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Kinetic modelling of moving bed biofilm sequencing batch reactor for treatment of sugar industry effluent

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ABSTRACT

India is the second-largest sugarcane producer and consumer in the world, with 29.66 million tonnes of annual production and 25.51 million tonnes of consumption, along with a high degree of contaminated wastewater from sugar industries. Sugar industries in India generate about 1,000 litres of wastewater for one tonne of crushed sugarcane. The effluent discharged from sugar industries contains high concentration of biochemical oxygen demand, chemical oxygen demand, total dissolved solids, nitrogen, and phosphorous, causing serious environmental pollution problems. A combination of suspended and attached growth wastewater treatment systems can be used by integrating a moving bed biofilm reactor (MBBR) with a sequencing batch reactor (SBR) known as the moving-bed biofilm sequencing batch reactor (MBSBR), which is an aerobic treatment method. It is a promising technology as it has no requirement for sludge recirculation and requires lesser reactor volumes. In this study, the moving-bed biofilm sequencing batch reactor has been modelled for treating sugar industry wastewater. At a cycle time of 2 h, the biochemical oxygen demand removal efficiency is around 87% at 500 mg/L, sludge loading rate is 13 kg BODm^{-2}d^{-1}, chemical oxygen demand removal efficiency is 84.2%, food to micro-organism ratio is 1.09, and the mixed liquor volatile suspended solids and mixed liquor suspended solids values are around 2909 mg/L and 3639 mg/L, respectively. The economic viability of this technology is still to be established for treating sugar industry wastewater. This study can guide scientists, researchers, designers, and consultants when selecting wastewater treatment technology for the sugar industry. This technology has the potential to be replicated in other industries with similar wastewater characteristics.

1. Introduction

Brazil is the second-largest sugarcane producer in the world with an annual production of 29.17 million tons, while India is the largest sugar producer with a production of 29.66 million tons in 2019 and a 17.9 percent share in the global market [1]. Sugar industries in India generate about 1000 litres of wastewater to crush one tonne of sugarcane. Treatment of such a huge quantity of

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wastewater is a challenge for sugar industries in India. The stringent norms from regulatory agencies for controlling water pollution make it difficult to increase the treatment capacity of the existing conventional wastewater treatment plants [2]. The sugarcane production process can be broadly classified into milling, clarification, evaporation, crystallization, centrifugation, drying, and packaging. Wastewater is generated during the processing of sugarcane to produce sugar during the milling, evaporation and crystallization processes. The Central Pollution Control Board (CPCB) in India restricts the quantity of wastewater generated from sugar processing to 200 litres per tonne of cane crushed [3]. Since effluent from sugar industries contains a high concentration of sugars and volatile fatty acids that are easily biodegraded by biological techniques, both anaerobic and aerobic treatments have been widely used, as shown in Table 1 [4]. Aerated lagoons, activated sludge processes, trickling filters, or a mix of these are all examples of aerobic wastewater treatment systems. Anaerobic batch reactors (ABR), Anaerobic fixed-bed reactors (AFR), Up-flow anaerobic fixed bed (UAFB) reactors, and Up-flow anaerobic sludge blanket (UASB) reactors are generally used for the anaerobic treatment of sugar industry wastewater.

Table 1. Treatment methods for sugar industry wastewater.

Reactor type	Aerobic/ Anaerobic	%COD reduction	BOD/COD loading	HRT	Methane yield (mL/g $COD_{removed}$)	Ref.
Anaerobic batch reactor (ABR)	Anaerobic	64 – 87	-	-	236 – 322	[5]
Anaerobic fixed-bed reactor (AFR)	Anaerobic	<90	-	4 days	-	[6]
Up-flow anaerobic sludge blanket (UASB)	Anaerobic	>90	16 kg COD $m^{-3}d^{-1}$	-	355 x 10^3	[7]
Up-flow anaerobic fixed-bed (UAFB)	Anaerobic	>90	10 kg COD $m^{-3}d^{-1}$	20 hours	-	[8]
Aerated fixed film biological (AFFB) systems	Aerobic	68 – 74	0.005 – 0.120 kg BOD $m^{-3}d^{-1}$	2 - 8 hours	-	[9]
Aerated submerged fixed-film (ASFF)	Aerobic	63 – 67	-	2 – 8 hours	-	[10]

The fill-and-draw activated sludge system with clarifier and intermittent aeration mode is used in Sequencing batch reactor (SBR) systems, which are non-steady-state, variable-capacity, and suspended-growth biological wastewater treatment systems where all metabolic reactions and solid-liquid segregation takes place in a unit tank through a timed control sequence [11,12]. The SBR system has several advantages: low installation and operational costs, no requirement of a secondary clarifier, high tolerance to various shock loadings, less energy consumption, robust design, and can be operated with better process control systems [13-15]. However, several parameters can affect the performance of SBR system, including influent characteristics, organic loading rate, pH, carbon source, dissolved oxygen, hydraulic retention time, solid retention time, settleability, anoxic/oxic ratio, temperature, and feed pattern [15,16]. MBBR is a wastewater treatment technology with an attached growth system that provides a large surface area for bacteria to stick to and multiply, forming biological films. Due to the combined effects of attached and suspended growth biomass, MBBR technology is more advanced and dominant than suspended growth technology [17]. Other benefits include system compactness, more biomass per unit volume of aeration tank, steady removal efficiency, resilience to peak organic and hydraulic loads, tolerance to pH and temperature variations, and no carrier clogging [18]. However, the MBBR process possesses several disadvantages such as excessive wear of propellers and aeration system when experiencing collisions with biofilm carrier material, relocation of the carrier material prior to maintenance within the reactors, high BOD/COD loadings leading to poor settling conditions (e.g., use of coagulants/flocculants in the clarifier), and requirement of high oxygen inputs at high ammonia loads during nitrification (under oxygen limited conditions) [19]. Biological methods such as the Membrane bioreactor (MBR), up-flow anaerobic sludge blanket, and biological aerated filter reactor have inherent disadvantages that include high capital and operating cost including maintenance costs, technological sophistication, etc. [20-23]. These restrictions limit the technological feasibility and economic viability of treatment systems, especially in developing nations [24]. Both the compliance and regulatory enforcement of wastewater discharge standards are critical for an effective wastewater treatment system [25]. A shift towards the development and operation of a moving-bed biofilm sequencing batch reactor (MBSBR) is required to overcome the disadvantages experienced by conventional wastewater treatment systems. MBSBR is an integration of MBBR and SBR processes that effectively treat high-strength organic wastewaters. High-density polyethylene or polypropylene plastic material with high surface areas are used as a support media in an MBSBR due to their ability to suspend in mixed liquor, being low in density compared to water. The MBSBR can be used for secondary wastewater treatment for organic carbon and nutrient removal from domestic and industrial wastewaters. The MBSBR can work efficiently with varying organic and inorganic loading and under various operating conditions [26]. This study presents the novel modelling of an MBSBR system based on the work of Faridnasr et al. 2016 [27]. The primary objective of this study is to develop and validate a model with the experimental data by simulating a MATLAB platform suitable for MBSBR using cycle time as a key criterion. The mathematical models used are:

