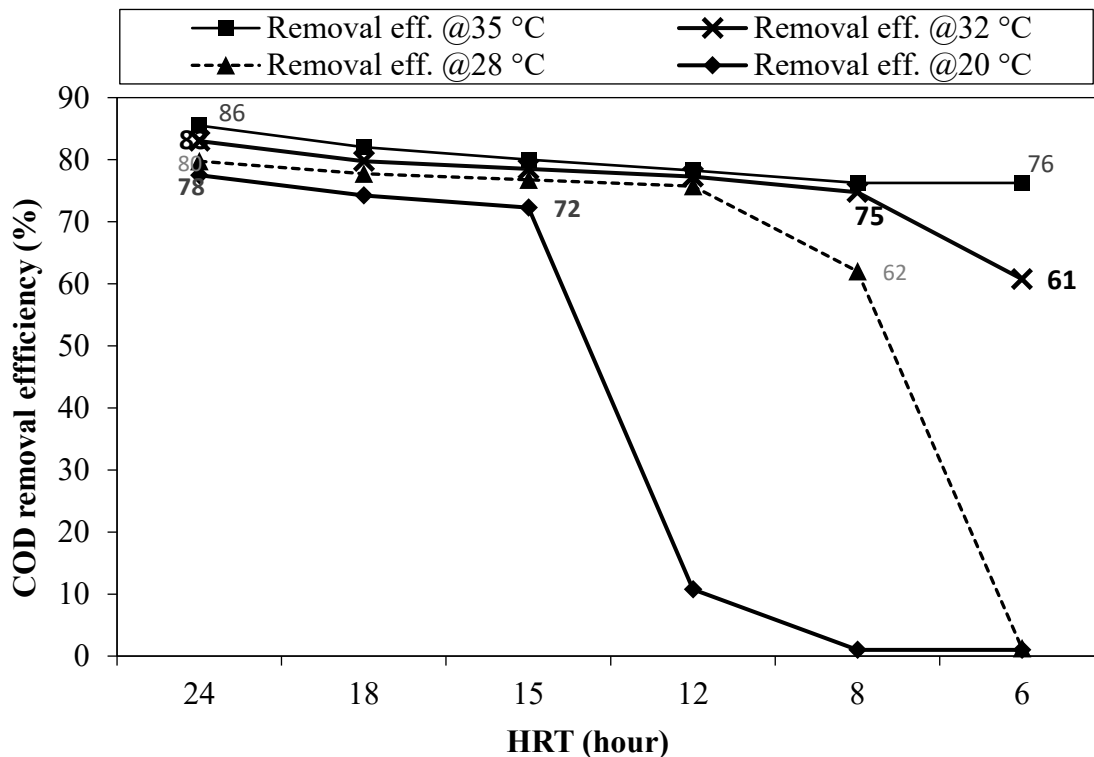


Figure 7. COD removal efficiency with different operating temperatures at various HRTs

At temperature 32 °C, reactor showed organics removal efficiency between 83 and 75% in shortening HRT from 24 to 08 h by increasing OLR from 0.4 to 1.20 (kg.COD/m³-day). Further shortening HRT to 06 h caused to reduce organics removal efficiency to 61%. Similarly, at temperature 28 °C, organics removal efficiency varied between 80 and 74% when HRT was shortened from 24 to 10 h by increasing OLR from 0.40 to 0.96 (kg.COD/m³-day). Feng et al., (2008) reported organics removal efficiency of 75% in treating municipal wastewater using bamboo carrier anaerobic baffled reactor at 28 ± 1 °C at OLR 0.40 (kg.COD/m³-day). Shortening HRT to 08 h caused to reduce organics removal efficiency to 62%. The reactor had very nominal organics removal efficiency in at HRT to 06 h and 28 °C.

At temperature 20 °C, reactor showed organics removal efficiency in the range of 78 to 72% while shortening HRT from 24 to 15 h. Further increasing OLR at this operating temperature showed negligible organics removal performance.

