

Research Article

Evaluation of Bio-kinetic Coefficients in an Activated Sludge Process for the Treatment of Pharmaceutical Wastewater

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Abstract

The pharmaceutical sector manufactures an extensive variety of products by utilizing a combination of organic and inorganic raw materials, which leads to the generation of significant quantities of liquid waste. The concept for evaluation of these critical parameters comes with the study of literature and burning issues of the environment, especially for pharmaceutical wastewater. This waste is characterized by its toxicity, resistance to biodegradation, and complex organic composition, often accompanied by elevated levels of inorganic total dissolved solids (TDS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). The pharmaceutical wastewater has a wide spectrum of characteristics in pH, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). The nature of pH is mildly acidic (5.2), COD ranges between 6,000 and 3,000mg/L, and BOD varies from 940 to 900mg/L. This research primarily aims to evaluate the bio-kinetic coefficients by treating pharmaceutical wastewater with an activated sludge process conducted on a pilot plant scale. Due to the novelty in evaluating the bio-kinetics of pharmaceutical wastewater the key could lie in developing an integrated modeling approach that combines real-time microbial activity monitoring to predict degradation rates of complex organic compounds, offering a more precise and dynamic assessment compared to traditional batch kinetic studies. K_{max} , K_s , K_d , Y , and μ_{max} were determined to have the following values: 2.09 d^{-1} , 55.41mg/l , 0.075 d^{-1} , 0.302g VSS/g COD , and 0.642 d^{-1} by altering the input variables, i.e., mixed liquor suspended solids (MLSS), retention time, etc. The study was conducted over a three-month time interval, i.e., on a quarterly basis, for the evaluation of bio-kinetic parameters. In the current study, the removal of COD was observed between 92% and 97% with the activated sludge process. The R^2 score ranges from 0.8356 to 0.9270, demonstrating a better fit between the results and the model utilized for the study. Apart from the evaluation of biokinetic studies of pharmaceutical wastewater, the other goals of the current study include producing high-quality effluent and disposing of it without affecting aquatic life or the environment, as well as reducing the pollution load from wastewater generated in the form of hazardous compounds/non-biodegradable substances. We may conclude that the results then obtained for the bio-kinetic parameters are within the acceptable range as per the available literature.

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Keywords

Wastewater, Activated Sludge Process, Bio-kinetic Coefficients, COD

1. Introduction

Pharmaceutical enterprises provide life-saving medications in large quantities and in a range of dosage forms. There is a chance that the active compounds from drugs won't be completely metabolized in the body, and they could end up in the sewage system [1]. Among the drugs that frequently turn up in wastewater systems are anti-psychoactive, antihypertensive, antibacterial, antibiotic, analgesic, and stimulant pharmaceuticals. Ciprofloxacin, enoxacin, ibuprofen, erythromycin, naproxen, ketoprofen, diclofenac, and enrofloxacin, etc., are all found in large quantities in Indian rivers [2]. In wastewater, the metabolites had been discovered in greater amounts than the parent drugs. These compounds could potentially kill the majority of aquatic animals, which would also lead to antibiotic wars with harmful microorganisms [3, 4]. According to the studies, the bulk of organic and inorganic compounds created by ordinary manufacturing processes are dangerous to human health and have a high organic loading rate in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and their ratio, i.e., BOD: COD [5, 6]. Pharmaceutical drugs are administered in medical institutions and homes either parenterally or internally, such as by oral injections and infusions, or topically, such as by inhalation and skin application, or all three [7]. [8] Provide examples of the several facets of the attributes of wastewater containing pharmaceuticals in the review. There is a high rate of consumption and production of pharmaceutical drugs, and effluent treatment for such characteristics is in high demand [9, 10]. Suspended growth system is a biological treatment approach that consists of the "Activated Sludge Process" (ASP), in which the microbes utilize oxygen to degrade the organic matter for survival and growth. Biological wastewater treatment is the most widely adopted method for managing organic and biodegradable waste, with the activated sludge process (ASP) being a key approach due to its effectiveness in degrading complex organic matter [11]. As the ASP method is a biological, either continuous or semi-continuous aerobic method that cleans up wastewater by using nitrification plus carbon-based oxidation to remove organics and biodegradable materials [12]. Arden and Lockett discover the activated sludge process in 1912-1914 [13]. In the activated sludge process (ASP), the aeration tank functions as a bioreactor where microbial degradation of organic matter occurs, while the settling tank, or final clarifier, separates the wastewater and activated sludge solids from the treated water. Additionally, a return activated sludge (AS) system is employed to recycle the settled activated sludge from the clarifier back to

the influent of the aeration tank, ensuring continuous microbial activity. Within the activated sludge process, microbes degrade complex organic molecules into simpler, stable compounds as they seek nourishment, effectively removing both soluble and suspended organic materials from the wastewater [14]. For lowering organic and inorganic loading rates, active sludge processes are used; there are many mathematical models available, ranging from straightforward to multi-component, multi-species, and more complex species [15]. There isn't enough information in the literature about processes that use activated sludge for researchers to assess the bio-kinetic parameters of pharmaceutical wastewater. Simultaneously, there is not a lot of information on developing activated sludge reactors in India for pharmaceutical wastewater using biokinetic criteria. Using the activated sludge technique, the optimization for the management of pharmaceutical waste liquid has been achieved for important parameters such as COD and BOD [16].

The activated sludge process has been utilized for the treatment of industrial wastewater [17]. Anaerobic digestion integrated with the chemical treatment process is utilized for biokinetic parameters [18]. Bio-kinetic coefficients were determined from the UASB reactor for sugarcane wastewater [19]. Kinetic coefficients were determined for synthetic oil wastewater in a suspended growth reactor [20]. Biokinetic parameters of an aerobic system for the removal of potato starch were examined [21]. Recent investigation of kinetics for real mixed industrial wastewater by activated sludge models [22].

The main goal is to evaluate the bio-kinetic parameters for a 12-month period on a quarterly basis for industrial (pharmaceutical) wastewater. The bio-kinetic coefficients, i.e., microorganism decay coefficient (K_d), half-velocity constant (K_s), maximum rate of substrate (BOD) utilization/microorganism (K_{max}), maximum yield coefficient (Y), and specific growth rate (μ_{max}), were assessed using the modified Monod equation and approximating the system's conditional variables. The removal effectiveness of pharmaceutical wastewater depends on the sludge age, treatment process, rainfall rate, and geography of the area [2]. Other goals of the current study include producing high-quality effluent and disposing of it without affecting aquatic life or the environment, as well as reducing the pollution load from wastewater generated in the form of hazardous compounds/non-biodegradable substances. The Central Composite Design-Response Surface Methodology (CCD-RSM) is

an additional specialized piece of equipment for examining crucial parameters in the industrial wastewater treatment process [23].

