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Kinetic and Prediction Modeling Studies of Organic Pollutants Removal from Municipal Wastewater using *Moringa oleifera* Biomass as a Coagulant

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Abstract: This study investigated the potential of *Moringa oleifera* (MO) seed biomass as a coagulant for the removal of turbidity, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) of municipal wastewater. Triplicated laboratory experiments using MO coagulant added at varying treatment dosages of 50, 100, 150, 200 mg/L, and a control (0 mg/L) treatment were performed for a settling period of 250 min at room temperature. Kinetics and prediction variables of cumulative turbidity, BOD, and COD removal were estimated using simplified first order and modified Gompertz models. Results showed that the maximum removal of turbidity, BOD, and COD were 94.44%, 68.72%, and 57.61%, respectively, using an MO dose of 150 mg/L. Various kinetic parameters, such as rate constant (r), measured (RE_m) versus predicted (RE_p) cumulative removal, and specific pollutant removal rate (μ_m), were also maximum when an MO dose of 150 mg/L was added, the standard error being below 5%. The developed models were successfully validated over multiple observations. This study suggests low cost and sustainable removal of turbidity, BOD, and COD of municipal wastewater using MO seed biomass as a coagulant.

Keywords: kinetic studies; *Moringa oleifera*; plant seed biomass; prediction modeling; wastewater treatment

1. Introduction

An increasing human population and emerging lifestyles, among other factors, have greatly influenced the quality and quantity of municipal wastewater generation. The discharge of wastewater, which most times contains toxic organic and inorganic pollutants, without proper treatment into the ecosystem is widespread in developing countries and has been a great threat to human and aquatic life [1,2]. The growing concern of environmental degradation and water causing health-related issues including pollution of the water body and the scarcity of clean water has recently become the interest of researchers to achieve one of the Sustainable Development Goals (SDGs) of clean water

and sanitation. It is estimated that about 1.1 billion people have no access to clean and safe potable water, and a significant number of them are in less developed countries of the world [3,4].

Owing to these, several techniques and processes have been developed and explored in the treatment of wastewater, among which are precipitation, ion exchange, filtration, electro dialysis, electrochemical process, coagulation, membrane process, and reverse osmosis [5]. However, the applicability of these technologies and techniques are limited in the developing world due to the cost and technical know-how constraints in the procurement of the raw materials and treatment processes required for these techniques [4–6]. Moreover, some of these treatment methods use excessive chemicals, generate secondary wastes which are often difficult to treat, and are found to be inefficient in the treatment of municipal wastewater due to the fact of varying forms of pollutants [7–9].

Recently, there has been a tremendous campaign on the use of sustainable approaches to address the environmental challenges of wastewater treatment and remediation [9–11]. In this regard, bio-coagulants such as *Moringa oleifera* (MO) biomass seeds have been recommended and extensively used as an effective alternative for the treatment of wastewaters, notably in Africa and Asia [2,12]. The MO biomass seeds, specifically, have gained remarkable attention in the research community due to its applicability as a coagulant and an antimicrobial agent in water and wastewater treatment [4,13]. The MO biomass offers a promising solution to wastewater treatment with less cost, availability of the raw materials, and higher efficiency in the removal of contaminants. In addition, the byproducts are ecofriendly as compared to other treatment processes or techniques including biological treatment methods [12,14].