Liu et al., (2023) reported COD removal performance of 62% at HRT 24 h with operating temperature of 15 °C treating low strength wastewater with influent average COD of 233 mg/L using biofilm-coupled ABR. The model predicted results for organics removal were consistent with the previous studies.

3.6.3 Suspended solids (SS) removal prediction

The model was run to predict SS removal efficiency. Influent SS were taken as 350 mg/L to represent SS concentration of real wastewater. Effluent SS varied were in the range 15 mg/L. Figure 8 shows SS removal efficiency of CABR with variation in HRT. The dotted line shows the effluent SS discharge standard of 35 mg/L (FAO, 2003). CABR sustained its removal efficiency above 90% and no significant reduction was observed while changing HRT from 24 to 6 h. Renuka et al., (2016) reported SS removal of more than 90% in reducing HRT from 24 to 6 h using panelled anaerobic baffle-cum filter treating municipal wastewater.

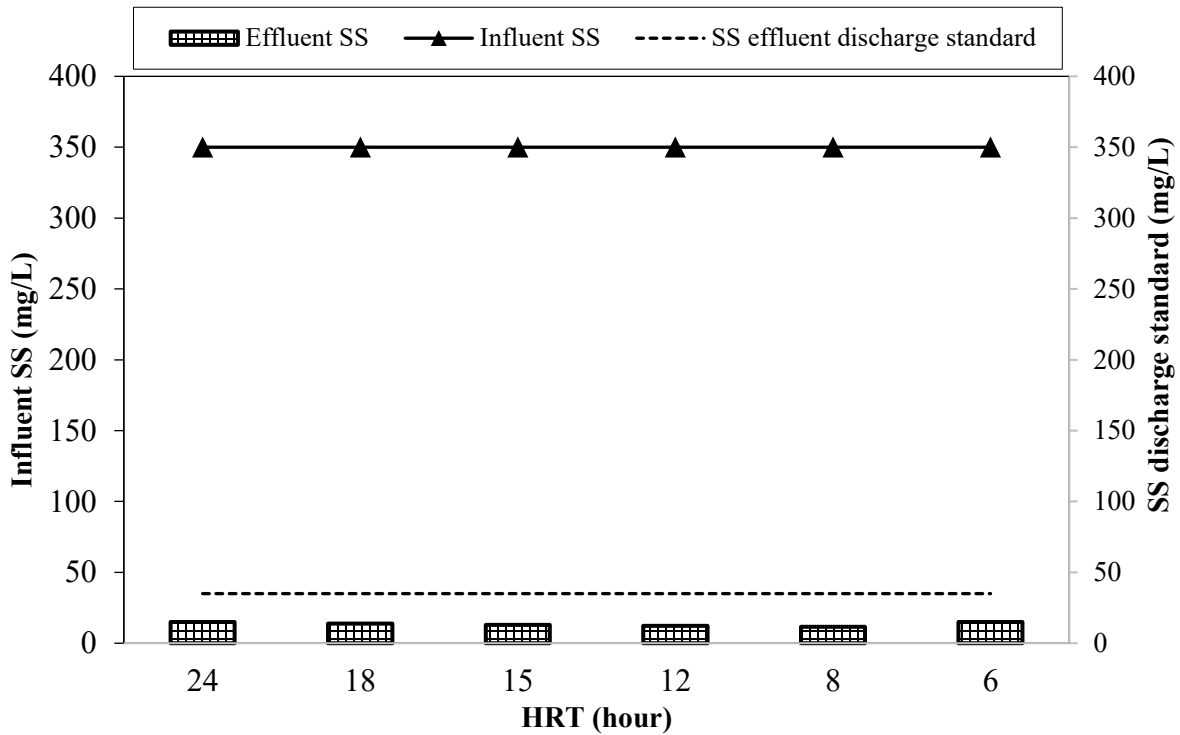


Figure 8. Influent SS, SS effluent discharge standard and effluent SS at various HRTs

CABR achieved SS effluent discharge standard at all operated HRTs. Also, no significant reduction in SS removal was observed in changing the operating temperature of the reactor. Although model predicted results for SS removal is not significantly affected by change in operating temperature but still these results provide an estimation of effluent SS concentration which may vary with change in influent SS concentration.