The current study also discusses the necessity of treating pharmaceutical companies' wastewater using an activated sludge process. Despite all the process's obvious drawbacks, there are certain advantages to the treatment approach that we might take into account.

Activated Sludge Process

Biological wastewater treatment is the most commonly used process, and ASP is also one of the important approaches [11]. This method helps in the removal of various types of organic waste like nitrogen and phosphorus [26]. The process was developed in 1912-1914 by Arden and Lockett. Generally, three components were included in ASP. In ASP, microbes break down complex organic molecules into biodegradable compounds in quest of nourishment. As a result, soluble and suspended organic materials are removed from wastewater [14]. Here, a bioreactor (aeration tank) and a fine clarifier (settling tank) separate treated water from wastewater solids. Settled activated sludge is then returned to the aeration tank. The formation of biological floc in the activated sludge process relies on a diverse group of bacteria, including *Achromobacter*, *Escherichia coli*, *Aerobacter*, *Flavobacterium*, *Alcaligenes*, *Nocardia*, *Arthrobacter*, *Sphaerotilus*, *Bacillus*, *Pseudomonas*, *Citromonas*, and *Zoogloea*, which collectively contribute to the aggregation and stabilization of microbial biomass [24]. In activated sludge plants, a mixture of primary treated sludge and microorganisms is aerated with atmospheric air or, in exceptional cases, pure oxygen. This aeration process supports biological activity within the aeration reactor, effectively reducing the amount of biodegradable components in the upstream flow. The efficiency of removing biodegradable components is influenced by factors such as BOD, temperature, COD, the food-to-microorganism (F:M) ratio, and oxygen levels. Following aeration, the mixed liquor is transferred to settling tanks, where treated wastewater is separated and either discharged into a natural water source or

directed for additional treatment prior to release. The settled activated sludge is sent back to the head of the aeration tank as return activated sludge (RAS) to reseed the incoming sewage or industrial wastewater, ensuring continuous microbial activity. Surplus sludge is periodically removed from the course of action to maintain a balanced (F:M) ratio, optimizing the treatment efficiency by controlling the biomass proportion relative to the available food supply.

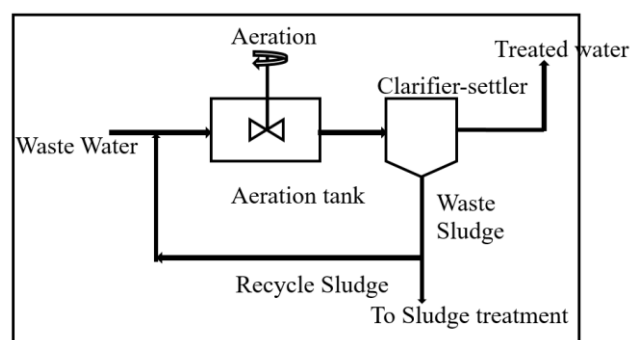


Figure 1. Shows the flow diagram for activated sludge process (ASP).

2. Materials and Methods

2.1. Source and Characteristics of the Wastewater

The wastewater, which was acquired from Anphar Laboratories Pvt. Ltd., Jammu, India, followed standard protocols, including the measurement of pH, total particles (total dissolved and total suspended particles), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and chlorides (all in mg l^{-1} , except pH) [25].

Table 1. The Characteristics of pharmaceutical wastewater pre and post Activated Sludge Treatment.

Parameter	Pre-treatment (Influent)		Post-treatment (Effluent)	
	Average value	Standard Deviation	Average value	Standard Deviation
Color	Dark Brown	----	Pale yellow	----
pH	5.7	± 0.51	7.18	± 0.19
TDS (mg/ L)	1011	± 98.50	790.39	± 113.99
TSS (mg/L)	252.1	± 85.46	61.89	± 9.18
Chloride (mg/L)	829.45	± 75.39	202.26	± 34.96
COD (mg/L)	4532.7	± 1650.78	146.78	± 5.96

Parameter	Pre-treatment (Influent)		Post-treatment (Effluent)	
	Average value	Standard Deviation	Average value	Standard Deviation
Color	Dark Brown	----	Pale yellow	----
BOD (mg/L)	923.34	±19.37	38.83	±3.55

2.2. Methods

The most widely used method for treating wastewater is the suspended growth system (biological), and one of the key strategies for handling organic and biodegradable waste is the activated sludge process (ASP) [11]. The elimination of major organic wastes, including BOD, COD, total dissolved solids (TDS), nitrogen, phosphorus, etc., is aided by this technique [26]. In general, ASP consists of three parts: an aeration tank as a bioreactor and a settling tank as a fine clarifier to separate activated sludge from wastewater and return active sludge (RAS). In order to obtain nutrients, microorganisms in ASP convert intricate organic molecules into biodegradable substances. As a result, wastewater is cleaned of soluble and suspended organic compounds [14]. Transporting settled AS from the clarifier to the influent of the aeration tank is done using solids removed from the treated water and a return of activated sludge. Bacteria, fungi, and viruses are utilized in the activated sludge process to produce the biological flocks [24]. When primary processed or filtered sewage (or industrial effluent) is combined with microorganisms, ambient air or, in rare cases, pure oxygen is added. In activated sludge plants, biological processes in the aeration tank reduce the amount of biodegradable substances in the influent. The effectiveness of biodegradable materials is influenced by vari-

ables such as pH, BOD, temperature, COD, food-to-microorganism ratio (F:M), oxygen, etc. Due to the continuous supply from the aeration tank, mixed liquor is collected in a settling tank, and treated wastewater is overflowed and discharged to a natural water source or permitted to get further treatment before being released at the effluent of the aeration tank. To re-seed the aeration tank with incoming sewage (or industrial wastewater), the partial portion of settling AS is returned to the head (RAS) of the tank. To keep the ratio of biomass to food provided to microorganisms, F:M, in a set range, extra sludge is removed from the treatment process. Microorganisms in the aerator break down the organic matter in the wastewater that comes in (biomass, activated sludge) so that endogenous respiration can happen and new cells can grow in the activated sludge process. It provides the oxygen required for microbial action. The final settler settles the microbiological agglomerates that are present in the aerator effluent, cleansing it. In the first step, microorganisms in the wastewater oxidize organic materials to produce CO_2 and H_2O . Energy is released during this oxidation process, and some portions of the organic waste are changed into fresh microbial cell tissue. The newly generated microbial cell tissue eventually consumes its own cell tissue to provide energy for cell upkeep. The basic mechanism behind the ASP process is shown in the diagram (Figure 2).

