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Beet sugar wastewater treatment in a hybrid biological reactor: operational optimization and kinetic coefficients calculation

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ABSTRACT

The lab-scale treatment of strong beet sugar wastewater was carried out with a combination of a moving bed biofilm reactor (MBBR) and upflow sludge blanket filtration (USBF). The hybrid bioreactor was filled (35% of volume) with industrial packings made of polyethylene with an effective surface area of 480 m^2/m^3 to provide the necessary surface for biofilm growth. The effect of various operating conditions, including hydraulic retention time (HRT = 12-20 hr), biomass concentration (6000– 8000 mg/L), and initial chemical oxygen demand (COD) (3000-5000 mg/L) level, were assessed on the overall COD removal efficiency using response surface methodology (RSM). The optimal conditions were an HRT = 20 hr, biomass concentration = 8000 mg/L, an initial COD = 3000 mg/L, and an organic loading rate (OLR) of 3.6 kg COD/m^3.day under which the COD removal efficiency was 98%. The modified Stover–Kincannon model was applied to predict the biokinetic coefficients for COD removal; the saturation constant (K_B) and the maximum total substrate utilization rate (U_{max}) were in the range 58-101.6 and 57.5- 97 as g/L.day, respectively. The results revealed that raising HRT or biomass concentration promoted COD removal while increasing the initial COD deteriorated the removal performance.

1. Introduction

There is a need for more efficient, low-cost wastewater treatment systems to reduce environmental pollution and recycle the treated water for subsequent application. In addition, treated wastewater must meet more stringent environmental regulations [1] to minimize the consequential environmental and health impacts. It is still difficult to remove trace elements, and this presents a potential problem for industrial wastewater with a high organic loading rate, such as beet sugar wastewater [2]. The beet sugar industry is one of the largest water consumers [3], utilizing around 1500-2000 dm^3 of water and producing around 1000 dm^3 of wastewater per ton of cane processing [1]. The effluent from this industry includes different complex organic

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materials [4], with its biochemical oxygen demand (BOD_5) and COD in the range of 1500-2000 mg/L and 3000-6000 mg/L, respectively. The former numbers imply a large environmental impact that can also increase treatment costs [2]; hence, it appears central to treat this type of industrial wastewater more efficiently. The high organic loading rate (OLR) content in this wastewater effluent makes it suitable for processes based on anaerobic technology [5]. The preceding technologies have dominated high OLR wastewater treatment, as they are capable of reducing such a high COD loading at a relatively shorter hydraulic retention time (HRT). These include upflow anaerobic sludge blanket (UASB reactors, upflow anaerobic fixed bed (UAFB) bioprocess, expanded granular sludge blanket (EGSB) reactors, and fluidized bed reactors (FBRs) [6]. Although previous research suggests that these methods may be effective for sugar factory wastewater treatment, advanced biological treatment (anaerobic mechanism followed by aerobic purification) may provide a more promising option. For that reason, these are becoming one of the conventional treatment methods applied to sugar factory wastewater [7]. The advantage of this complex system over less intricate techniques comes from the particular composition of this industrial wastewater, which contains carbohydrates such as lactose, maltose, and sucrose. These organic compounds promote the growth of filamentous bacteria, leading to the sludge bulking phenomenon often observed as a result of bacteria responding to various stresses. Combined systems offer a plausible resolution for the previous problem. In other words, combined anaerobic (or anoxic)-aerobic systems are ideally suited for treating food industry wastewater, e.g., beet sugar industry wastewater, that contains a highly biodegradable organic content [5]. Apart from the necessity of gaining a high COD removal efficiency, low energy requirements, reduced excess sludge production, and a small footprint are the primary objectives when industrial wastewater treatment is the goal [8]. In particular, one of the most efficient systems for this goal is an upflow sludge blanket filtration (USBF) clarifier. This type of bioreactor is a developed and modern activated sludge system composed of three compartments: an anoxic part at the entrance, followed by an aerobic system, and finally, a sludge blanket filter bed [9]. The integrated upflow sludge blanket filtration bioreactor incorporates anoxic and aerobic compartments and an upflow sludge blanket filter/clarifier. The principle of separation by filtration of suspended solids of biological sludge applied in USBF is much more efficient compared with sedimentation. In this bioreactor, the funnel-shaped sedimentation tank is placed in the middle of the chamber. This funneled tank reduces the upflow velocity while increasing the rate of sludge settling. In due course, a sludge blanket forms, which acts as a filter to trap biomass flocks and produce clear and treated effluent. Ease of operation, lower power consumption, and less space requirement compared to other wastewater treatment processes are known as the benefits of this type of bioreactor. So far, only a few studies have been conducted on the performance of these systems for the treatment of strong industrial effluents [10]. This efficiency manifests in two major ways: by high separation efficiency that results in higher treated water quality and by higher separation velocity, enabling the reduction of the size of the USBF separator [9]. Although there are many advantages of USBF, it has a drawback of a high volume of escaped sludge. This study introduces the combination of an USBF and a moving bed biofilm reactor (MBBR)to overcome this disadvantage. This combination consists of advantages of attached growth, suspended growth, and all USBF advantages. Moving bed biofilm reactors (MBBRs) are biological wastewater treatment vessels in which microbial films (biofilms) grow on the surface of suspended solid packing material (that is, the moving bed) with a density slightly lower than that of water [11]. An MBBR is a biological wastewater treatment process, meaning it is a natural process that uses biofilm to remove organic pollutants from wastewater. This process provides a safe and environmentally sustainable means of removing organic substances, measured in terms of biochemical oxygen demand, as well as achieving nitrification and denitrification. One major advantage of MBBR is that this process doesn't require a lot of physical space. In fact, MBBR is known for its small footprint compared to other biological wastewater treatment methods. The same volume of wastewater flow can be treated by an MBBR tank a fraction of the size of a tank used for an activated sludge process. MBBRs possess appealing characteristics, including shock resistance, comfortable utilization, and high efficiency [12]. The turbulence regime inside the reactor has to be in a manner that the moving bed travels upwards to prevent biofilm loss, and it also results in working with a relatively long SRT [13-14]. The moving is induced by either aeration (in aerobic reactors) or mechanical agitation (in anoxic). This technology has shown promise compared to activated sludge systems and biofilters [15]. For that reason, its association with conventional USBF systems would probably enhance the overall capability of the previous technology. The current study aimed to evaluate the performance of a hybrid biological reactor using floating packings in the aeration compartment of the USBF bioreactor, investigate the impact of operational factors on efficiency, and investigate the maximum organic loading rate (OLR) that allows a stable long-term operation and characterized the developed biomass. Further, the kinetic coefficients for the treatment process under different COD concentrations, HRTs, and biomass concentration values were determined by means of the modified Stover–Kincannon model.

