

Kinetic Modeling of Downflow Hanging Sponge (DHS) System Treating Synthetic Domestic Wastewater[†]

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Abstract: A downflow hanging sponge (DHS) unit was established for treating synthetic domestic wastewater (SDW) for over 100 days of continuous feed. The DHS system was operated at a chemical oxygen demand (COD) concentration of 531.62 ± 93.6 mg/L, and different hydraulic retention times (HRTs) = 6.0–2.0 h to determine the system kinetics. The substrate removal kinetics of the DHS reactor was calculated using modified Stover–Kincannon, Monod, Grau’s second-order and first-order models. The Monod model has the following decay coefficient (K_d), yield coefficient (Y), and maximum specific growth rate of bacteria (μ_{max}) that were, respectively, 0.0025 1/d, 0.1337 gVSS/gCOD, and 0.0364 1/d. Maximum substrate utilization rate (U_{max}) and saturation value constant (K_B) for the modified Stover–Kincannon model were determined to be, respectively, 15.46 and 14.45 g/L/d. While the kinetic coefficient for the second-order model ranged was 0.516–0.641 1/d versus 27.627 1/d for the first-order model, the constants of the Grau second-order model (a and b) were estimated as 0.0366 and 0.9215. The Grau second-order and modified Stover–Kincannon models showed an R^2 value of 0.995, making them the most convenient for the experimental results. The results indicated that these models could be used to predict the DHS reactor behavior at different scales.

Keywords: long-term continuous feed; operating condition; sewage; sponge-based technology; Monod; Grau second-order model; first-order model



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1. Introduction

Selecting effective wastewater treatments is crucial, particularly in undeveloped nations with limited resources, little experience, and a lack of skilled staff [1]. Downflow hanging sponge (DHS) technology is considered a practical solution for easing sewage issues because it is simple to implement, has low treatment costs, and discharges a small quantity of sludge [2]. The DHS unit is built on the idea of a conventional trickling filter, but rather than utilizing rocks, gravel, or plastic pieces, it uses sponge holders with high porosity [3]. The sponge media have a huge capacity to hold a lot of activated biomasses on top of and inside the sponges, allowing the microbial plants in the reactor to grow and create biofilms. Environmental engineers are presently using kinetic models to help with the design and optimization of wastewater treatment systems. To manage and evaluate the DHS reactor performance, experimental results should be organized and governed by kinetic models within a certain framework [4]. The removals of COD and nitrogen in many reactors have been studied using a variety of kinetic models. Grau’s second-order,

Monod, Stover–Kincannon, and first-order were widely used to calculate the substrate removal rate [5].

Despite the increasing number of kinetic models for numerous reactor types, the DHS system for domestic wastewater treatment has not been investigated to evaluate kinetic models [6]. The kinetic parameters and the interactions between many factors in the DHS unit treating domestic wastewater are not fully understood. Kinetic models were used in the current work to determine the COD elimination rate. The results of the kinetic models would evaluate the DHS performance for large-scale applications.

2. Materials and Methods

2.1. Characteristics of Influent Wastewater

Synthetic wastewater (Table 1) was prepared to simulate the domestic wastewater characteristics [7].

Table 1. Synthetic domestic wastewater (SDW) characteristics.

Parameter	COD	NH ₃	pH	TSS	Conductivity
Unit	mg/L	mg/L		mg/L	(μ S)
Value	531.62 $\pm$ 93.6	66.22 $\pm$ 3.47	7.12 $\pm$ 0.82	102.26 $\pm$ 13.12	1316.18 $\pm$ 40

2.2. Configuration of DHS Reactor

Figure 1 depicts the graphical layout of the pilot-scale DHS. The cylindrical reactor was composed of polymethyl methacrylate and measured 1.5 m $\times$ 0.15 m (height $\times$ diameter). The DHS was filled with 250 sponge pieces; each sponge has 0.63 mm-wide pores, 3.20 cm height, and a 1.60 cm radius. It has a specific surface area of 250 m²/m³, a density of 30 kg/m³, and a porosity of 90% [8].