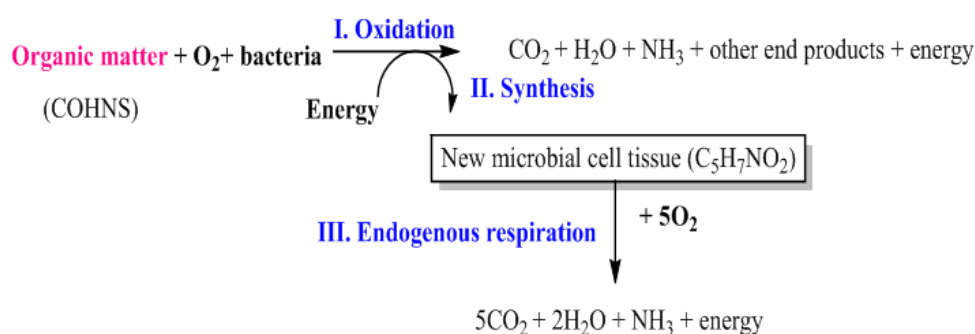


Figure 2. Displays the mechanism of the activated sludge process flow diagram [16], For organic materials, COHNS stands for Carbon, Oxygen, Hydrogen, Nitrogen, and Sulfur.

To maintain a sufficient level of microorganisms in the process, a partial portion of the concentrated settling sludge is returned to the aeration tank. Two key factors for this goal are

withdrawing a portion of the extra sludge regularly per unit mass of partially activated sludge and processing bio-activated sludge at a specific rate [27]. To reduce the

settling of sludge, different activated sludge plants were designed with different parameters. The plug flow process includes tapered aeration (for uniform oxygen distribution), step aeration (to distribute two-thirds of air towards the front half and one-third to the latter half of the plant), and a thoroughly mixed system (complete mixing of biomass with the return activated sludge) [26]. It is, in general, more environmentally friendly than harsh chemical methods such as chlorination [28]. However, the production of large amounts of sludge, high energy consumption [29], and operational problems such as foaming, coloring, and bulking in secondary clarifiers are associated with activated sludge plants. The microbial species selection depends on the temperature of the activated sludge. Several studies show the relationship between the impact of pharmaceuticals and the activated sludge process. A study shows that when the concentration of pharmaceuticals is small, its impact is negligible [30]. At high concentrations, it was observed that its effects cannot be neglected.

2.3. Coefficients of Biokinetics for the Activated Sludge Process

The bio-kinetic coefficients like microorganism decay coefficient (K_d), concentration of substrate (K_s), maximum rate of substrate (K_{max}), yield coefficient (Y), and maximum specific growth rate (μ_{max}) are used in the design of bioreactors. All these parameters are utilized to understand the kinetics of sludge creation and the design of activated sludge treatment facilities. Mixed Liquor Suspended Solid (MLSS): The amount of suspended solids in mixed liquor from the bioreactor (aeration tank) was monitored at various time intervals to determine the bio-kinetic coefficient values of the original and final COD. The mean cell residence time (θ_c), defined as the ratio of mass of volatile suspended solids within the aeration tank to the mass of volatile suspended solids leaving from the aeration tank, is also used for the calculation of bio-kinetics. Multiple mathematical models are available for the mapping of critical bio-kinetic parameters. For the growth of microorganisms, a mathematical model named the Monod model is utilized. Monod (1) equation: A mathematical equation can be used to model the proliferation of microbes in an ASP [31].

$$\mu = \mu_{max} \frac{S}{K_s + S} \quad (1)$$

Where S represents the concentration of growth-limiting substrate in solution, μ : Specific growth rate, μ_{max} : Maximum specific growth rate, and K_s : concentration of substrate.

The numerical value of k is inversely related to the reactor's size. K_s give information regarding growth-inhibiting substrates. While K_d offers information on the expenses related to the infrastructure required for sludge management, Y gives details on sludge generation. For the calculation of coefficients, the mean cell residence time is required, which is exhibited as the half-velocity constant. Mean Cell Residence

Time (MCRT), which is calculated as the half-velocity constant θ_c :

$$\theta_c = \frac{\text{mass of volatile suspended solids (VSS) in the reactor}}{\text{mass of volatile suspended solids (VSS) leaving the system per day}}$$

$$\theta_c = \frac{V_x}{Q_w X_w + Q_e X_e}$$

In a wastewater treatment process, the hydraulic retention time (θ) is much lower. In contrast, the residence time of biological solids can be much higher. Although the mixed liquor passes through the aeration tank only once during the hydraulic retention time, the system repeatedly recycles the resulting biological growth and extracted organic solids from the secondary settling cylinder to the aeration reactor, thus increasing the mean cell residence time (MCRT). On rearranging and placing the terms in equation (1),

$$\frac{X\theta_c}{S_0 - S} = \frac{K_s}{k} \frac{1}{S} + \frac{1}{k} \quad (2)$$

Which is a linear equation form i.e. $y = mx + c$, where S_0 , S and X are Initial COD, Final COD, and Mixed liquor suspended solids, respectively.

Equation (2) is used to determine the values of k and K_s with the help of intercept and slope [32] on charting the values between on the x-axis ($\frac{1}{S}$) and y-axis ($\frac{X\theta_c}{S_0 - S}$). Again on shuffling of equation we got new derived equation in the linear form.

$$\frac{1}{\theta_c} = Y \frac{S_0 - S}{X\theta_c} - K_d \quad (3)$$

Which is also a linear form of equation, i.e., $y = mx + c$. By creating a graph between the x-axis ($\frac{S_0 - S}{X\theta_c}$) and the y-axis ($\frac{1}{\theta_c}$) and using equation (3), the intercept and slope of the graph provide the values of K_d and Y . For both anaerobic and aerobic processes, Monod models are commonly used to predict process kinetics [33]. Researchers performed experimental work on-site and in various units to determine bio-kinetic coefficients until achieving the desired outcomes [34, 35]. The bioreactor and secondary settling tank have an individual capacity of 4,000 L and 2,000 L, respectively. 1000 LPD is the flow rate of pharmaceutical wastewater discharge. Depending on aeration effectiveness, we measured physical and chemical parameters such as pH, MLSS, BOD, and COD over 50 to 408 hours at intermittent time intervals. Many researchers have used COD analysis instead of BOD analysis since it is faster and more trustworthy.