2. Materials and methods

2.1. Wastewater characteristics

The wastewater was synthetically prepared based on real process information from Iranian sugar factories to mimic the sugar beet factory wastewater in our experiments. The average values of the wastewater characteristics fed into the lab scale during the experimentation period are summarized in Table 1. In all the experiments, wastewater with different COD values was prepared using molasses. Diluted sugar beet molasses solutions with added nutrients were used to feed the bioreactors. Feeds with COD values of 3000-5000 mg/L were prepared using different molasses concentrations. Urea and K_2HPO_4 were used as nitrogen and phosphorus supplements, respectively. The nutrients were added to the solution before feeding to the hybrid reactor. The nutrient addition was done to achieve a COD: N: P ratio of 100:5:1. The average composition of 1g sugar beet molasses in 1 L of water had a COD = 610 mg/L and BOD_5 = 428 mg/L. The presence of molasses-suspended, or colloidal solids, was responsible for the turbid and brownish appearance of the wastewater [10].

Table 1. Average characteristics of the molasses used for synthesizing wastewater.

Characteristics	Mean concentration value (mg/L)
TKN	10.25
Fe^{2+}	0.2
Ni^{2+}	0.08
Zn^{2+}	0.25
Mn^{2+}	0.04
S^{2-}	4.04

2.2. Experimental setup

The schematic of the lab scale used in this work is shown in Figure 1. It includes a 30-L USBF reactor (27 L effective volume) composed of an anoxic compartment (5.6 L), an aeration compartment (16.1 L) in which 35 % was packed, and a cone-shaped precipitation tank (5.6 L) in the middle of the bioreactor. Industrial packing made of polyethylene (PE) was used in the bioreactor; the effective surface area of the packing was 480 m^2/m^3 with a density of 0.96 g/cm3 and an average diameter of 1.2 cm. Five sampling ports were located at two different heights along each compartment of the reactor. Furthermore, three separate tanks were devised for influent wastewater preparation (feed tank), equalization, and final effluent collection with volumes of 220 L, 5.5 L, and 10 L, respectively. The synthetic wastewater was prepared in the first tank by adding the necessary nutrients to a molasses solution with the predetermined concentration. Then, it was transferred to the equalization tank before introduction into the hybrid bioreactor.