- Monod model (first order)
- Modified Stover-Kincannon model (second order)
- First Order Kinetic Removal model
- Second Order Substrate Removal model

2. Materials and methods

2.1. Wastewater characteristics

The wastewater from sugar industries have a high biodegradable organic content that rapidly depletes the available oxygen supply when discharged into water bodies, endangering aquatic life. A high biochemical oxygen demand (BOD) also creates a septic condition and foul smell of hydrogen sulphide. Excess nitrogen and phosphorous lead to eutrophication, whereas high total dissolved solids (TDS) and total suspended solids (TSS) increase the conductivity rendering wastewater unfit for irrigation. It also precipitates iron and other soluble salts to make the wastewater discharge highly toxic to aquatic life. The treatment of sugar industry wastewater requires physico-chemical and biological treatment. CPCB has prescribed permissible limits for the discharge of treated effluent for the sugar industry. Table 2 provides the characteristics of combined wastewater from the sugar industry. The influent wastewater characteristics used for MBSBR pilot plant modelling are provided in Table 3.

Table 2. Characteristics of combined wastewater before and after treatment.

S.No.	Parameters	Raw wastewater concentration (mg/L)	Treated wastewater concentration (mg/L)	Discharge limits*
1.	Suspended Solids	250-300	50-100	100
2.	BOD	500-800	<30	100
3.	Oil and Grease	5-10	<5	10
4.	COD	1000-1600	<250	-
5.	Total dissolved solids	1000-1200	800-1000	2100

* Central Pollution Control Board [28].

Table 3. Influent wastewater characteristics used for MBSBR modelling [27].

S. No.	Parameter	Average value (mg/L)			
1.	COD	750	1500	2250	3750
2.	BOD_5	500	1000	1500	2500
3.	Na	3.2	6.4	9.6	16
4.	K	10.8	21.6	32.4	54
5.	Ca	8.6	17.2	25.8	43
6.	Mg	0.72	1.44	2.16	3.6
7.	Fe	0.1	0.2	0.3	0.5
8.	Zn	0.06	0.12	0.18	0.3
9.	Cu	0.0078	0.0156	0.0234	0.039
10.	Mn	0.0026	0.0052	0.0078	0.013
11.	Urea	100	200	300	500
12.	KH_2PO_4	10.4	20.3	30.9	50.1
13.	K_2HPO_4	10.9	21.3	32.4	52.6

2.2. Reactor configuration

The dimensions of the reactor used for modelling the MBSBR system were 0.25 x 0.25 x 0.5 m in width (B), length (L), and height (H), respectively. The total volume of the MBSBR was 31 litres, of which 84% was effective for operation. A Kaldness® (K_1) carrier made of high-density polyethylene (HDPE) with a surface area of 500 m^2/m^3, nominal diameter of 0.0071 m, and nominal height of 0.0072 m was used for modelling MBSBR. The line diagram of the MBSBR system modelled in this study and the bio carrier are shown in Figures 1 and 2 respectively.

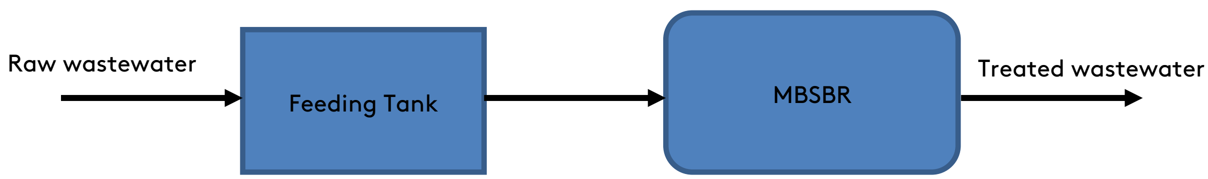

Fig. 1. Modelled MBSBR system.

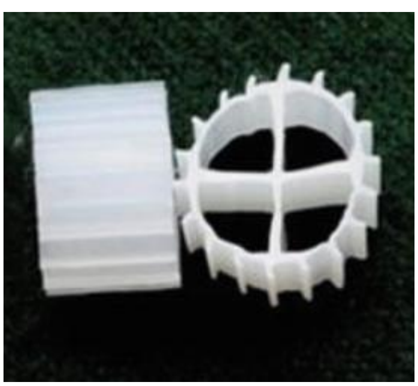

Fig. 2. Biocarrier Kaldness® K_1.

2.3. Determination of kinetic coefficients

It is important to understand the importance of biokinetic parameters in order to design and operate a biological wastewater treatment system optimally. The major goal of kinetics is to develop microorganisms and substrate balances, determine the concentration of effluent microorganisms and substrate, establish design specifications for the process, and determine the performance and consistency of the process. Kinetic modelling is one of the analytical tools for predicting and optimizing reactor performance. The four prominent models used for evaluating the performance of MBSBR are given below:

- Monod model
- Modified Stover Kincannon model
- First Order Kinetic Removal model
- Optaken and Grau Second Order Substrate Removal model

Out of the four models, the model with the least cycle time error percentage is found to be the most suitable for the MBSBR. The model equation and linearized model equation for different models are given in Table 4 and 5.

Table 4. Model equation for different kinetic models.

S. No.	Kinetic Model	Model Equation
1.	Monod	$\frac{\theta X}{S_0 - S} = \left(\frac{K_s}{K}\right)\left(\frac{1}{S}\right) + \frac{1}{K}$
2.	Stover Kincannon [29]	$\frac{V_r}{(S_0 - S)Q} = \left(\frac{K_b}{U_{max}}\right)\left(\frac{V_r}{QS_0}\right) + \frac{1}{U_{max}}$
3.	First-Order [30]	$\frac{S_0 - S}{\theta} = k_1 S$
4.	Second-Order [30]	$\frac{\theta}{E} = m + n\theta$

Table 5. Linearized model equation for different kinetic models.