In this study, researchers subjected the pilot-scale activated sludge aeration tank reactor to studies to identify the kinetic coefficients based on COD analysis. The novelty in evaluating the bio-kinetics of pharmaceutical wastewater could lie in developing an integrated modeling approach that combines real-time microbial activity monitoring with advanced machine learning algorithms to predict degradation rates of complex

organic compounds, offering a more precise and dynamic assessment compared to traditional batch kinetic studies.

3. Results and Discussion

The evaluation of bio-kinetics for pharmaceutical wastewater treatment revealed significant insights into microbial degradation processes. The study employed an acti-

vated sludge process (ASP) to assess the degradation rates of key pharmaceutical compounds under varying initial concentrations of COD (1050-3500mg/L) and hydraulic retention times (HRT) of 12 hours. The variation of MCRT and MLSS concentration provided the results that are shown in tables. Tables 2, 3, 4, and 5 present the first, second, third, and fourth quarters' data generated during the study.

Table 2. Exhibits the second quarter's numerical values.

Sr. No.	MLSS (X) (mg/L)	θ (d)	S (mg/L)	S_o (mg/L)	$S_o - S$ (mg/L)	θ^*X	$(\theta^*X / S_o - S)$	θ_c (d)	$(S_o - S / \theta^*X)$	1/S	1/ θ_c
1	3850	0.5	105	2110	2005	1925	0.960	4.1	1.0416	0.0095	0.2439
2	3700	0.5	208	3000	2792	1850	0.663	2.2	1.5092	0.0048	0.4545
3	3460	0.5	48	2320	2272	1730	0.761	2.6	1.3133	0.0208	0.3846
4	4550	0.5	30	1350	1320	2275	1.723	16.9	0.5802	0.0333	0.0592
5	2960	0.5	210	2850	2640	1480	0.561	2.6	1.7838	0.0048	0.3846
6	3740	0.5	22	1100	1078	1870	1.735	10	0.5765	0.0455	0.1000

Bio-kinetic study numerical data on wastewater treatment for the first quarter is shown in (Table 2), detailing parameters across six experimental runs. The mixed liquor suspended solids (MLSS, denoted as X) range from 2960 to 4550mg/L, with a constant hydraulic retention time (θ) of 0.5 days. Initial substrate concentrations (S_o) vary from 1100 to 3000mg/L, while final substrate concentrations (S) range from 22 to 210mg/L, resulting in substrate removal ($S_o - S$) between 1078 and 2792mg/L. The product of θ and X (θX) spans 1480 to

2275mg·d/L, and the ratio $\theta^*X / (S_o - S)$ ranges from 0.561 to 1.735, indicating varying biomass-substrate dynamics. The sludge age (θ_c) fluctuates significantly from 2.2 to 16.9 days, while the substrate removal rate per biomass ($S_o - S / \theta^*X$) ranges from 0.5765 to 1.7838. Inverse substrate concentration (1/S) varies from 0.0048 to 0.0455, and inverse sludge age (1/ θ_c) ranges from 0.0592 to 0.4545, reflecting diverse microbial growth and treatment efficiencies across the runs.

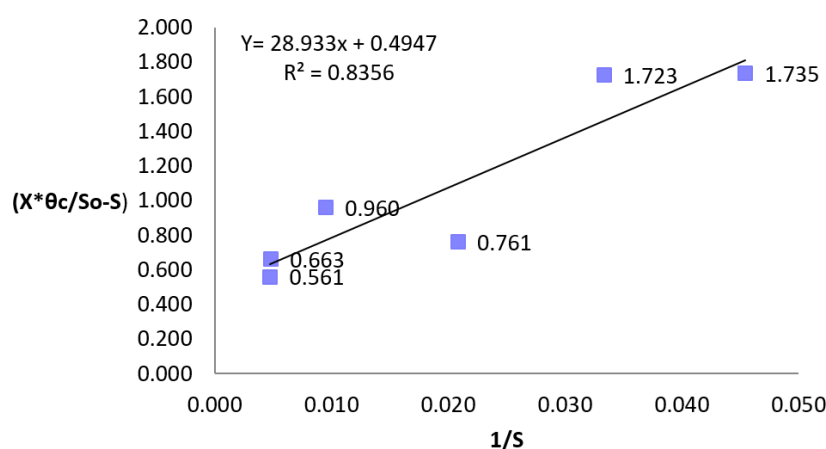


Figure 3. Correlation received between abscissa and ordinate.

The demonstration of the relationship between two variables (likely derived from the bio-kinetic study data, such as

substrate removal rates and biomass activity) to highlight trends or dependencies in the wastewater treatment process is

shown in Figure 3. The (Figure 3) displays the results of the study for the measurement of kinetic parameters for the first quarter. Throughout the monitoring period, the food-to-microorganism ratio was kept between 0.2 and 0.4.

By drawing a graph between the x-axis ($\frac{1}{S}$) and the y-axis ($\frac{X\theta c}{S_0-S}$) in (Figure 3), is used to determine the values of k and K_s with the help of intercept and slope.

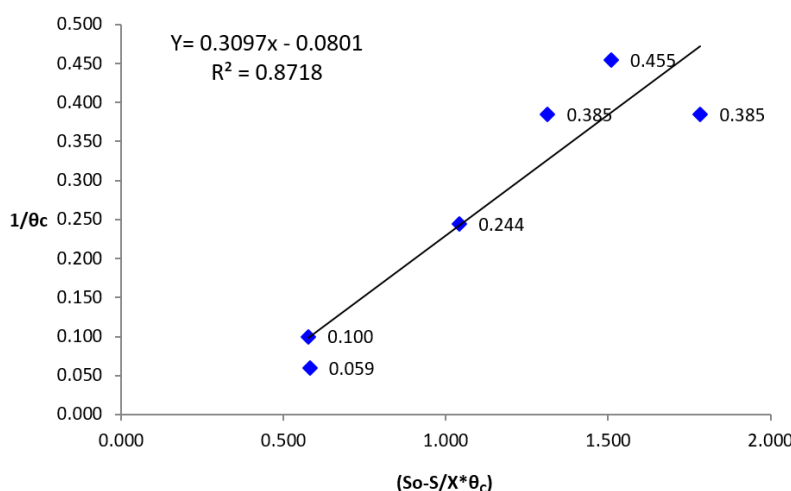


Figure 4. Received correlation between abscissa and ordinate.