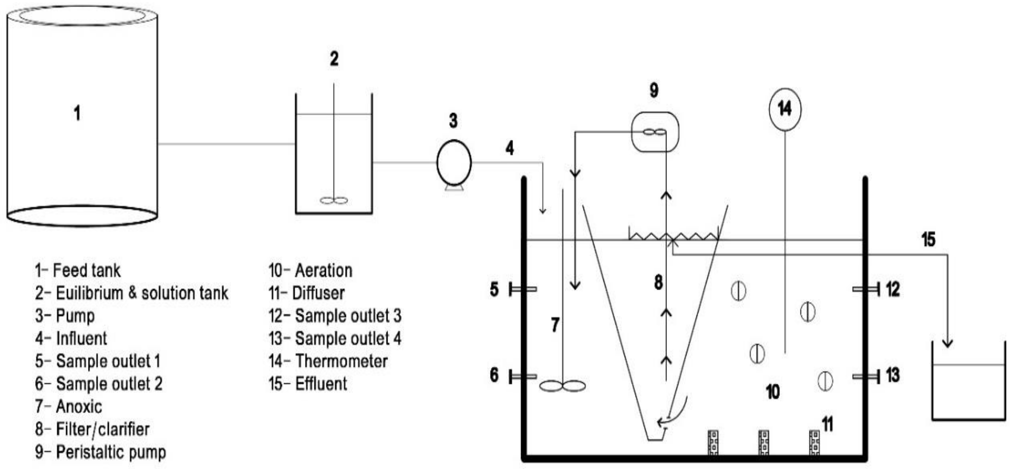


Fig. 1. Lab-scale schematic of the hybrid biological reactor.

2.3. Experimental design and optimization

2.3.1. Response surface methodology (RSM)

Using various statistical and mathematical methods, a substantial procedure in the design of experiments (DOE) called response surface methodology was applied, which is a well-known technique in developing and optimizing the performance of new processes and modifying a design. The primary goal of this method was the optimization of the response surface, which is the outcome of different process parameters [16-18]. Assuming that all the variables are measurable, the response surface can be expressed as:

$$y = f(x_1 . x_2 . x_3 \, . \dots x_k) \qquad (1)$$

where y is the response of the system and x_1, x_2, x_3,..., x_k are the experimental variables, or the so-called factors. The goal is to optimize the response function, y. Estimating the actual functional relation that connects independent variables to the response surface is of high importance. To that end, second-order models seem to provide suitable choices in RSM. The experiments can presumably control the independent variables without any significant error (Eq. 2) [19].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

x_1, x_2, x_3, ..., x_k are the input factors which have influence on the response (y), β_i (i = 1,2,...,k) are the coefficients of linear, β_{ii} (i = 1,2,...,k) are the coefficient of quadratic, β_{ij} (i = 1,2,...,k; j = 1,2,...,k) are the second order terms coefficients, β_0 is the constant coefficient, k is the number of independent parameters, and ε is the error. The β coefficients determined in the second-order model were achieved by the least square method.

2.3.2. Box-Behnken design

The most popular class of RSM methods is the Box-Behnken design. This approach is based on three-level incomplete factorial designs to evaluate the relationship between the experimental and predicted results [20]. It is well-suited for estimating the coefficients in a second-order polynomial that does not involve a large number of design points [19]. The total number of experimental points required for a Box-Behnken design is:

$$N = k^2 + k + C_p \qquad (3)$$

where k is the number of factors and C_p is the number of certain points used to find the experimental error [21]. For the three-factor in a three-level Box–Behnken experimental design, a total of fifteen experimental runs are necessary. The model thus assumes the following form:

$$\begin{aligned} y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \\ + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 \\ + \beta_{23} x_2 x_3 \end{aligned} \qquad (4)$$

where y is the predicted response, x_1, x_2, x_3 are the variable parameters, β_1, β_2, β_3 are the linear coefficients, β_{12}, β_{13}, and β_{23} are the cross coefficients, β_{11}, β_{22}, and β_{33} are the quadratic coefficients, and β_0 is a constant coefficient [20]. In the current article, the Box-Behnken method with three factors in three levels was applied using

Design-Expert software (version 7). Each variable was coded at three various levels between –1 and +1 in the ranges determined by the preliminary experiments. According to screening tests, the factors and their selected levels are presented in Table 2.

Table 2. Factors and their selected levels in Box-Behnken design.