S. No.	Kinetic Model	Linearized Model Equation
1.	Monod	$\frac{\theta X}{S_0 - S} = m\left(\frac{1}{S}\right) + c$
2.	Stover Kincannon	$\frac{V_r}{(S_0 - S)Q} = m\left(\frac{V_r}{QS_0}\right) + c$
3.	First Order	$\frac{S_0 - S}{\theta} = mS + c$
4.	Second Order	$\frac{\theta}{E} = m\theta + c$

In this study, the zero order kinetic model has not been considered for evaluating the performance of MBSBR due to its non-suitability for BOD and phosphorous removal [31].

2.3.1. Kinetic modelling

The key steps for kinetic computational modelling using cycle time as a criterion for predicting the performance of MBSBR are as follows: (1) Predicted and experimental cycle time (CTs) are compared using a statistical error indicator i.e., normalized root mean square error (NRMSE), and (2) Comparison of model performances. NRMSE is a number between 0 and 1, in which the smaller the number, the smaller the model prediction error. The NRMSE is calculated by

$$NRMSE = \frac{RMSE}{CTmax - CTmin} \quad (1)$$

The root mean square error (RMSE) is calculated by

$$RMSE = \frac{\sqrt{\sum_{t=1}^{n}(CT - \overline{CT})^2}}{n} \quad (2)$$

Where,

n= total number of cycle time

$\overline{CT}$= mean of cycle time

Kinetic modelling is done in this study because of the following reasons:

- It describes the changes and their rates quantitatively
- It helps to unravel basic reaction mechanisms [32]

The kinetic coefficient determined through modelling sugar industry wastewater will depend on the key raw material (i.e., sugarcane or sugar beet for the manufacture of sugar).

2.3.2. Cycle time

The cycle time of MBSBR includes a) filling time, b) aeration time, c) settling time, and d) decantation time. The cycle time of the MBSBR is calculated as:

$$Q = \left[\frac{V_m}{\theta}\right] = \left[\frac{V_d}{T_F}\right]$$

$$T_F = \left[\frac{V_m}{\theta}\right] \times \theta$$

$$T_F = VER \times \theta$$

$$\frac{1}{2}CT = VER \times \theta$$

$$CT = 2\theta \times VER$$

Where:

Q = Flow rate (L/day)

θ = Hydraulic retention time (h)

T_F= Filling time (hr)

VER = Volume exchange ratio

The volume exchange ratio is given by:

$$\mathrm{VER} = \left[\frac{V_d}{V_{max}}\right] \quad (8)$$

$$V_d = Q \times T_a \quad (9)$$

Where;
Q = Flow rate (L/day)
T_a= Aeration time (hr)
V_d= Decanted volume (L)
Cycle time error is given by:

$$CT_{error}(\%) = \left[\frac{CT_{exp} - CT_{calc}}{CT_{exp}}\right] \times 100 \quad (10)$$

Where;
CT_{exp} = Experimental cycle time
CT_{calc} = Calculated cycle time
A model that has the least percentage of cycle time error is considered as the most suitable among the four models. Cycle time is used as a key criterion because of the following reasons [33]:

- The key phase of wastewater treatment takes place within the same reactor, i.e., filling, aeration, sludge formation and settling, decanting and removal of excess sludge. Thus, the maintenance period or number of hours for each phase is very important.
- Cycle time helps in maintaining a time-paced wastewater treatment operation, which avoids less or excessive treatment.
- Cycle time also helps in maintaining a appropriate sludge level to manage high / low organic and volumetric loading as the wastewater treatment system can optimize cycle time via programmable logic controller automation.

2.3.3. Simulation of developed model

Four prominent models were used for the MBSBR. The simulation is done based on an experimental study of MBSBR for the sugar industry [27]. The values of the constants are obtained by the slope and intercept of the graphs of four models. The cycle time error of MBSBR is estimated for the four models using these constants. MATLAB 2013 is used to validate the model because [34]:

- Programming/ debugging tasks can be easily simplified.
- It has the ability to read both common and domain specific image formats.
- It can easily plot the data and change colours, sizes, scales, etc. using the graphical interactive tools.
- It has the ability to auto generate C code for complex mathematical functions using the MATLAB Coder.
- It can add two arrays together using one command.

The MATLAB codes were developed for the following:

- Regression analysis for finding the slope and intercept of the four models for MBSBR performance evaluation.
- Finding the cycle time error percentage for the Monod model, modified Stover kincannon model, first order kinetic model, Optaken and Grau second order substrate removal model.
- Finding the NRMSE for different models.

3. Results and discussion

The simulated results obtained by solving the model developed are presented in this section. The results obtained are represented in graphical form and tabulated. Coefficients (Ks, k) of the Monod model are estimated by plotting [Xθ/(So-S)] versus 1/S, as shown in Figure 3.

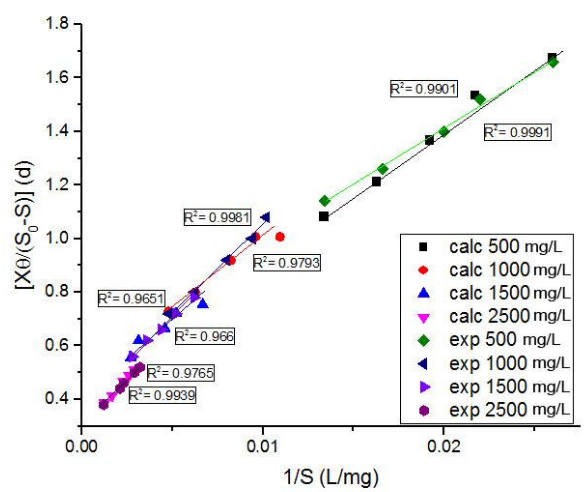

Fig. 3. Performance evaluation of MBSBR using Monod model.

The values of R^2 in Figure 3 imply a good fit and is approximately equal to 1. The value of 1 implies the best fit. The findings reveal that the experimental data fit the model; therefore, the model performance is in good conformance with Ahmadi et al. [35]. The values of the constants used for plotting are shown in Table 6. With the increase in BOD_5 concentration, the value of k and K_s increases, resulting in the high removal of substrate in the wastewater. The performance of MBSBR using the Monod model shows that R^2 value is the best fit for BOD_5 value of 2500 mg/L. Using Figure 3, the model equations developed are presented in Table 7, which is then compared with the experimental model equations.