The relationship between two variables (potentially related to bio-kinetic parameters like substrate concentration and microbial growth rates), providing insights into their inter-dependence during the wastewater treatment process is shown in (Figure 4). By drawing a graph between the x-axis ($\frac{S_0-S}{X\theta c}$) and the y-axis ($\frac{1}{\theta c}$) in (Figure 4), the intercept and slope of the

graph provide the values of K_d and Y .

In terms of the summary of both the (Figures 3 and 4), the kinetic coefficients for K_{max} , K_s , K_d , Y , and μ_{max} were determined for the first quarter, and these coefficients were 2.02 d^{-1} , 58.35 mg/L , 0.08 d^{-1} , 0.30 g VSS/ g COD, and 0.62 d^{-1} , respectively. R^2 is equal to 0.8356 and 0.8718, respectively.

Table 3. Exhibits the second quarter's numerical values.

Sr. No.	MLSS (X) (mg/L)	θ (d)	S (mg/L)	S_0 (mg/L)	S_0-S (mg/L)	$X \theta$	$\frac{\theta * X}{S_0-S}$	θc	$\frac{S_0-S}{\theta * X}$	1/S	1/ θc
1	3460	0.5	213	3520	3307	1730	0.523	1.9	1.912	0.0047	0.5263
2	2980	0.5	178	3610	3432	1490	0.434	1.5	2.303	0.0056	0.6667
3	3860	0.5	35	1980	1945	1930	0.992	3.6	1.008	0.0286	0.2778
4	3160	0.5	80	2340	2260	1580	0.699	3.5	1.430	0.0125	0.2857
5	3770	0.5	48	2460	2412	1885	0.782	3	1.280	0.0208	0.3333
6	2860	0.5	178	2510	2332	1430	0.613	2.1	1.631	0.0056	0.4762

The second quarter bio-kinetic study numerical data are present in (Table 3) on wastewater treatment across six experimental runs. The mixed liquor suspended solids (MLSS, denoted as X) range from 2860 to 3860 mg/L , with a constant hydraulic retention time (θ) of 0.5 days. Initial substrate concentrations (S_0) vary from 1980 to 3610 mg/L , while final substrate concentrations (S) range from 35 to 213 mg/L , re-

sulting in substrate removal (S_0-S) between 1945 and 3432 mg/L . The product of θ and X (θX) spans 1430 to 1930 mg d/L, and the ratio $\theta X/(S_0-S)$ ranges from 0.434 to 0.992, reflecting variations in biomass-substrate interactions. The sludge age (θc) ranges from 1.5 to 3.6 days, while the substrate removal rate per biomass ($S_0-S/\theta * X$) varies from 1.008 to 2.303. Inverse substrate concentration (1/S) ranges

from 0.0047 to 0.0286, and inverse sludge age ($1/\theta_c$) spans 0.2778 to 0.6667, indicating diverse microbial activity and

treatment performance across the runs.

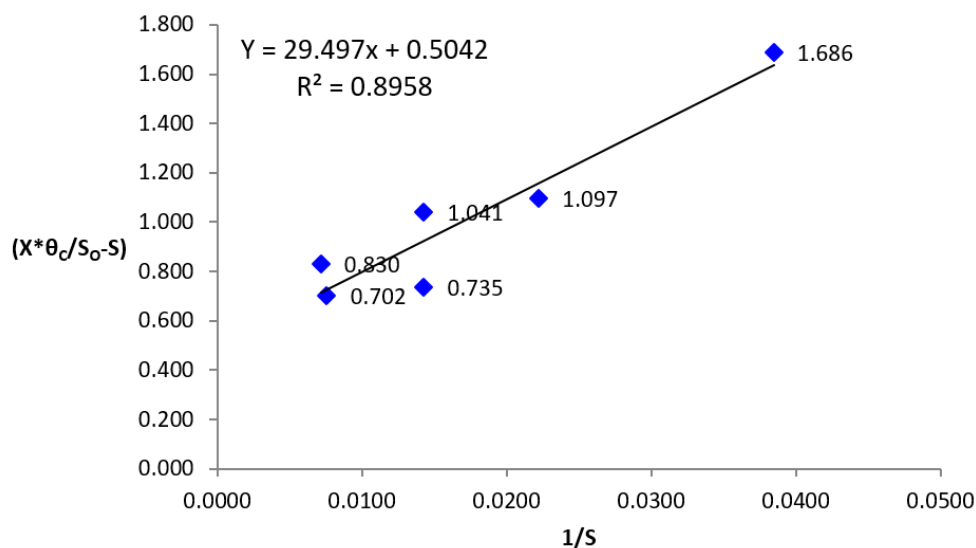


Figure 5. Received correlation between the X and Y axes.

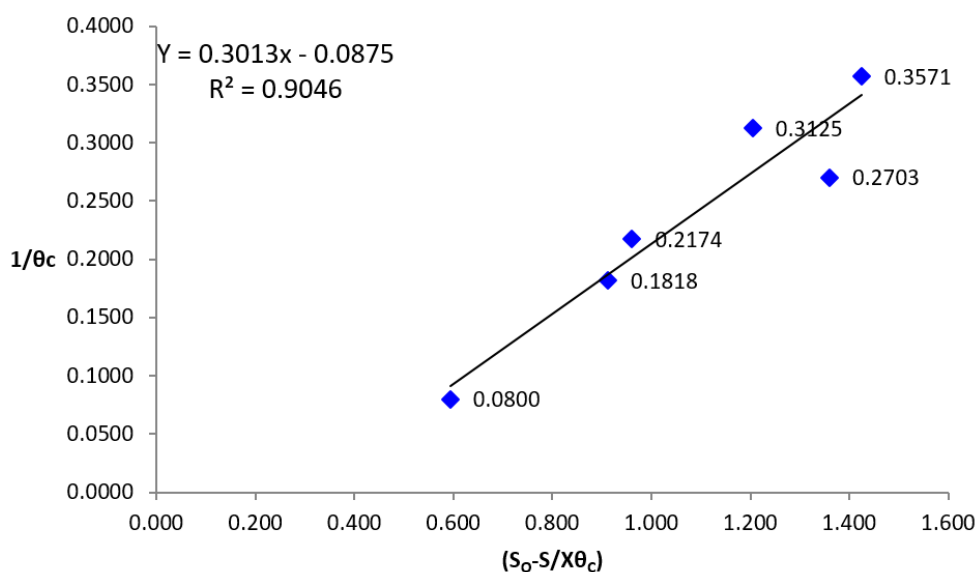


Figure 6. Received correlation between the X and Y axes.