Factor	Level 1	Level 2	Level 3
HRT (hr)	12 (-1)	16 (0)	20 (+1)
COD (mg/L)	3000 (-1)	4000 (0)	5000 (+1)
Biomass (mg/L)	6000 (-1)	7000 (0)	8000 (+1)

The response surface plots were used to analyze the results to evaluate the performance of the hybrid biological reactor. The levels were also selected based on their real ranges in the sugar beet wastewater samples. These individual goals were combined into an overall desirability function by Design-Expert software to find the best local maximum. All the measurements were performed according to commonly used water and wastewater standards [22]. The contaminant removal percentage was calculated from Eq. 5:

$$R = [1 - \left(\frac{C_o}{C_i}\right)] \times 100 \qquad (5)$$

where R is the removal percentage and C_o and C_i are contaminant concentration values in the output and input, respectively. In this work, the purpose was to maximize the removal percentage, which was considered as the response function.

2.4. Kinetic coefficients from the modified Stover–Kincannon model

The kinetic coefficient for treating simulated beet sugar wastewater in the hybrid biological reactor were estimated from modified Stover–Kincannon model. The model is given by:

$$\frac{dS}{dt} = \frac{Q}{V}\,(S_i - S_e) = \frac{U_{max}\,(\frac{QS_i}{V})}{K_B + (\frac{QS_i}{V})} \qquad (6)$$

By inverting Eq. 8 the following is obtained:

$$(\frac{dS}{dt})^{-1} = \frac{V}{Q(S_i - S_e)} = \frac{K_B}{U_{max}}\left(\frac{V}{QS_i}\right) + \frac{1}{U_{max}} \qquad (7)$$

In Equation 7, dS/dt is the substrate removal rate (g/ (L.d)), Q is the flow rate (L/d), V is the reactor liquid volume (L), and S_i and S_e are the influent and effluent substrate concentrations (g/L), respectively. The U_{max} represents the maximum substrate removal rate (g/(L.d)), and K_B is the saturation constant (g/(L.d)). In this model, the suspended solid which had been neglected was considered. To do so, the biomass concentration was expressed by the volume in the modified version [23-24]. According to Equation (7), by plotting $V/Q(S_i - S_e)$ vs. V/QS_i, one can extract the kinetic parameters K_B and U_{max}. The plots give K_B/U_{max} and $1/U_{max}$ as the slope and y-intercept, respectively, under various total biomass concentrations, based on which the modified Stover–Kincannon kinetic coefficients are obtained. The K_B and U_{max} values can be either used to determine the volume necessary for decreasing the influent organic concentration from S_i to its effluent value, S_e, or to calculate the effluent substrate concentration for a given reactor volume and influent organic concentration. By substituting Equation 7 in Equation 6:

$$QS_i = QS_e + (\frac{U_{max}(\frac{QS_i}{V})}{K_B + (\frac{QS_i}{V})})V \qquad (8)$$

Equation 8 shall be solved for either the reactor volume (more precisely that of the reaction medium) or the effluent substrate concentration. By doing this:

$$V = \frac{QS_i}{\left(\frac{U_{max}S_i}{S_i - S_e}\right) - K_B} \qquad (9)$$

$$S_e = S_i - \frac{U_{max}S_i}{K_B + (\frac{QS_i}{V})}V \qquad (10)$$

The values of V and S_i are obtainable by substituting K_B and U_{max} in Equations 9 and 10 for certain biomass levels.

3. Results and discussion

3.1. Selection of factors

In this study, the performance of the proposed hybrid biological reactor in removing COD concentration was evaluated by employing three factors, namely HRT, biomass, and COD inlet concentration, which were found to have significant impacts. After reaching a steady state, these three factors were employed in three different levels to determine the highest COD removal efficiency as a function of the organic loading rate pattern change, which ranged from 3.6 to 10 kg COD/ (m^3.d). These controllable factors were used to provide a range of organic loading rates to evaluate the performance of this developed combination in a wide range of it.

3.2. Experimental results

A total of fifteen experiments were designed to optimize the process. The RSM experimental design approaches and the results of each experiment are presented in Table 3.

According to the ANOVA results for COD removal efficiencies in Table 4, the factors with a *p*-value less than 0.05 and a confidence level range of 95% are assumed to be significant factors. In this regard, the *p*-values of biomass concentration, HRT, and COD were less than 0.05. Hence, these parameters would play a significant role in the performance of the proposed combined system. Among these factors, those with higher *F*-values had a more significant impact on the response. Here, HRT sounds to be the most influential factor in COD removal. Besides, the interactions between the parameters appear to be insignificant. These results agree with the research conducted by Noroozi et al., where all three proposed factors were also found significant in investigating COD removal efficiency using the hybrid activated sludge process for treating domestic wastewater [9].