Table 6. Monod model coefficients at different BOD_5 concentrations.

S.No.	BOD_5 Concentration (mg/L)	Ks (Pred) (mg/L)	Ks (Exp) (mg/L)	Ks Deviation (%)	k (Pred) (1/hr)	k (Exp) (1/hr)	k Deviation (%)
1.	500	99.198	83.158	16.17	2.005	1.856	7.43
2.	1000	105.063	126.319	16.82	2.213	2.207	0.27
3.	1500	110.936	137.129	19.10	2.279	2.449	6.9
4.	2500	259.589	223.935	13.73	3.435	3.313	3.55

Table 7. Modelled versus experimental linearized equation for the Monod model.

S.No.	BOD_5 Concentration	Linearized Model Equation (Predicted)	Linearized Model Equation (Experimental)
1.	500	$\frac{\theta X}{S_0 - S} = 48.6767\left(\frac{1}{S}\right) + 0.4368$	$\frac{\theta X}{S_0 - S} = 44.7553\left(\frac{1}{S}\right) + 0.5391$
2.	1000	$\frac{\theta X}{S_0 - S} = 49.4554\left(\frac{1}{S}\right) + 0.4986$	$\frac{\theta X}{S_0 - S} = 56.9022\left(\frac{1}{S}\right) + 0.4536$
3.	1500	$\frac{\theta X}{S_0 - S} = 47.4677\left(\frac{1}{S}\right) + 0.4516$	$\frac{\theta X}{S_0 - S} = 55.7011\left(\frac{1}{S}\right) + 0.4081$
4.	2500	$\frac{\theta X}{S_0 - S} = 75.5587\left(\frac{1}{S}\right) + 0.2911$	$\frac{\theta X}{S_0 - S} = 66.9700\left(\frac{1}{S}\right) + 0.3021$

The percentage deviation of the experimental and predicted values is also provided. The best fit equation with the least error is given as Equation 11.

$$\frac{\theta X}{S_0 - S} = 75.5587\left(\frac{1}{S}\right) + 0.2911 \quad (11)$$

The coefficients (k_b, U_{max}) for the Modified Stover Kincannon model are estimated by plotting $[V_r/Q(S_o\text{-}S)]$ versus (V_r/QS_o) in. The values of R^2 in Figure 4 imply a good fit and is approximately equal to one. The value of one implies the best fit. The performance of MBSBR using Modified Stover Kincannon model showed that R^2 value is the best fit for BOD_5 value of 2500 mg/L. The values of the constants used for plotting are provided in Table 8. The predicted and experimental linearized model equation developed using Figure 3 for the Modified Stover Kincannon model is presented in Table 9 and then compared with experimental model equations.

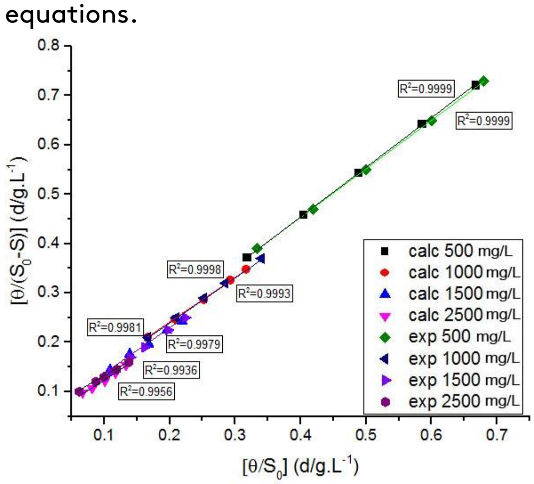

Fig. 4. Performance evaluation of MBSBR using Modified Stover Kincannon model.

Table 8. Stover Kincannon coefficients at different BOD_5 concentrations.

S.No.	BOD_5 Conc. mg/L	K_b (g.BOD_5 /L. d) (Pred)	K_b (g.BOD_5 /L. d) (Exp)	K_b Deviation (%)	U_{max} (gBOD_5 /L. d) (Pred)	U_{max} (gBOD_5 /L. d) (Exp)	U_{max} Deviation (%)
1.	500	16.519	16.631	0.67	17.898	16.690	6.75
2.	1000	17.843	17.880	0.20	17.985	19.024	5.93
3.	1500	18.033	21.356	15.56	20.112	23.195	13.29
4.	2500	21.848	21.579	1.23	25.654	25.583	0.28

Table 9. Modelled versus experimental linearized equation for the Stover Kincannon model.

S.No.	BOD_5 Concentration	Linearized Model Equation (Predicted)	Linearized Model Equation (Experimental)
1.	500	$\frac{V_r}{(S_0-S)Q} = 1.0027\left(\frac{V_r}{QS_0}\right) + 0.0556$	$\frac{V_r}{(S_0-S)Q} = 0.9961\left(\frac{V_r}{QS_0}\right) + 0.0599$
2.	1000	$\frac{V_r}{(S_0-S)Q} = 0.9229\left(\frac{V_r}{QS_0}\right) + 0.0559$	$\frac{V_r}{(S_0-S)Q} = 0.9396\left(\frac{V_r}{QS_0}\right) + 0.0525$
3.	1500	$\frac{V_r}{(S_0-S)Q} = 0.8872\left(\frac{V_r}{QS_0}\right) + 0.0497$	$\frac{V_r}{(S_0-S)Q} = 0.9203\left(\frac{V_r}{QS_0}\right) + 0.0430$
4.	2500	$\frac{V_r}{(S_0-S)Q} = 0.8517\left(\frac{V_r}{QS_0}\right) + 0.0390$	$\frac{V_r}{(S_0-S)Q} = 0.8433\left(\frac{V_r}{QS_0}\right) + 0.0390$

The percentage deviation of the experimental and predicted values is also estimated. The best fit equation with the least error is given as Equation 12.

$$\frac{V_r}{(S_0-S)Q} = 0.8517\left(\frac{V_r}{QS_0}\right) + 0.0390 \quad (12)$$

With the increase in BOD_5 concentration, the value of K_b and U_{max} increases, which results in the removal of the substrate in the wastewater. The first order k_1 coefficient was estimated by plotting $(S_o-S)/\theta$ versus S in Figure 5, and the values of the constant k_1 are provided in Table 10.