In (Figure 5) create a graph where the x-axis represents $(\frac{1}{S})$ and the y-axis represents $(\frac{X\theta_c}{S_0-S})$, as well as plotting $(\frac{1}{\theta_c})$ against $(\frac{S_0-S}{X\theta_c})$ in (Figure 6), the K_{max} and K_s values (calculated via intercept and slope), and K_d and Y values on the x- and y-axes, respectively. Similarly, when looking at the correlation between the X and Y axes in (Figures 5 and 6), for the second

quarter, the kinetic coefficients for K_{max} , K_s , K_d , Y , and μ_{max} were observed and determined to be 2.35 per day, 45.28 mg l^{-1} , 0.08 per day, 0.31 grams of VSS/g of COD, and 0.75 per day, respectively. The coefficients of determination, or R^2 values, are 0.8958 and 0.9046.

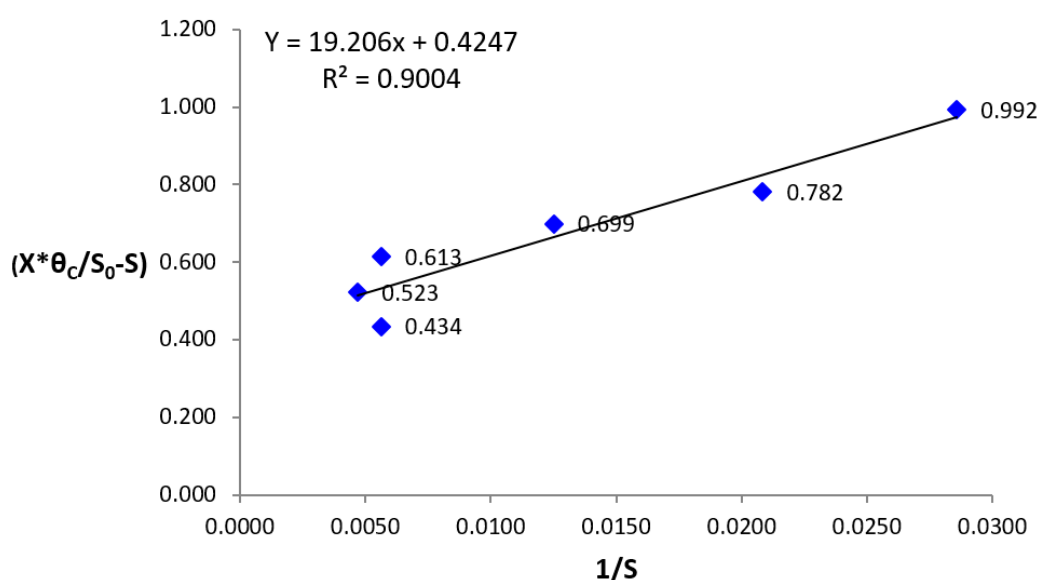
Table 4. Displays the third quarter's numerical values.

Sr. No.	MLSS (X) (mg/L)	θ (d)	S (mg/L)	S ₀ (mg/L)	S ₀ -S (mg/L)	X θ	$(\theta \cdot X / S_0 - S)$	θ_c	$(S_0 - S) / (\theta \cdot X)$	1/S	1/ θ_c
1	3170	0.5	45	1490	1445	1585	1.097	5.5	0.912	0.0222	0.1818
2	3846	0.5	140	2456	2316	1923	0.830	3.2	1.204	0.0071	0.3125
3	3370	0.5	70	1689	1619	1685	1.041	4.6	0.961	0.0143	0.2174
4	3420	0.5	26	1040	1014	1710	1.686	12.5	0.593	0.0385	0.0800
5	3270	0.5	132	2460	2328	1635	0.702	2.8	1.424	0.0076	0.3571
6	2530	0.5	70	1790	1720	1265	0.735	3.7	1.360	0.0143	0.2703

Table 4 presents the numerical data for the third quarter of a bio-kinetic study on wastewater treatment across six experimental runs. The mixed liquor suspended solids (MLSS, denoted as X) range from 2530 to 3846mg/L, with a consistent hydraulic retention time (θ) of 0.5 days. Initial substrate concentrations (S_0) vary from 1040 to 2460mg/L, while final substrate concentrations (S) range from 26 to 140mg/L, resulting in substrate removal (S_0-S) between 1014 and 2328mg/L. The product of θ and X (θX) spans 1265 to 1923mg d/L, and the ratio $\theta X/(S_0-S)$ ranges from 0.702 to 1.686, indicating fluctuating biomass-substrate dynamics. The sludge age (θ_c) varies from 2.8 to 12.5 days, while the substrate removal rate per biomass ($S_0-S/\theta \cdot X$) ranges from 0.593 to 1.424. Inverse substrate concentration (1/S) ranges from 0.0071 to 0.0385, and inverse sludge age (1/ θ_c) spans 0.0800 to 0.3571, reflecting

diverse microbial activity and treatment efficiencies across the runs.

By putting a graph between the x-axis 1/s, and the y-axis $\frac{X\theta_c}{S_0-S}$ we utilized it to get Y and K_d. K_d and Y values are determined by the intercept and slope in (Figure 7). Similarly, to get the values of k and K_s, the correlation between $(\frac{S_0-S}{X\theta_c})$ the abscissa and $(\frac{1}{\theta_c})$ the ordinate has been prepared and shown in (Figure 8). The kinetic coefficients for K_{max}, K_s, K_d, Y, and μ_{max} for the third quarter were determined after going through the correlation and are 2.00 d⁻¹, 58.98 mg/l⁻¹, 0.08 d⁻¹, 0.30 g VSS/gCOD, and 0.60 d⁻¹ between the ordinate and abscissa, along with the R² values of 0.9004 and 0.9089 were obtained for (Figures 7 and 8), respectively.