Table 3. Box–Behnken design with actual values for three size fractions and results.

Experiment No.	COD (mg/L)	HRT (hr)	Biomass (mg/L)	COD Removal (%)
1	4000 ± 50	12 ± 0.1	6000 ± 100	90.5
2	3000 ±50	16 ± 0.1	6000 ± 100	92.3
3	5000 ± 50	12 ± 0.1	7000 ± 100	89.9
4	3000 ± 50	16 ± 0.1	8000 ± 100	97.9
5	4000 ± 50	12 ± 0.1	8000 ± 100	92.3
6	3000± 50	12 ± 0.1	7000 ± 100	95.0
7	4000 ± 50	16 ± 0.1	7000 ± 100	95.1
8	5000 ± 50	20 ± 0.1	7000 ± 100	96.0
9	5000 ± 50	16 ± 0.1	6000± 100	90.7
10	4000± 50	16 ± 0.1	7000 ± 100	96.5
11	3000± 50	20 ± 0.1	7000 ± 100	98.8
12	4000± 50	20 ± 0.1	6000± 100	93.7
13	4000± 50	16 ± 0.1	7000 ± 100	95.6
14	5000 ± 50	16 ± 0.1	8000 ± 100	94.9
15	4000± 50	20 ± 0.1	8000 ± 100	97.2

Table 4. Variance analysis in COD removal percentages.

Model terms	Mean square error	Sum of the error squares	Degree of freedom	F-value	P-value	Status
Model	11.48	103.28	9	10.98	<0.0001	Significant
A: COD	19.94	19.94	1	19.07	<0.0001	Significant
B: Biomass	29.03	29.03	1	27.77	<0.0001	Significant
C: HRT	40.55	40.55	1	38.78	<0.0001	Significant
A×B	0.52	0.52	1	0.5	0.5127	Not significant
A×C	1.36	1.36	1	1.3	0.3062	Not significant
B×C	0.72	0.72	1	0.69	0.4437	Not significant
A×A	0.084	0.084	1	0.081	0.7876	Not significant
B×B	9.98	9.98	1	9.54	0.0272	Significant
C×C	1.76	1.76	1	1.69	0.2506	Not significant
Lack of fit	4.12	0.81	3	2.48	0.2999	Not significant

3.3. The effect of significant factors

Response surface plots were drawn to study the effect of significant factors (HRT, biomass, and inlet COD) on COD removal efficiency (Figure 2). According to Figure 2a, an increase in inlet COD concentration and the decrease in HRT deteriorated the removal efficiency. This was due to the increased OLR, ranging from 3.6 kg COD/ (m^3.day) to 10 kg COD/ (m^3.day). On the contrary, raising the biomass concentration resulted in an enhanced COD removal efficiency at all inlet COD concentrations (Figures 2b and 2c). The preceding is a consequence of the larger microorganism population that decomposed more organic material in the biological system. Thus, according to the results presented in Table 3, the maximum and minimum COD removal efficiencies occurred at, the lowest tested here an inlet COD value of 3000 mg/L, the highest level of biomass (8000 mg/L), and the highest level of HRT (20 hr). The COD removal efficiency had a linear relationship with HRT, as shown in Figure 2a. Longer retention provided more time for microorganisms to consume the organic pollutants, which was equal to a higher removal percentage. Noroozi et al. 2014, obtained a similar pattern of COD removal efficiency from 90 to 96 percent by increasing biomass from 6000 to 8000 mg/L and decreasing OLR from 1.6 to 0.5 kg COD/(m^3.day). In another study regarding sugar wastewater treatment using the aerated fixed film biological approach, a gradually decreasing COD removal trend was observed from 73 to 67 percent by surging OLR (5-120 g BOD/(m^3.day)) [24].