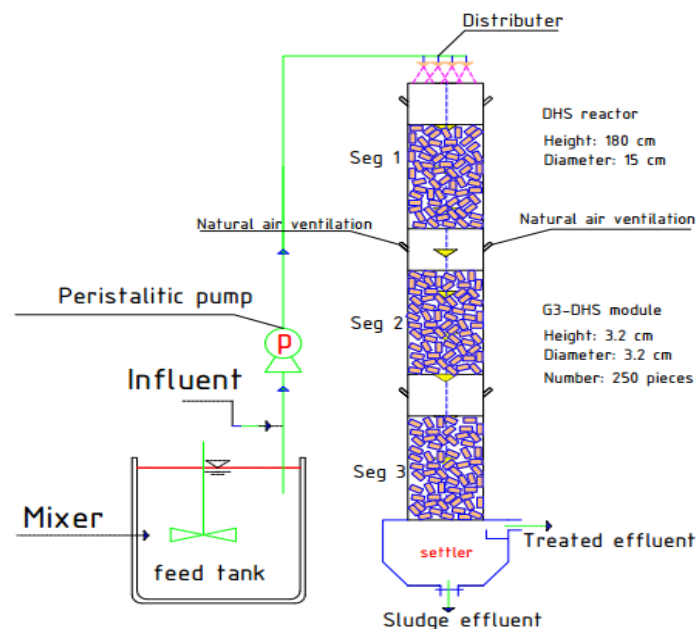


Figure 1. Configuration of the DHS unit utilized to treat SDW.

2.3. Reactor Operation

Before beginning the experimentation, the DHS system was operated for half a month until stable effluent COD and NH₃ concentrations (within 6% change for three sequential readings) are achieved. The DHS reactor was operated by increasing the flow rate from 20.4 to 61.2 L/d, corresponding to various hydraulic retention time (HRT) conditions (Table 2).

Table 2. Operational conditions of DHS reactor.

Parameters	(Unit)	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
HRT	(h)	6.0	5.0	4.0	3.0	2.0
Flow rate (Q)	(L/d)	20.4	24.5	30.6	40.8	61.2
HLR	(m ³ /m ² /d)	1.15	1.39	1.73	2.31	3.46
SRT	(d)	151.96	86.74	70.33	60.91	52.03
F/M ratio	(Kg COD/kg VS/d)	0.12	0.14	0.15	0.20	0.28
Temperature	°C	25–32				

HLR: hydraulic loading rate, F/M: food to microorganism ratios.

2.4. Analytical Methods

COD was analyzed from the effluent and the influent three times per week to assess reactor performance. Analyses were carried out according to the “Standard Method for Examination of Water and Wastewater” by APHA [9].

2.5. Kinetic Modeling for Substrate Removal

2.5.1. Monod Model

In the DHS reactor with no biomass recycling, the rate of change in biomass and substrate concentrations are given by Equations (1) and (2), respectively [10]:

$$\frac{dx}{dt} = \frac{Q \times X_i}{V} - \frac{[(Q - Q_w) \times X_e + (Q_w \times X_w)]}{V} - r_{su} \times Y - K_d \times X \quad (1)$$

$$-\frac{ds}{dt} = \frac{Q \times S_i}{V} - \frac{Q \times S_e}{V} - \frac{\mu \times X}{Y} \quad (2)$$

At a steady-state condition ($dX/dt = 0$), and the influent biomass concentration can be ignored ($X_i = 0$), Equation (3) can be obtained:

$$\frac{(Q - Q_w) \times X_e + Q_w \times X_w}{VX} = -\frac{Y \times r_{su}}{X} - K_d \quad (3)$$

Hence, the average solid retention time (SRT) is given by Equation (4):

$$\frac{1}{SRT} = -\frac{Y \times r_{su}}{X} - K_d \quad (4)$$

$(-r_{su}/X)$ equals the specific substrate utilization rate (U), measured as Equation (5):

$$U = \frac{r_{su}}{X} = \frac{S_i - S_e}{HRT \times X} = \frac{Q \times (S_i - S_e)}{V \times X} \quad (5)$$

From Equations (4) and (5), a new form is obtained (Equation (6)):

$$\frac{1}{SRT} = Y \frac{S_i - S_e}{HRT \times X} - K_d \quad (6)$$

By graphing Equation (6), Y and K_d parameters can be determined.

Equation (7) can express the following correlation among the specific growth rate (μ), the rate-limiting substrate concentration, and SRT:

$$\mu = \frac{\mu_{max} \times S_e}{K_s + S_e} \quad (7)$$

From these equations, Equation (8) can be derived:

$$\mu = \frac{1}{SRT} + K_d \quad (8)$$

$$\frac{\mu_{\max} \times S_e}{K_s + S_e} = \frac{1}{\text{SRT}} + K_d \quad (9)$$

Plotting Equation (10) gives the values of $\mu_{\max}$ and K_s :

$$\frac{\text{SRT}}{1 + K_d \times \text{SRT}} = \frac{K_s}{\mu_{\max}} \times \frac{1}{S_e} + \frac{1}{\mu_{\max}} \quad (10)$$

Also, Equation (11) is applied to predict COD concentration in the final effluent:

$$S_e = \frac{K_s (1 + K_d \times \text{SRT})}{\text{SRT} (\mu_{\max} - K_d) - 1} \quad (11)$$

where r_{su} refers to substrate utilization rate (g/L/day), and K_s is a half-saturation constant.