The values of R^2 in Figure 5 imply a good fit and is nearly equal to one. The value of one implies the best fit. As the value of the BOD_5 concentration increases, the value of k_1 also increases because the substrate removal is high. The performance of MBSBR using first order kinetic removal model shows that R^2 value is the best fit for BOD_5 value of 2500 mg/L. Using Figure 5, the model equations are developed are presented in Table 11, which is then compared with the experimental model equations. The percentage deviation of experimental and calculated values is also estimated. The best fit equation with the least error is given as Equation 13.

$$\frac{S_0-S}{\theta} = 7.6830S + 4.3447 \quad (13)$$

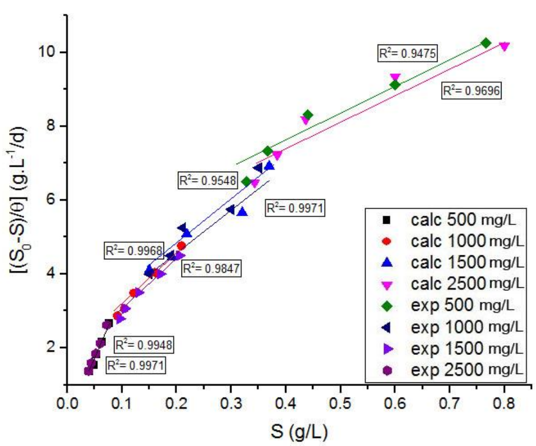

Fig. 5. Performance evaluation of MBSBR using First Order Kinetic Removal model.

The findings revealed that the experimental data fit this model, and therefore the model performance was in conformance with the reference study [27]. The coefficients (n,m,k_s) of the Second Order Substrate Removal model are estimated by plotting $[(\theta*So)/(So-S)]$ versus θ in Figure 6 and the values of the constants used for plotting are given in Table 12.

Table 10. First order kinetic coefficients at different BOD_5 concentrations.

S.No.	BOD_5 Concentration (mg/L)	k_1(1/h) (Pred)	k_1(1/h) (Exp)	k_1 Deviation (%)
1.	500	22.078	33.353	34.11
2.	1000	18.186	16.990	6.58
3.	1500	14.846	13.988	5.78
4.	2500	8.586	7.891	8.1

The values of R^2 in Figure 6 imply a good fit and is approximately equal to one. The value of one implies a best fit. The performance of MBSBR using Monod model shows that R^2 value is the best fit for BOD_5 value of 2500 mg/L. Using Figure 6, it is observed that with the increase in BOD_5 concentration, the value of k_s decreases, which results in an increase in the substrate removal efficiency. The model equations developed are presented in Table 13, which is then compared with the experimental model equations.

Table 11. Modelled versus experimental linearized equation for First Order Kinetic Removal model.

S.No.	BOD_5 Concentration	Linearized Model Equation (Predicted)	Linearized Model Equation (Experimental)
1.	500	$\frac{S_0 - S}{\theta} = 36.448S + 0.0680$	$\frac{S_0 - S}{\theta} = 33.5327S + 0.0485$
2.	1000	$\frac{S_0 - S}{\theta} = 16.1284S + 1.4324$	$\frac{S_0 - S}{\theta} = 16.9897S + 1.2724$
3.	1500	$\frac{S_0 - S}{\theta} = 11.7503S + 2.3113$	$\frac{S_0 - S}{\theta} = 13.9878S + 1.9139$
4.	2500	$\frac{S_0 - S}{\theta} = 7.6830S + 4.3447$	$\frac{S_0 - S}{\theta} = 7.8910S + 4.3897$

Table 12. Second order substrate removal model coefficients at different BOD_5 concentrations.

S.No.	BOD_5 Conc. (mg/L)	n (h) (Pred)	n (h) (Exp)	n Dev. (%)	m (L/mg) (Pred)	m (L/mg) (Exp)	m Dev. (%)	ks (mg/L) (Pred)	ks (mg/L) (Exp)	ks Dev. (%)
1.	500	0.997	0.996	0.1	0.033	0.030	9.09	6.191	6.189	0.03
2.	1000	0.942	0.940	0.18	0.055	0.053	5.17	6.495	6.5	0.08
3.	1500	0.922	0.921	0.11	0.066	0.065	1.51	7.749	7.743	0.08
4.	2500	0.845	0.843	0.23	0.099	0.098	1.01	7.766	7.76	0.08

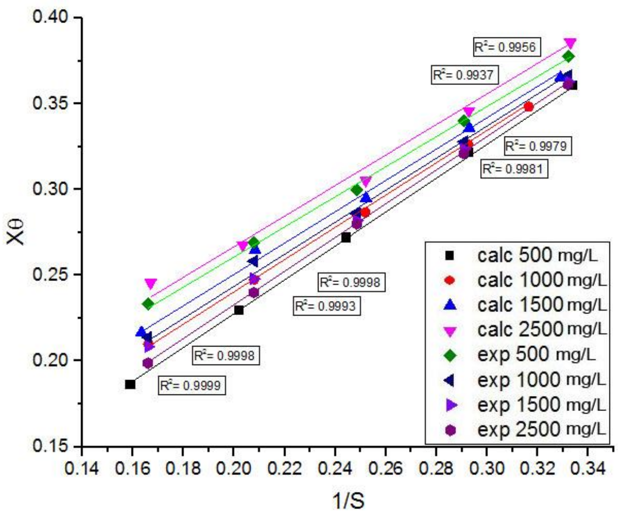

Fig. 6. Performance evaluation of MBSBR using the Optaken and Grau Second Order Substrate Removal Model.

The percentage deviation of the experimental and calculated values is also estimated. The best fit equation with the least error is given as Equation 14.

$$\frac{\theta}{E} = 0.099 + 0.845\theta \quad (14)$$

The graph of a cycle time versus BOD removal efficiency is given in Figure 7. At cycle time of 2 h, the BOD removal efficiency is very high at 500 mg/L (67%) and low at 2500 mg/L (86%). Due to the increase in the cycle time, the contact period between the substrate and the micro-organism increases, thus increasing the time for metabolism; as a result, the BOD_5 removal efficiency increases. From Figure 7, it is observed that the increase in the cycle time increases the BOD_5 removal efficiency, which results in better performance of MBSBR. Figure 7 can be used by researchers, designers, and consultants to determine the different cycle times for their respective biological wastewater treatment systems. The graph of cycle time versus surface loading rate is given in Figure 8. At a cycle time of 2 h, the SLR is 13 kg BOD/ m^2d for 500 mg/L and 62 kg BOD/ m^2d for 2500 mg/L.