3.4. Evaluation of experimental results by Design-Expert software

Experimental results were evaluated using Design-Expert software to derive approximating functions to investigate a correspondence model that predicted COD removal based on significant parameters. This approximating equation in terms of coded factors can be formulated as:

$$\begin{aligned} R_1(\%) = &+95.75 - 1.58 \times A + 1.9 \times B \\ &+ 2.25 \times C - 0.36 \times A \times B \\ &+ 0.58 \times A \times C + 0.43 \times B \times C \\ &- 0.15 \times A^2 - 1.64 \times B^2 \\ &- 0.69 \times C^2 \end{aligned} \tag{11}$$

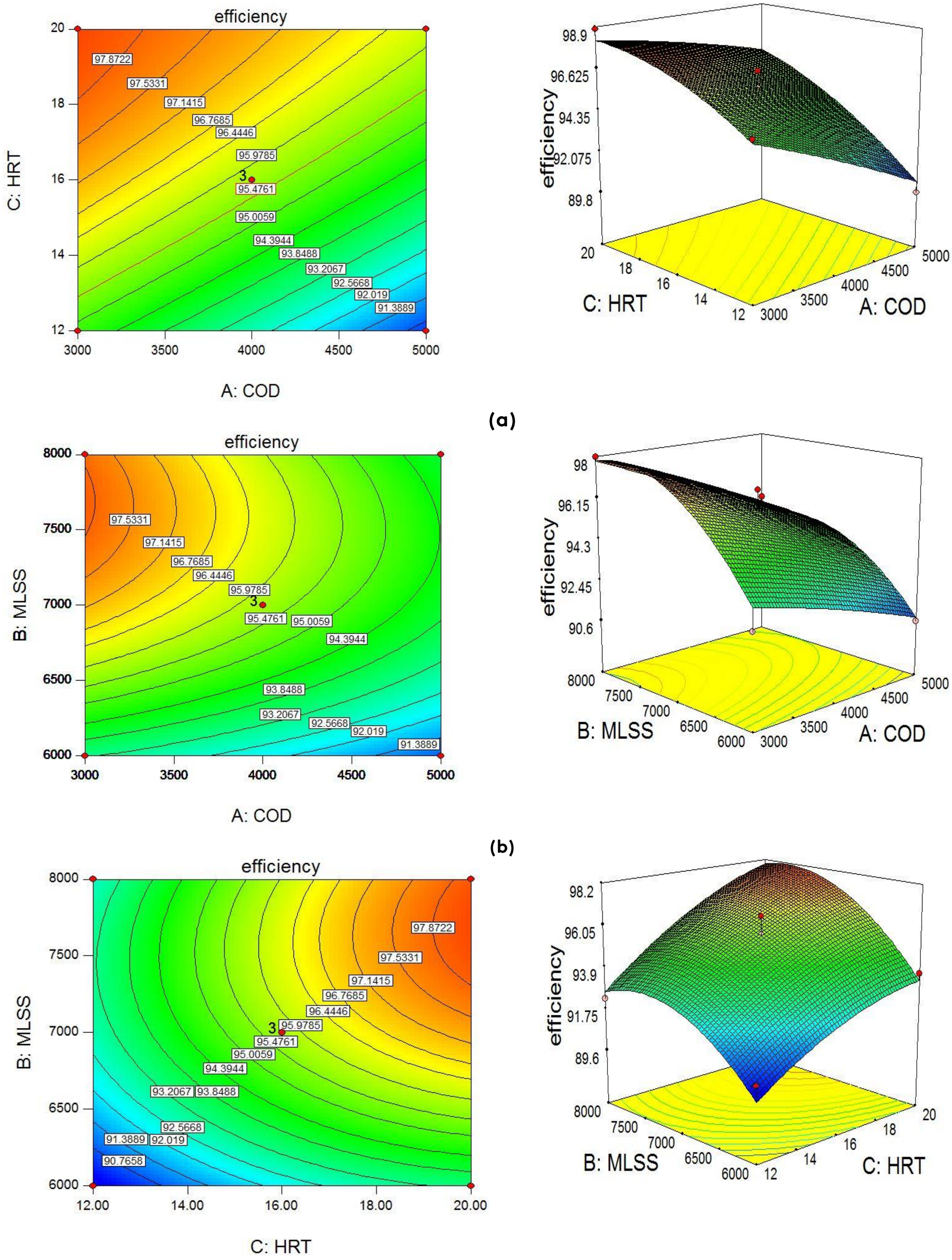
The results yield R^2 = 0.95, suggesting a good correspondence between the experimental results and predicted COD removal efficiencies. The previous polynomial prediction is valid over the range studied in the current hybrid biological reactor. Figure 3 depicts the correspondence between the experimental and predicted results.