2.5.2. Modified Stover–Kincannon Model

This model has the unique property of expressing the rate of substrate utilization as a function of the organic loading rate under a steady state. Based on the substrate removal rate as a function of substrate concentration, the removal of the organic substrate in the aerobic reactors may be calculated (Equations (12) and (13)):

$$\frac{ds}{dt} = \frac{Q}{V} (S_i - S_e) \quad (12)$$

where ds/dt refers to the removal rate of COD (g/L/d), V is the actual volume of the DHS reactor

$$\frac{ds}{dt} = \frac{U_{\max} \left[\frac{Q \times S_i}{V} \right]}{K_B + \left[\frac{Q \times S_i}{V} \right]} \quad (13)$$

The aforementioned Equation (13) is linearized as follows (Equation (14)):

$$\frac{dt}{ds} = \frac{\text{HRT}}{(S_i - S_e)} = \frac{K_B \times \text{HRT}}{U_{\max} \times S_i} + \frac{1}{U_{\max}} \quad (14)$$

By plotting the $\text{HRT}/(S_i - S_e)$ vs. the HRT/S_i , $K_B/U_{\max}$ is the slope while $1/U_{\max}$ gives the intercept of the straight line. The effluent substrate may be measured by Equation (15):

$$S_e = S_i - \frac{U_{\max} \times S_i}{K_B + \frac{S_i}{\text{HRT}}} \quad (15)$$

2.5.3. Grau's Second-Order Model

The model's equation is written as:

$$-\frac{ds}{dt} = \left(\frac{S_e}{S_i} \right)^2 \times K_2 \times X \quad (16)$$

Equation (16) can be linearized and simplified as Equation (17):

$$\frac{S_i \times \text{HRT}}{S_i - S_e} = \text{HRT} + \frac{S_i}{K_2 \times X} \quad (17)$$

Since $S_i/K_2 \times X$ is constant and $(S_i - S_e)/S_i$ reflects the effectiveness of COD elimination, Equation (18) can be given:

$$\frac{\text{HRT}}{\text{COD Removal}} = b \times \text{HRT} + a \quad (18)$$

The constants a and b could be determined from a straight line on a plot between HRT and HRT/COD removal, where “ a ” can be calculated by ($a = \frac{S_i}{k_2 \times X}$).

HRT is utilized to predict the final effluent of COD concentration according to Equation (19):

$$S_e = S_i \left(1 - \frac{\text{HRT}}{a + b \times \text{HRT}} \right) \quad (19)$$

2.5.4. First-Order Substrate Removal Model

By applying the first-order model for substrate removal, the rate of variation in substrate content in the reactor can be represented as Equation (20):

$$-\frac{ds}{dt} = \frac{Q}{V} (S_i - S_e) - K_1 S_e \quad (20)$$

At pseudo-steady-state conditions where the rate of change in substrate content owing to accumulation ($-dS/dt$) is minimal, Equation (21) can be obtained:

$$\frac{(S_i - S_e)}{\text{HRT}} = K_1 S_e \quad (21)$$

Plotting $(S_i - S_e)/\text{HRT}$ against S_e in Equation (21) is used to obtain the value of K_1 and Equation (22) is applied to predict the effluent COD concentration.

$$S_e = \frac{S_i}{1 + K_1 \times \text{HRT}} \quad (22)$$

3. Results and Discussion

3.1. Monod Model

As shown in Figure 2a, the relationship between the $(1/\text{SRT})$ and (U) was plotted to calculate (Y) and (k_d) . The intercept and slope of the straight line seen in Figure 2a were used to estimate the Y and k_d values, which were determined to be $0.1337 \text{ g VSS/g COD}$ and 0.0025 1/d , respectively, while the values of $(\mu_{\max})$ and (K_S) were calculated from Figure 2b as 0.036 1/d and 0.085 g COD/L , respectively. This was achieved by graphing $1/S_e$ versus $\text{SRT}/(1 + K_d \times \text{SRT})$. Also, the correlation coefficient for the Monod model was in the range of 0.9272 to 0.8201.