3.7 Optimization of CABR performance

The model predicted effluent COD concentrations with operating temperatures of 35, 32, 28 and 20 °C at HRTs of 24, 18, 15, 12, 08 and 06 h are presented in Figure 9. The horizontal dotted line represents effluent COD discharge standard of 120 mg/L (FAO, 2003).

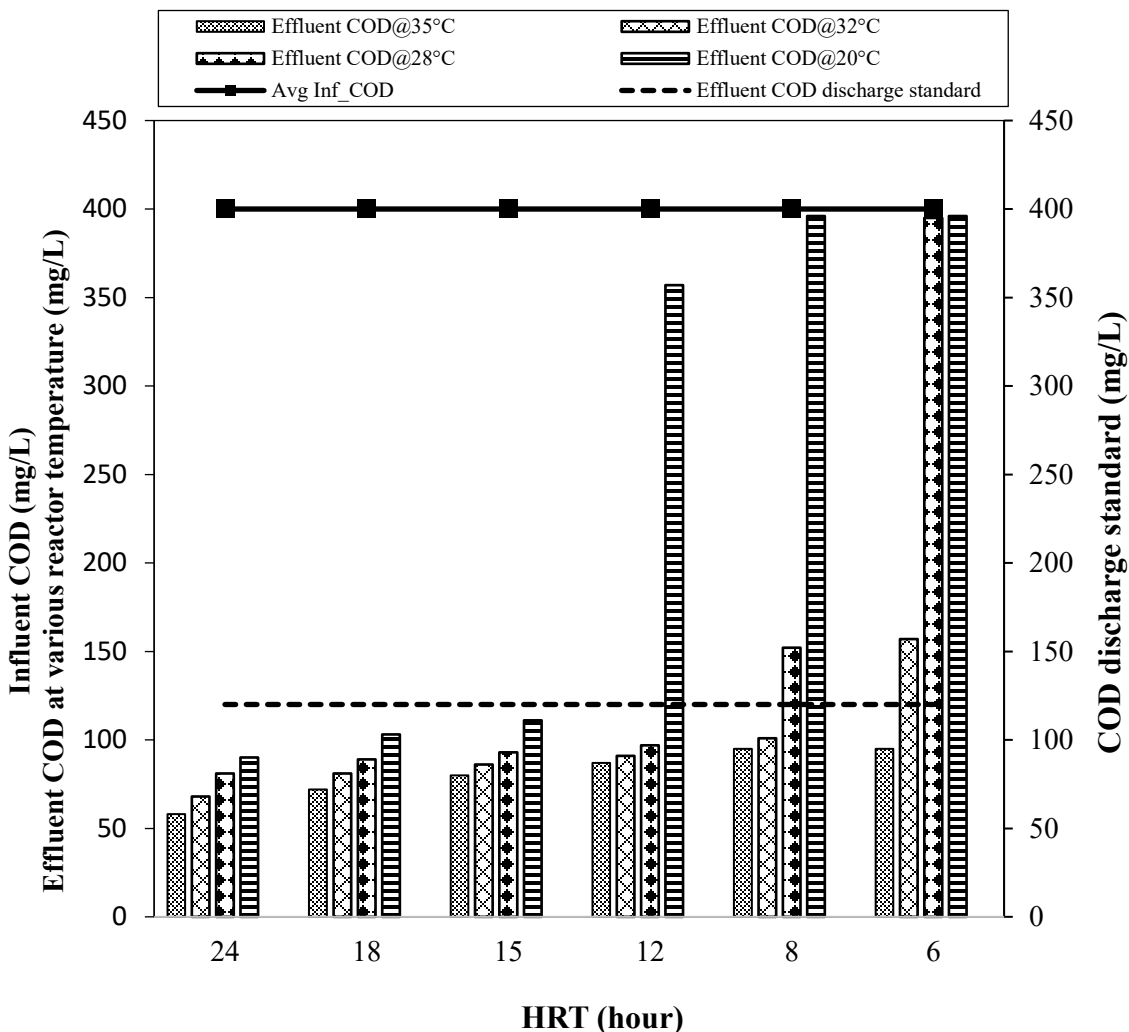


Figure 9. COD removal prediction at various operating temperatures and HRTs

Influent COD was set at 400 mg/L. Reducing the HRT from 24 to 15 h resulted in effluent COD concentrations between 58 and 111 mg/L, corresponding to a decline in operating temperature from 35 to 20 °C. The observed COD profile demonstrates that the reactor maintained compliance with the effluent discharge standard across this HRT interval, despite the imposed temperature reduction.

At an HRT of 12 h, the reactor achieved the effluent COD discharge standard at operating temperatures of 35, 32, and 28 °C, but failed to comply at 20 °C. Similarly, at an HRT of 8 h, compliance with the COD standard was maintained at 35 and 32 °C. At the lowest HRT

of 6 h, the reactor met the permissible COD limit only at 35 °C. These findings demonstrate that process stability and COD removal efficiency were increasingly constrained by lower operating temperatures at shorter HRTs, reflecting the temperature-dependent kinetics of anaerobic degradation.

Model optimization results are presented in Table 7. The Table shows influent and effluent COD & SS concentrations, operating temperature ranges and optimum HRTs to meet effluent discharge permissible standards of organics and SS. As depicted in the Table, the low operating temperature requires longer HRT to meet the desired removal results. Increase in operating

temperature facilitated the reactor to remove the required pollutants at comparatively low HRT. Thus, the model optimization defined the optimum HRT to achieve effluent permissible standards of organics and SS depending upon the

various ranges of operating temperature. Optimum HRT in connection with operating temperature was 15 h for 20 – 27 °C, 10 h for 28 – 31°C, 8 h for 32 – 34 °C and 6 h for 35 °C and above.