3.5. Contribution percentage

Based on the data from the Box-Behnken design for COD removal, the contribution percentage for each factor was determined from Equation 12:

$$CP(\%) = \frac{SS_i}{SS_{total}} \times 100 \tag{12}$$

The extent of influence for each of the factors could be described as a percentage of the whole, which was as follows: 37.4 HRT, 26.8 biomass concentration, 18.4 COD. This showed that the most influential factors in the process of COD removal were 1- HRT, 2- biomass, and 3- inlet COD level. One notable point about these values was that the individual factors contributed more to the process compared to the cross factors, which was concluded from the fact that the most prominent cross factor, i.e., biomass×biomass (B×B), had an influence percentage less than 10% that was approximately half of the influence percentage of inlet COD, as the least contributive individual factor. This fact suggested a strong correlation between individual factors, namely HRT, biomass, and inlet COD and COD removal efficiency calculated in Equation 6, with a fit accuracy of over 95% (see Figure 4).



(c)

Fig. 2. (a) Response surface plots and contour plots depicting the effect of inlet COD concentration and HRT on the efficiency of COD removal at constant biomass concentration; (b) The effect of inlet COD concentration and biomass on the removal efficiency at constant HRT; (c) The effect of HRT and biomass on the removal efficiency at constant inlet COD concentration.

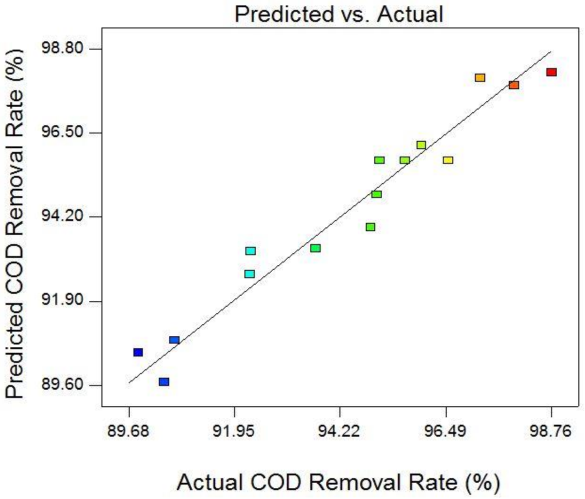


Fig. 3. Relationship between the experimental and predicted COD removal rates.

3.6. *Kinetic coefficients from modified Stover–Kincannon model*

The results of plotting $\mathrm{V/Q(S_i - S_e)}$ vs. $\mathrm{V/QS_i}$ derived from modified the Stover-Kincannon model are demonstrated in Figure 4. Each plot belongs to a specific mean biomass, with values of 6000, 7000, and 8000 mg/L for 4(a) through 4(c), respectively. The line of best fit was used to extract the kinetic parameters, saturation constant ($\mathrm{K_B}$), and maximum substrate utilization rate ($\mathrm{U_{max}}$), and are summarized in Table 5.