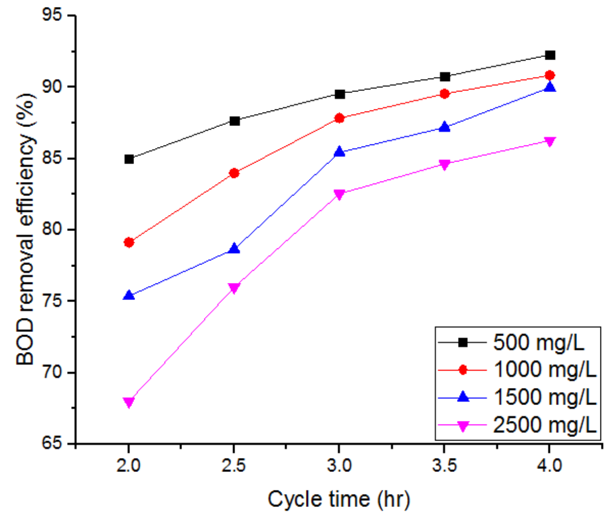

Fig. 7. Calculated BOD removal efficiency versus cycle time.

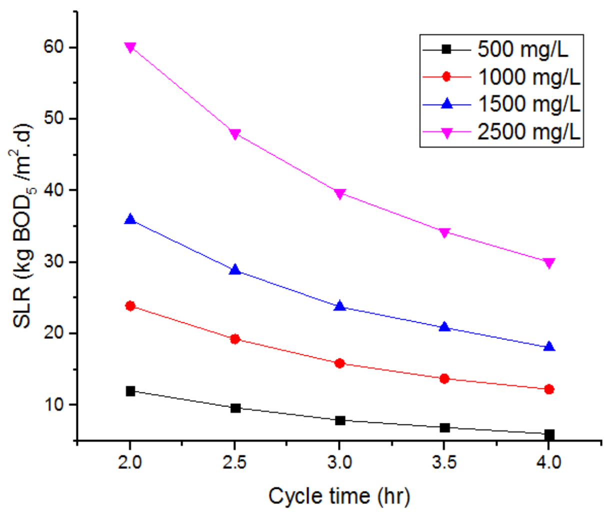

Fig. 8. Experimental surface loading rate versus cycle time.

Due to an increase in the cycle time, the BOD_5 load increases, which results in an increase of SLR. From Figure 8, it is observed that an increase in the cycle time decreases the SLR, resulting in a better performance of MBSBR._The OLR versus BOD removal efficiency is shown in Figure 9. The OLR and BOD_5 removal efficiencies at different concentrations of 500, 100, 1500, and 2500 mg/L depicts the relationship between decreasing OLR and proportional increase in BOD_5 removal efficiencies.

Table 13. Modelled versus experimental linearized equation for the Optaken and Grau second order substrate removal model.

S.No.	BOD_5 Concentration	Linearized Model Equation (Predicted)	Linearized Model Equation (Experimental)
1.	500	$\frac{\theta}{E} = 0.033 + 0.997\theta$	$\frac{\theta}{E} = 0.030 + 0.996\theta$
2.	1000	$\frac{\theta}{E} = 0.055 + 0.942\theta$	$\frac{\theta}{E} = 0.053 + 0.940\theta$
3.	1500	$\frac{\theta}{E} = 0.066 + 0.922\theta$	$\frac{\theta}{E} = 0.065 + 0.921\theta$
4.	2500	$\frac{\theta}{E} = 0.099 + 0.845\theta$	$\frac{\theta}{E} = 0.098 + 0.843\theta$

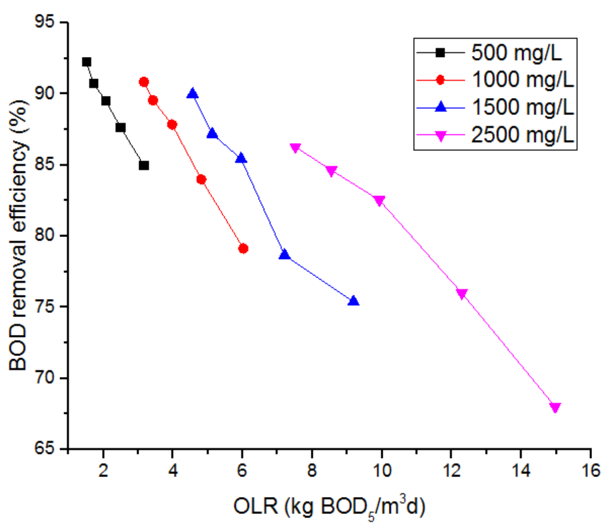

Fig. 9. Calculated BOD removal efficiency versus Organic loading rate.

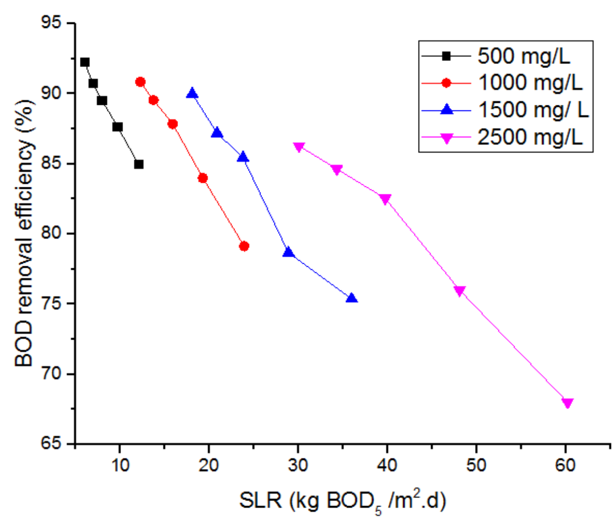

Fig. 10. Calculated BOD removal efficiency versus surface loading rate.

It is observed from Figure 9 that at an OLR of 8 $kg/m^3.d$, the BOD_5 at 2500 mg/L and 1500 mg/L have removal efficiencies of 78.1% and 87.2%, respectively. This is due to the fact that at the same OLR, there is a variation in the cycle times. It can also be observed that an increase in the cycle time decreases the OLR, which results in a better performance of MBSBR. This graph can be used by researchers, designers, and consultants to arrive at a different OLR for their respective biological wastewater treatment systems. The removal efficiency of SLR versus BOD is shown in Figure 10. It is observed in this figure that at an SLR of 30 $kg/m^2.d$, the BOD_5 at 2500 mg/L and 1500 mg/L depicts removal efficiencies of 86.8% and 75.1%, respectively. This is due to the fact that at the same SLR, there is a variation in the cycle times.