**Figure 7.** Abscissa and ordinate correlation created.

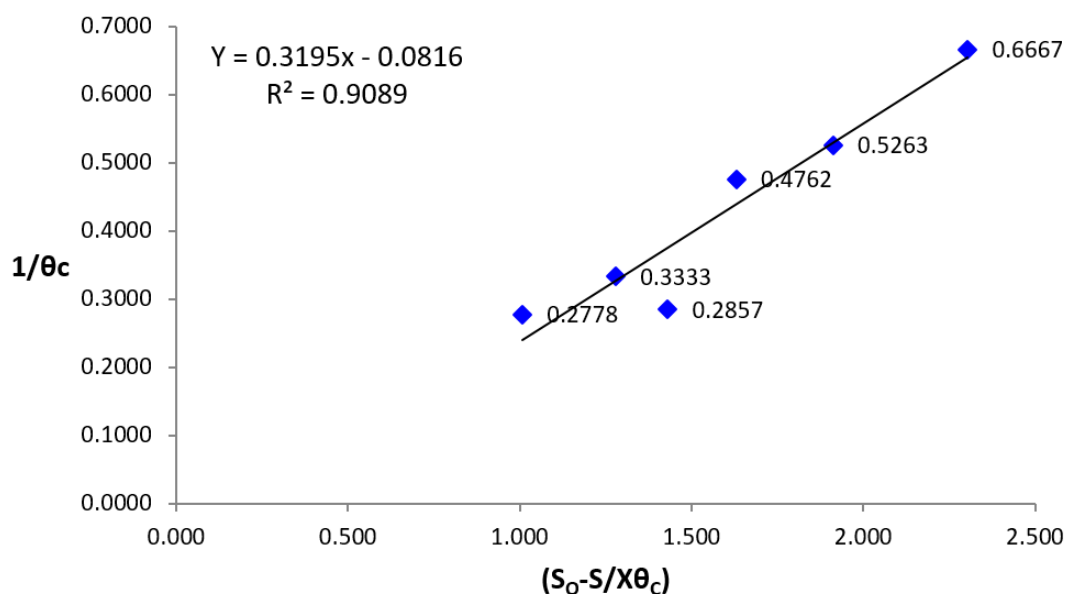


Figure 8. Abscissa and ordinate correlation at both the axes.

Table 5. Displays the data for the fourth quarter.

Sr. No.	MLSS (X) (mg/L)	θ (d)	S (mg/L)	S_o (mg/L)	S_o-S (mg/L)	$\theta \cdot X$	$(\theta \cdot X)/(S_o-S)$	θc	$(S_o-S)/(\theta \cdot X)$	1/S	1/ θc
1	4419	0.5	105	2718	2613	2210	0.846	3.1	1.183	0.0095	0.3226
2	4312	0.5	180	3480	3300	2156	0.653	2.5	1.531	0.0056	0.4000
3	4280	0.5	45	1980	1935	2140	1.106	5.3	0.904	0.0222	0.1887
4	3510	0.5	48	1530	1482	1755	1.184	4.9	0.844	0.0208	0.2041
5	3810	0.5	80	2460	2380	1905	0.800	3.5	1.249	0.0125	0.2857
6	4130	0.5	88	2587	2499	2065	0.826	3.3	1.210	0.0114	0.3030

The last quarter, i.e., the fourth quarter for the bio-kinetic study on wastewater across six experimental runs is exhibited in (Table 5). The mixed liquor suspended solids (MLSS, denoted as X) range from 3510 to 4419mg/L, with a constant hydraulic retention time (θ) of 0.5 days. Initial substrate concentrations (S_o) vary from 1530 to 3480mg/L, while final substrate concentrations (S) range from 45 to 180mg/L, resulting in substrate removal (S_o-S) between 1482 and 3300mg/L. The product of θ and X (θX) spans 1755 to 2210mg d/L, and the ratio $\theta X/(S_o-S)$ ranges from 0.653 to 1.184, indicating varying biomass-substrate interactions. The sludge age (θc) ranges from 2.5 to 5.3 days, while the substrate removal rate per biomass ($S_o-S/\theta \cdot X$) varies from 0.844 to 1.531. Inverse substrate concentration (1/S) ranges from 0.0056 to 0.0222, and inverse sludge age (1/ θc) spans 0.1887 to 0.4000, reflecting diverse microbial activity and treatment performance across the runs.

In (Figure 9) the correlation between the x-axis ($\frac{1}{S}$), and

y-axis $\frac{X\theta c}{S_o-S}$ with the help of equation (2) to get k and K_s values are determined by the intercept and slope, while (Figure 10) ensures the values of Y and Kd by plotting a graph between 1/ θc as the abscissa and $\frac{S_o-S}{X\theta c}$ as the ordinate.

For four distinct quarters, the kinetic coefficients for K_{max} , K_s , K_d , Y, and μ_{max} were determined for the fourth quarter and were 2.00 d⁻¹, 59.03 mg l⁻¹, 0.06 d⁻¹, 0.30 g VSS/gCOD, and 0.60 d⁻¹, respectively. For Figures 8 and 9, respectively, the coefficient of determination, or R^2 , values, are 0.9190 and 0.9270. The near proximity of 1.0 to R^2 demonstrates the exceptional goodness of fit of the data.

The average kinetic coefficients for K_{max} , K_s , K_d , Y, and μ_{max} were 2.09 d⁻¹, 55.41 mg l⁻¹, 0.075 d⁻¹, 0.302 g VSS/gCOD, and 0.642 d⁻¹, respectively, from the four quarters.

The experimental activities for assessing bio-kinetic parameters and treating wastewater involved characterizing pharmaceutical wastewater through a structured experimental

setup, followed by detailed parameter analysis until the targeted results were achieved.

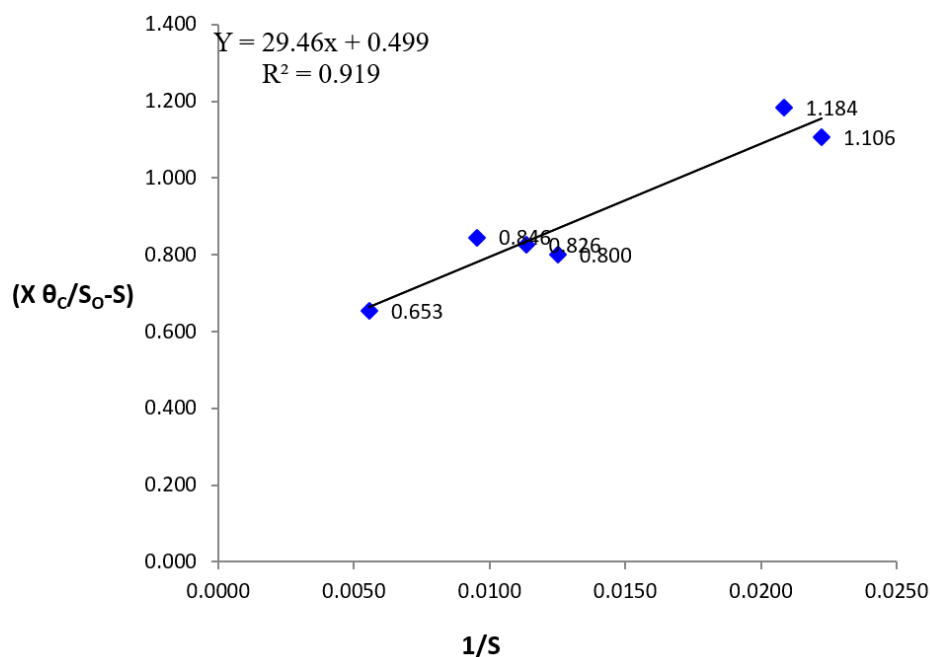


Figure 9. Correlation between the ordinate and abscissa at both the axes.