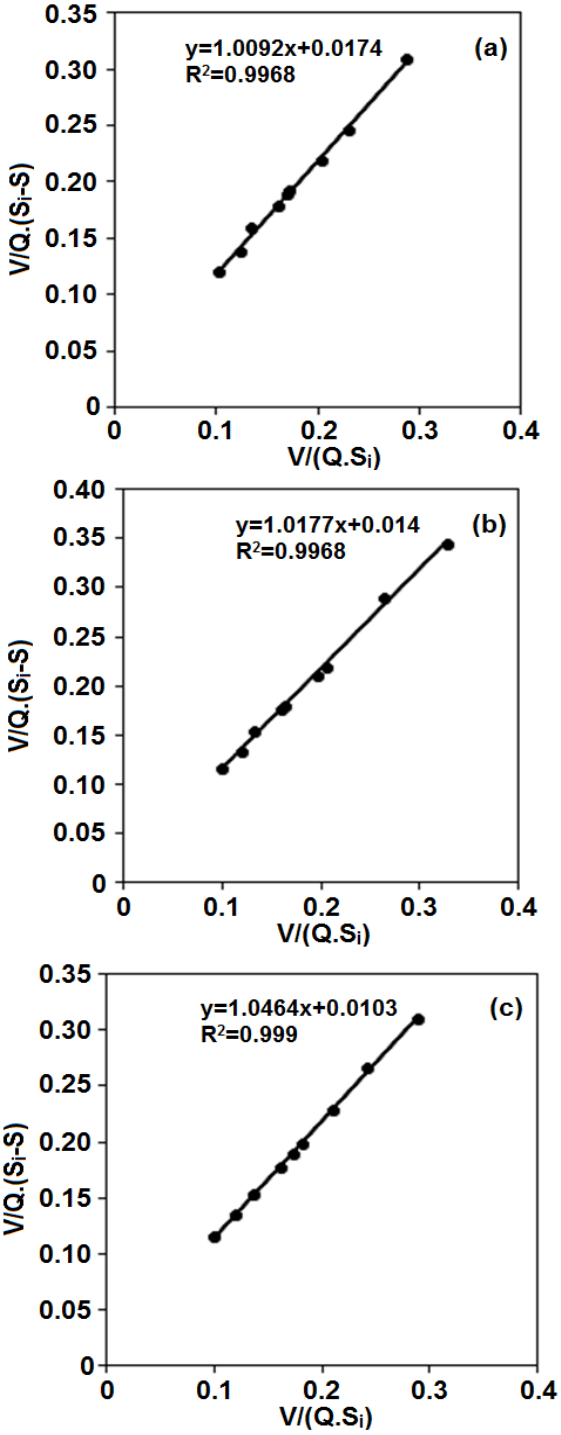


Fig. 4. Modified Stover–Kincannon plots for extracting the kinetic parameters.

Table 5. Modified Stover–Kincannon kinetic parameters and goodness of fit.

Substrate	Biomass concentration (mg/L)	$\mathrm{U_{max}}\ (\frac{g}{L.d})$	$\mathrm{K_B}(\frac{g}{L.d})$	$\mathrm{R^2}$
Beet sugar industry	6000	57.47	58.00	0.997
	7000	71.43	72.69	0.997
	8000	97.09	101.59	0.999

The values of V and $\mathrm{S_i}$ are obtainable by substituting $\mathrm{K_B}$ and $\mathrm{U_{max}}$ from Table 5 in Equations (11) and (12) for biomass levels of 6000, 7000, and 8000 mg/L. The results indicated that by raising the biomass concentration, $\mathrm{K_B}$ and $\mathrm{U_{max}}$ went up as a result of enhanced microorganism population in the biological system. In other words, the microbial community consumed the organic compounds faster, which translated to larger $\mathrm{K_B}$ and $\mathrm{U_{max}}$ values. The $\mathrm{K_B}$ and $\mathrm{U_{max}}$ values obtained from Figures 4(a)–(c). Previous literature reports experiments conducted at different pollutant concentrations and constant biomass content [28-31]. However, in the current study, kinetic coefficients were extracted under a constant COD circumstance, while the impact of biomass level was evaluated. Constant values determined via various kinetic models in previous studies are summarized in Table 6 and contrasted to coefficients obtained here. The $\mathrm{K_s}$ values in our experiments were larger than those previously reported in the literature. The lower rates of substrate utilization may justify the discrepancy. Based on the Stover–Kincannon kinetic model, both the saturation constant $\mathrm{K_B}$ and the $\mathrm{U_{max}}$ values obtained in the current study were in the range of data previously reported by Yu and coworkers [25-26] and Borghei and coworkers 2008, while they were more significant than the other values reported in the literature [27]. Table 6 summarizes the kinetic parameters calculated by other researchers along with those calculated in the current work.

Table 6. Comparison between modified Stover–Kincannon kinetic parameters in the current study with those obtained previously by other groups.

Wastewater nature	Pollutant concentration (mg/L)	HRT (day)	Kinetic parameters		Reference
			K_B	U_{max}	
Soybean	7520-11450	1-1.45	85.5	83.3	[28]
Simulated	750-4500	1	9.5	8.3	[29]
Molasses	800-2400	0.5-1	24.9	18.1	[30]
Simulated	750-2250	0.5-1	106.8	101	[31]
Molasses	3000-5000	0.5-0.8	58-101.5	57.5-97.1	Current study

4. Conclusion

A hybrid biological reactor was investigated for treating simulated beet sugar industry wastewater on a lab-scale under a long-term operation. The limited nitrogen and phosphorous content in these synthetic wastewater samples necessitated the nutrient addition to achieve a proper C: N: P ratio. The DOE approach suggested that three parameters, HRT, COD, and biomass concentration, would be significant factors, among which HRT had the most effect. An increase in HRT and/or MLSS enhanced COD removal efficiency, while raising the inlet COD concentration lowered the efficiency. The proposed polynomial model for the prediction of COD removal efficiency had an excellent correspondence with the experimental results. The maximum OLR introduced to the hybrid bioreactor was 3.6 kg COD/ ($\mathrm{m^3}$.d). The data also revealed that the modified Stover–Kincannon highly correlated with the experimental results for the biokinetic modeling of this combined reactor. The modeling demonstrated that by increasing biomass concentration in the biological systems, the biokinetic coefficients increased. In summary, the current combined system could be considered a practical approach to reducing the COD content of beet sugar industry wastewater.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that would influence this paper.

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