From Figure 10, it is observed that a decrease in the SLR increases the BOD_5 removal efficiency, which results in better performance of MBSBR. Figure 10 can be used by researchers, designers, and consultants to determine the different SLRs for their respective biological wastewater treatment systems. The graph of COD removal efficiency versus cycle time is given in Figure 11. At 500 mg/L, the BOD removal efficiency is 84.2% for a cycle time of 2 hr, while it is 93.1% for a cycle time of 4 hr. At the same cycle time, there is a variation in the COD removal efficiencies. This is due to the fact that COD loading rates vary with the increasing concentration of COD load. In Figure 11, it is observed that an increase in the cycle time increases the COD removal efficiency, which results in the better performance of MBSBR. The F/M ratio versus cycle time is shown in Figure 12. SRT indirectly measures the efficiency of the separation of sludge from wastewater and affects the F/M ratio. SRT must be maintained at a level greater than the maximum generation time of micro-organisms in the MBSBR to prevent washout of biomass along with the effluent.

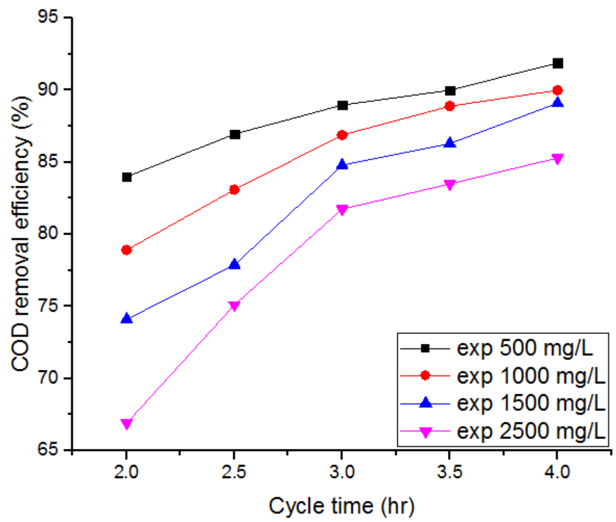

Fig. 11. Experimental COD removal efficiency versus cycle time.

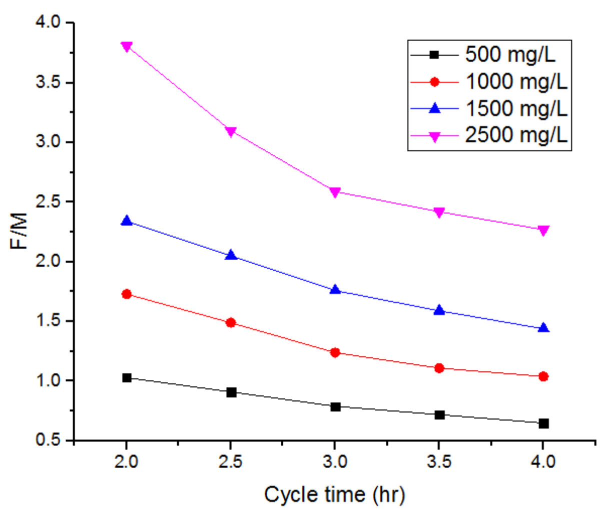

Fig. 12. Experimental F/M ratio versus cycle time.

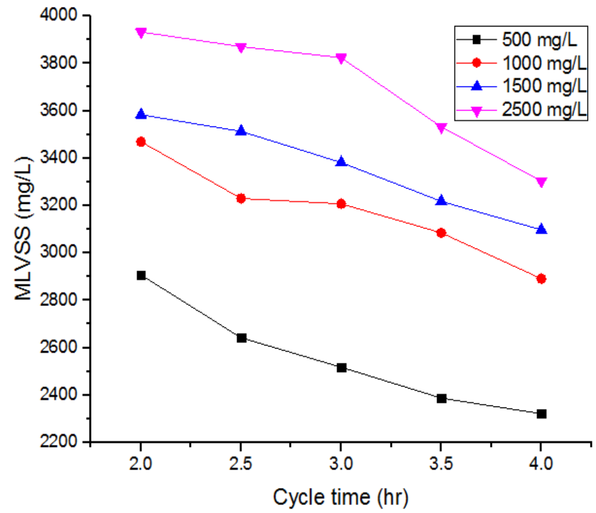

Fig. 13. Experimental MLVSS concentration versus cycle time.

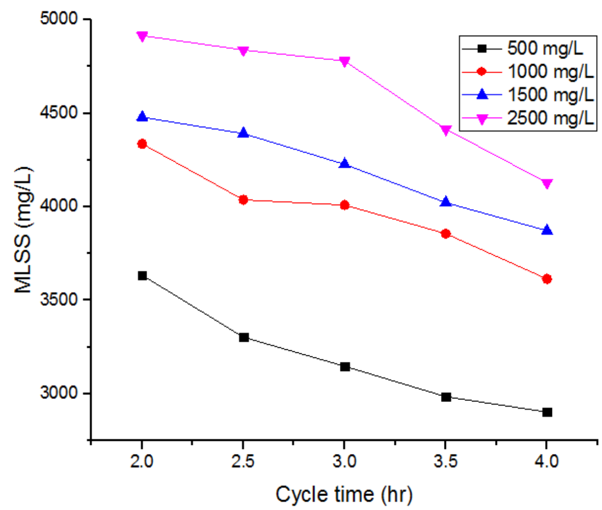

Fig. 14. Calculated MLSS concentration versus cycle time.