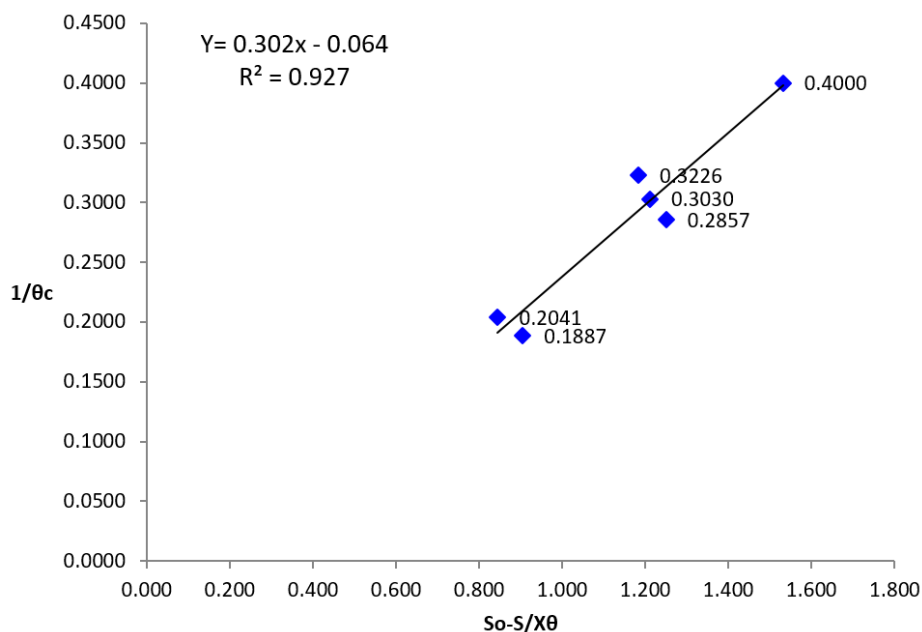


Figure 10. Received correlation between the ordinate and abscissa.

4. Conclusions

The bulk organic waste can be treated using the activated sludge treatment method, which finally reduces the environ-

mental load. The data collection took place over a 12-month period, and Monod's equation was used to evaluate the bio-kinetic coefficients: K_{max} , K_s , K_d , Y , and μ_{max} [36, 37].

Table 6. Average and total coefficients for each quarter are summarized.

Sr. No.	Parameters	Quarter-I	Quarter-II	Quarter-III	Quarter-IV	Average Value	Typical rang as per literature
1	$K_{\max}$	2.02	2.35	2.00	2.00	2.09	2-10
2	K_s	58.35	45.28	58.98	59.03	55.41	15-70
3	K_d	0.08	0.08	0.08	0.06	0.075	0.04-0.08
4	Y	0.30	0.31	0.30	0.30	0.302	0.3-0.6
5	$\mu_{\max}$	0.62	0.75	0.60	0.60	0.642	----

Summary of the average and total coefficients for bio-kinetic parameters across all four quarters of the study in (Table 6). The maximum specific substrate utilization rate ($K_{\max}$) ranges from 2.00 to 2.35 d^{-1} , with an average of 2.09 d^{-1} , falling within the typical literature range of 2-10 d^{-1} . The half-saturation constant (K_s) varies from 45.28 to 59.03 mg l^{-1} , averaging 55.41 mg l^{-1} , consistent with the literature range of 15-70 mg l^{-1} . The endogenous decay coefficient (K_d) ranges from 0.06 to 0.08 d^{-1} , with an average of 0.075 d^{-1} , aligning with the typical range of 0.04-0.08 d^{-1} . The yield coefficient (Y) remains stable between 0.30 and 0.31 g VSS/gCOD, averaging 0.302 g VSS/gCOD, within the literature range of 0.3-0.6 g VSS/gCOD. The maximum specific growth rate ($\mu_{\max}$) ranges from 0.60 to 0.75 d^{-1} , with an average of 0.642 d^{-1} [38]. These values indicate consistent microbial performance across quarters, with parameters generally aligning with established norms for wastewater treatment processes. With the use of such a procedure, between 92 and 97 percent of COD can be removed. The goodness-of-fit model, or R^2 score, ranges from 0.8356 to 0.9270, demonstrating a better fit between the results and the model. The most recent research can be used by researchers to improve their work, particularly in the AS process. Results indicated that the maximum specific growth rate ($\mu_{\max}$) of the microbial consortium ranged from 0.60 to 0.75 d^{-1} . This suggests an optimal balance takes place between substrate availability and microbial activity.

$K_{\max}$	Maximum Rate of Substrate (BOD) Utilization/Microorganism
MLSS	Mixed Liquor Suspended Solids
NH_3	Ammonia
O_2	Oxygen
pH	Measurement of Acidity/Basicity
Q_w	Waste Sludge Flowrate
Q_e	Treated Effluent Flowrate of How
	Acidic/Basic Water Is
RAS	Return Activated Sludge
R^2	Regression Coefficient
S_0	Initial COD
S	Final COD
TDS	Total Dissolved Solids
V	Volume of Aeration Tank
x	Concentration of Volatile Suspended Solids (MLSS) Within Reactor
x_e	Concentration of Volatile Suspended Solids (Treated Effluent)
x_w	Concentration of Volatile Suspended Solids (Waste Sludge Stream)
Y	Maximum Yield Coefficient
θ	Retention Time
θ_c	Mean Cell Residence Time
$\mu_{\max}$	Specific Growth Rate

Abbreviations

AS	Activated Sludge
ASP	Activated Sludge Process
BOD	Bio Chemical Oxygen Demand
CCD-RSM	Central Composite Design-Response Surface Methodology
COD	Chemical Oxygen Demand
CO_2	Carbon Dioxide
F: M	Food to Microorganisms Ratio
H_2O	Water
Kd	Microorganism Decay Coefficient
KS	Half-velocity Constant

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Sarita Sharma: Conceptualization, Investigation, Supervision

Ethics Approval and Consent to Participate

All authors approved the study, and it was implicitly or explicitly endorsed by the relevant authorities at the institutions where the research was conducted.

Date Availability Statement

The datasets used and/or analyzed in this study can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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