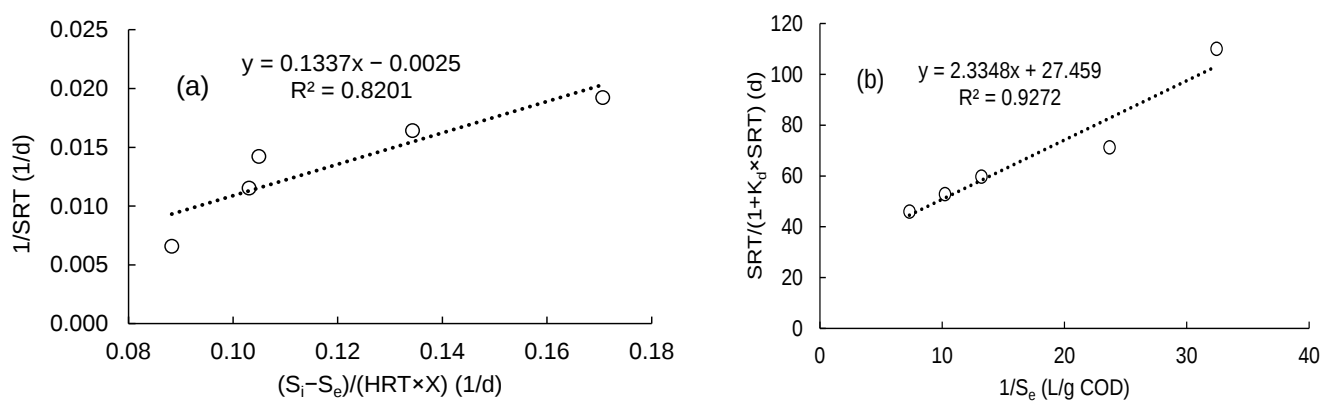


Figure 2. Determination of the kinetic constants using a linear plot of the Monod model: (a) k_d and Y ; (b) $\mu_{\max}$ and K_S .

According to Equation (11), the equation for calculating the effluent COD concentration based on SRT is defined as Equation (23):

$$S_e = \frac{0.085(1 + 0.0025 \times \text{SRT})}{(0.0339)\text{SRT} - 1} \quad (23)$$

3.2. Modified Stover-Kincannon Model

Figure 3a displays a graph plot between the HRT/S_i against the $\text{HRT}/(S_i - S_e)$ for calculating $U_{\max}$ and K_B values for synthetic domestic wastewater treatment using a DHS unit. It is highly supported by a straight line with a coefficient of regression of 0.995 that this model is valid. The calculated values for the kinetic coefficient (K_B) and maximum COD removal rate ($U_{\max}$) are 14.45 and 15.46 g/L/d, respectively. Hence, Equation (24) can be used to predict effluent COD values.

$$S_e = S_i - \frac{15.46S_i}{14.45 + \frac{S_i}{\text{HRT}}} \quad (24)$$

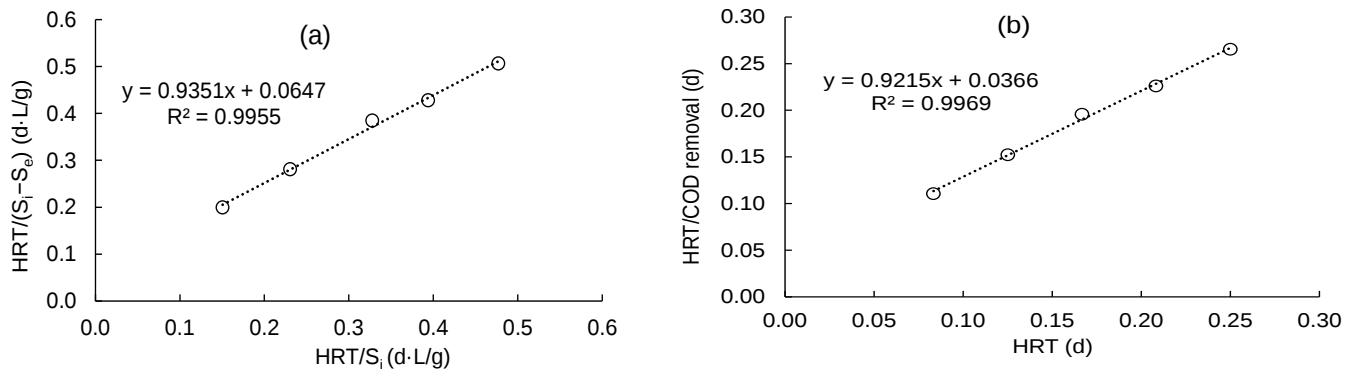


Figure 3. Determine the kinetic constants of (a) K_B and $U_{\max}$ using the modified Stover–Kincannon model; (b) “a” and “b” using a Grau second-order model.