From Figure 12, it is observed that an increase in the cycle time decreases the F/M ratio, which results in better performance of MBSBR. The graph of MLVSS versus cycle time is shown in Figure 13. At 500 mg/L, the MLVSS is 2909 mg/L for a cycle time of 2 hr while it is 2330 mg/L for a cycle time of 4 hr. MLVSS decreases with an increase in cycle time. At 3300 mg/L, the cycle time is 2.51 hr and 3.29 hr for 1000 mg/L and 1500 mg/L, respectively. It is concluded from Figure 13 that an increase in the cycle time decreases the MLVSS concentration at the outlet, which results in better performance of MBSBR. The researcher, designer, and consultant can use this to find the amount of MLVSS at the outlet._The graph of MLSS versus cycle time is given in Figure 14. At 500 mg/L, the MLSS concentration is 3639 mg/L for a cycle time of 2 hr and 2909.1 mg/L for a cycle time of 4 hr. MLSS decreases with an increase in the cycle time. At 4250 mg/L, the cycle time is 2.2 hr and 3.25 hr for 1000 mg/L and 1500 mg/L, respectively. From Figure 14, it is observed that an increase in the cycle time decreases the MLSS concentration, which results in better performance of MBSBR. The researcher, designer, and consultant can use this to find the amount of MLSS at the outlet. A summary of kinetic coefficients for different models is provided in Table 16. The modelled and experimental linearized equation for the four models having the least deviation is presented in Table 17. The values of cycle time error (%) for the four models are provided in Table 18. It is evident from Table 18 that the Monod model and Second Order Substrate Removal model are the most suitable models for predicting the optimum cycle time. The value of NRMSE of cycle time for different models is given in Table 19. It is evident from Table 19 that after normalizing different models having different kinetics, the Monod and Second Order Substrate Removal model are the most suitable as they possess least error. In the referenced research [27], an MBSBR was used to treat sugar industry wastewater (BOD_5 = 500-2500 mg/L and COD = 750-3750 mg/L) at 2-4 h of cycle time (CT). The modelling data showed that the MBSBR reached high BOD and COD removal efficiencies; however, it failed to achieve the standard limits at the mentioned CTs. The results of normalized root mean square error revealed that the Stover-Kincannon (error 6.40%) and Grau (error 6.15%) models provide a better fit to the experimental data and may be used for CT optimization in the reactor. The predicted models required CTs of 4.5, 6.5, 7, and 7.5 h for effluent standardization of 500, 1000, 1500, and 2500 mg/L influent BOD_5 concentrations, respectively. A similar pattern of modelling data also confirmed these findings.

Table 16. Predicted versus experimental kinetic coefficients of different models.

S.No.	Model name	Coefficients	Influent BOD (mg/L)			
			500	1000	1500	2500
1.	Monod	K_s (calc) (mg/L)	99.198	105.063	110.936	259.589
2.		K_s (exp) (mg/L)	83.158	126.319	137.129	223.935
3.		k (calc) (1/h)	2.005	2.213	2.279	3.435
4.		k (exp) (1/h)	1.856	2.207	2.449	3.313
6.	Stover Kincannon	U_{max} (calc) ($gBOD_5$/L d)	17.898	17.985	20.112	25.654
7.		U_{max} (exp) ($gBOD_5$/L d)	16.690	19.024	23.195	25.583
8.		K_B (calc) ($gBOD_5$/L d)	16.519	17.843	18.033	21.848
9.		K_B (exp) ($gBOD_5$/L d)	16.631	17.880	21.356	21.579
10.	First order	k_1 (calc) (1/h)	22.078	18.186	14.846	8.586
11.		k_1 (exp) (1/h)	33.353	16.990	13.988	7.891
12.	Second order	m (calc) (L/mg)	0.033	0.055	0.066	0.099
13.		m (exp) (L/mg)	0.030	0.058	0.065	0.098
14.		n (calc) (h)	0.997	0.942	0.922	0.845
15.		n (exp) (h)	0.996	0.940	0.921	0.843
16.		k_s (calc) (mg/L)	6.191	6.495	7.749	7.766
17.		k_s (exp) (mg/L)	5.989	6.533	6.797	6.928

Table 17. Modelled linearized equations for different models.

S.No.	Kinetic Model	Linearized Model Equation (Predicted)	Linearized Model Equation (Experimental)
1.	Monod	$\frac{\theta X}{S_0 - S} = 75.5587\left(\frac{1}{S}\right) + 0.2911$	$\frac{\theta X}{S_0 - S} = 66.9700\left(\frac{1}{S}\right) + 0.3021$
2.	Stover Kincannon	$\frac{V_r}{(S_0 - S)Q} = 0.8517\left(\frac{V_r}{QS_0}\right) + 0.0390$	$\frac{V_r}{(S_0 - S)Q} = 0.8433\left(\frac{V_r}{QS_0}\right) + 0.0390$
3.	First Order	$\frac{S_0 - S}{\theta} = 7.6830S + 4.3447$	$\frac{S_0 - S}{\theta} = 7.8910S + 4.3897$
4.	Second Order	$\frac{\theta}{E} = 0.845\theta + 0.099$	$\frac{\theta}{E} 0.843\theta + 0.098$

Table 18. Cycle time error percentage for different kinetic models.

S.No.	Type of Model	%CT error
1.	Monod model	9.12
2.	Modified Stover Kincannon model	70.25
3.	First Order Kinetic Removal model	35.37
4.	Second Order Substrate Removal model	5.98

Table 19. NRMSE of cycle time for various kinetic models.

S.No.	Concentration (mg/L)	NRMSE			
		First Order	Second Order	Stover Kincannon	Monod
1.	500	58.3	5.11	61.3	9.1
2.	1000	61.7	5.98	66	9.7
3.	1500	64.3	6.1	70	10.2
4.	2500	69.1	6.7	75	11.5

4. Conclusions

This study presents the modelling of MBSBR system using different kinetic models to treat sugar industry wastewater. The effects of different kinetic models on parameters such as cycle time, BOD and COD removal efficiency, and sludge and organic loading rates have been investigated. The main findings of the study are as follows:

- Among the four kinetic models, the model with the least cycle time error percentage is found to be the most suitable model for MBSBR.
- Modelling results show that the Modified Monod model and Second Order Substrate Removal model are the most suitable models for predicting the optimum cycle time of MBSBR.
- An increase in the cycle time of MBSBR increases the BOD_5 and COD removal efficiency due to an increase in the contact period between the substrate and the microorganisms, resulting in an increased performance of MBSBR.
- An increase in the cycle time of MBSBR decreases the SLR and OLR, resulting in better performance of MBSBR.
- Agreement between predicted and simulated results based on modelling and real data indicates that other industries with similar wastewater characteristics can use an optimized MBSBR to capitalize on their investment and comply with applicable environmental regulations.
- Predicted and experimental results based on the modelling and real-time data show that sugar industries could apply an optimized MBSBR to save on costs and comply with the national and international standards and limits.

- Outcome of this study can be applied to assess the performance of MBSBR not only for sugar industries but also for other industrial sector having similar wastewater characteristics.

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