The wastewater treatment using MO biomass is based on the coagulation-flocculation process in which the pollutant removal is achieved due to the presence of cationic protein in MO biomass seed [15,16], thereby forming small flocs with suspended particles and organic matters in the wastewater which are allowed to settle or sediment under varying contact times [10,17]. The coagulation mechanism of an MO biomass seed has been well discussed in the literature. Ndabigengesere et al. [17] described the coagulation mechanism of the MO biomass coagulant as adsorption and neutralization of charges, while Muyibi and Evison [18] attributed it to the bridging of destabilized particles. Okuda et al. [19] on the other hand, associated the variations in the coagulation mechanism of MO biomass coagulant in pollutant removal to the type of extractant used for the active component of the coagulant. Hoa and Hue [10] referred to the adsorption process as one of the main mechanisms of the coagulation process used by MO biomass. Despite the significant contributions on the coagulation mechanism of the MO biomass coagulant, the mechanism of pollutant removal by MO biomass through the settling ability of the flocs is not well discussed. Viotti et al. [20,21] re-emphasized the need for further studies on the removal of organic pollutants using the MO biomass. The inadequate details in this area create an important knowledge gap that needs to be considered. Appropriate models that describe the pollutant removal process could be valuable tools in this regard [22,23]. The studies that model the kinetic removal of pollutants in municipal wastewater using MO biomass as a coagulant are few, and to the best of our knowledge, there are no available publications on the applicability of a modified Gompertz model for the prediction of pollutant removal using MO biomass. The kinetic study offers valuable information on the mechanism of the reaction and pollutant removal process [14,24]. Also, MO biomass offers a cost-effective, easily accessible, and efficient pollutant removal from water and wastewater system as compared to other regular coagulants, such as alum and ferric chloride, making it a sustainable alternative to the developing countries [4,16].

Therefore, this study investigated the kinetic study of pollutants removal from municipal wastewater to further understand the MO biomass removal mechanism. The simplified form of the first-order kinetic model was applied to describe the pollutant removal process and the model parameters were subsequently estimated. The predictions of removal pollutants for turbidity, BOD, and COD were further conducted using the modified Gompertz model.

2. Materials and Methods

2.1. MO Biomass and Sample Preparation

The MO seed pods were collected from the Kwara State Ministry of Agriculture, Ilorin, Nigeria. The seeds were allowed to mature in the pod while still on the tree before plucking. This procedure was to ensure that the bioactive coagulants in the seed were effective [17]. The preparation of MO seeds involved two processes; the shelling of MO seeds from the dry pods, and the extraction of oil from the seeds to obtain MO powder as described by Farzadkia et al. [22] and Muyibi et al. [25], respectively. The MO pods were manually shelled using a knife to obtain the seeds after which the seeds were air-dried to maintain its uniform weight. The MO dried seeds were powdered using an electric grinder (Eurosonic Model ES-242) and sieved through a 0.5 mm mesh screen size to obtain MO biomass with uniform particle size.

Sixty grams of MO powder, mixed with 170 mL of hexane solvent, was fed into electro-thermal soxhlet extractor at 70 °C to extract the oil. The oil extraction process lasted for 4 h after which the solvent was left to condense and thereby separated from the oil. The resulting residue of MO after the oil extraction of 35% w/w was oven-dried at 50 °C overnight to obtain MO cake. Muyibi et al. [25] reported the enhanced coagulating potential of MO seeds after oil extraction. The obtained MO cake was, therefore, used in this study.

2.2. Sampling and Characterization of Wastewater

The samples of wastewater were taken from the main outlet of the sewer network system of the University of Ilorin main campus, Ilorin, Nigeria. The collected wastewater samples were transported to the laboratory within the University and then characterized about 1 h after the collection. The sample collection and analyses were carried out following the Standard Methods for Water and Wastewater Examination [26].

2.3. Experimental Design and Calculation of Turbidity, BOD and COD Removal Efficiency

The sampled wastewater of 1000 mL each, after the initial analyses for various parameters including turbidity, BOD, and COD, was filled into the five beakers in a Jar test set-up of Janke and Kunkel (Lovibond ET 730). The prepared samples of MO coagulants were then added at varying treatment dosages of 50, 100, 150, and 200 mg/L, with the last beaker used as control (0 mg/L). The samples of wastewater with the MO biomass coagulant were adjusted for pH levels (7.26 ± 0.09) using 0.5 M of NaOH or 0.5 M of HCl after which the samples were mixed rapidly at 100 rpm for 2 min, followed by slow mixing at 40 rpm for 20 min to aid sludge formation. Then the samples were gently transferred and allowed to settle in the sedimentation cones (Imhoff) at a different contact time of 50, 100, 150, 200, and 250 min. An aliquot of 250 mL was sampled from each sedimentation cone, and turbidity, BOD, COD were determined for each contact time, in triplicate. The removal efficiency of turbidity, BOD, and COD using varying MO dosage for each of the contact time was calculated using Equation (1)

$$\text{Removal efficiency (RE\%)} = \left(\frac{C_i - C_f}{C_i} \right) \times 100 \quad (1)$$

where C_i and C_f are the initial and final values of the analyzed parameters, respectively, expressed in NTU for turbidity, and mg/L for BOD and COD.