3.3. Grau’s Second-Order Model

Figure 3b displays the plot of this model for the removal of COD by the DHS reactor. The intercept and slope of the straight line could be utilized to determine the “a” and “b” coefficients. Both “a” and “b” were estimated to have values of 0.037 and 0.922, respectively, with a high correlation coefficient ($R^2 = 0.997$). This demonstrates the model’s applicability for simulating the treatment of synthetic domestic wastewater in a DHS reactor. Hence, the effluent COD concentration could be predicted using Equation (25):

$$S_e = S_i \left(1 - \frac{\text{HRT}}{0.037 + 0.922\text{HRT}} \right) \quad (25)$$

and the removal efficacy of the COD is described by Equation (26):

$$E = \frac{\text{HRT}}{0.037 + 0.922\text{HRT}} \quad (26)$$

3.4. First-Order Substrate Removal Model

Figure 4a displays the plot of the first-order model for substrate removal by the DHS reactor. For this model, the $(S_i - S_e)/\text{HRT}$ values were plotted against the matching S_e values in order to obtain a straight line. The values of k_1 , which were calculated to be 27.627 1/d, are reflected in the line’s slope. The correlation coefficient (R^2) was high, 0.9396, suggesting that the first-order model is suitable with reasonable accuracy for the DHS reactor. From Equation (22), the formula for predicting the final effluent of COD concentration is presented in Equation (27):

$$S_e = \frac{S_i}{1 + 27.627\text{HRT}} \quad (27)$$

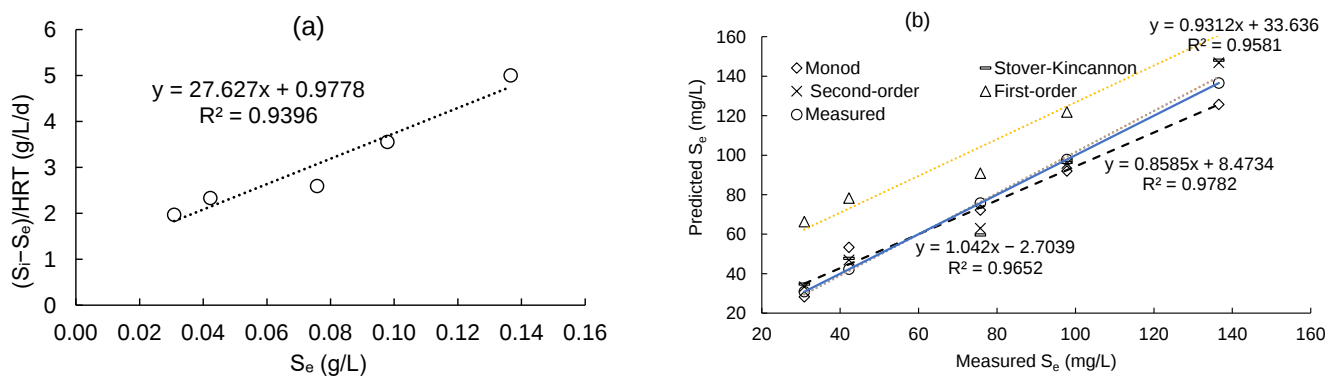


Figure 4. (a) COD removal plot by first-order model; (b) linear correlation between predicted values and measured values.

3.5. Prediction Performance of DHS System Using the Kinetic Parameters

The models' accuracies were further assessed by comparing the experimental data of the lab-scale DHS system with the predicted COD concentrations computed from several models by Equations (23)–(27). According to Figure 4b, there is a strong correlation (>96%) between the COD concentrations predicted by the Grau second order, Stover–Kincannon, and Monod models and the actual COD concentrations obtained from the DHS system. As a result, it is possible to predict the effluent COD value of the DHS system by the kinetic constants of these models.

4. Conclusions

In this work, the kinetics of the DHS reactor treating SDW was examined by a variety of models, including first- and second-order kinetic, modified Stover–Kincannon, and Monod models. For estimating the performance of a lab-scale DHS system along with substantial kinetic coefficients, modified Stover–Kincannon, and Grau second-order kinetic models were discovered to be more appropriate than the other applicable models, with correlation values of 0.99. The microbial kinetics of the DHS system was likewise found to be adequately expressed by a Monod-type kinetic model with a correlation coefficient of 0.9272. Despite having a strong first-order correlation coefficient (0.9396), it was not acceptable for predicting how well the DHS system would perform. If the SDW was treated under equivalent loading circumstances and wastewater characteristics, the outcomes of the kinetic studies calculated from the lab-scale DHS system could be utilized to predict the performance of full-scale DHS systems.

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