Table 7 Optimum HRT to meet organics and SS discharge permissible standards for various ranges of operating temperature

Influent COD (mg/L)	Influent SS (mg/L)	Temp- range (°C)	Optimum HRT (h)	Effluent COD (mg/L)	Effluent SS (mg/L)
400	350	20 - 27	15	111	13
		28 - 31	10	104	12
		32 - 34	8	101	12
		35 and above	6	95	15

*COD and SS effluent permissible standards are 120 and 35 mg/L respectively ((FAO, 2003)

The model optimization for SS removal demonstrated that CABR SS removal performance was not significantly affected by variation in temperature. Effluent SS concentrations were well below the SS effluent discharge standard at all operated HRTs. Model optimization is of vital importance to provide deep insight into the CABR process design. This helps to select the optimum HRT based on the ambient air temperature to minimize capital, construction and operational cost of CABR without compromising on removal performance of the reactor.

5. Conclusion

The performance of the CABR was successfully modeled and optimized using the GPS-X software. The model reliably predicted organics and suspended solids (SS) removal across a range of HRTs and operating temperatures, eliminating the need for extensive laboratory experiments and thereby saving time, materials, and equipment costs. The optimization results provide practical guidelines for field-scale implementation of CABR technology, taking into account ambient temperatures and wastewater flow rates, and support environmentally sustainable wastewater management. The study also highlights GPS-X as a valuable tool for modeling and simulating ABR systems, facilitating the optimal design of decentralized wastewater treatment plants. Future

research is recommended to extend modeling studies for the evaluation of CABR performance in the removal of COD, SS, and nutrients using real municipal wastewater.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. Requests for data should be directed to Dr. Nadeem Ullah (nadeem.ullah@cusit.edu.pk; nadeem.phdnust@gmail.com)

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