2.4. Kinetics of Turbidity, BOD and COD Removal

The pollutant removal rate of any wastewater treatment processes is one of the most important parameters used to define the effectiveness of reaction-based systems [23,27–29]. Therefore, the rate of solute sorption onto MO biomass was estimated. To evaluate the kinetics of turbidity, BOD,

and COD removal process, a simplified form of the first-order kinetic model was used [28]. The form of the equation is given in Equation (2).

$$r = \log\left(\frac{C_i}{C_t}\right) \cdot \frac{2.303}{t_2 - t_1} \quad (2)$$

where r represents the rate constant of pollutant removal reaction (NTU min^{-1} and mg/L min^{-1}), while C_i and C_t are the initial and final parameter at the sampling interval ($t_2 - t_1$ min).

2.5. Modified Gompertz Model for Prediction of Turbidity, BOD and COD Removal

Recent studies have confirmed that the application of the Gompertz equation can be used for modeling the processes having a non-linear or exponential trend [29]. In this study, the cumulative removal of turbidity, BOD, and COD as a dependent variable to predict over settling time as an independent variable was considered. The cumulative parameter removal efficiency was calculated using Equation (3).

$$\text{RE}_m = \sum_{x=1}^n \text{RE} \quad (3)$$

where RE_m is the cumulative parameter removal efficiency (measured) in terms of the sum of n number of observations per timespan.

This model is a modified form of a modified Gompertz model which can be expressed as:

$$\text{RE}_p = P_{\text{exp}} \left\{ -\exp\left[\frac{\mu_m}{P}(\lambda - t) + 1\right] \right\} \quad (4)$$

where RE_p is the cumulative pollutant removal (predicted), P is the maximum pollutant removal potential, μ_m is the maximum specific pollutant removal (%), λ and t are the lag phase and settling time (min), respectively.

2.6. Statistics

All the experiments were performed in the triplicated form. The analysis of variance (ANOVA) test was conducted with least significance difference (LSD) for the mean difference before and after treatment for the selected parameters. Data were processed using OriginPro Version 9 (Origin Corp., Northampton, MA, USA), IBM SPSS Version 23.0 (IBM Corp., Chicago, IL, USA). A model fitting tool, namely, Rank Models of OriginPro was used to simulate the prediction models. Finally, the model data were validated over multiple experimental trials.

3. Results and Discussion

3.1. Characteristics of Municipal Wastewater Used in This Study

The characteristics of municipal wastewater before and after treatment with MO biomass coagulants are presented in Table 1. The variables measured include pH, TSS, electrical conductivity, turbidity, BOD, COD, alkalinity, and total hardness, and each of which was found to be statistically significant after treatment with a varying dosage of MO (50, 100, 150, 200 mg/L) as indicated in their respective p -value ($p < 0.05$) in Table 1. In general, the sample wastewater before treatment was found to be neutral (7.26 ± 0.09) because of the anthropogenic activities in the University environment where the wastewater emanated. Nevertheless, the observed pH values, before and after treatment, were within the permissible limit for wastewater reuse in agriculture [30] and the national acceptable wastewater discharge range of 6–9 [31]. The cumulative variance (CV%) of wastewater parameters defined the less variation suitable for model building.

Table 1. Characteristics of municipal wastewater used for this study.

Parameter	MO Treatment	Before Treatment	CV (%)	After Treatment	USEPA Permissible Limit for Wastewater Reuse in Agriculture	NESREA Permissible Limit for Wastewater Discharge	Unit
pH	Control	7.26 ± 0.09	0.01	7.37 ± 0.03 **	6–8.4	6–9	-
	50 mg/L			6.93 ± 0.05 ***			
	100 mg/L			6.88 ± 0.05 ***			
	150 mg/L			7.02 ± 0.05 ***			
	200 mg/L			7.01 ± 0.05 ***			
Total suspended solids (TSS)	Control	111.93 ± 15.23	13.50	91.88 ± 4.25 ***	5	25	mg/L
	50 mg/L			70.43 ± 2.05 ***			
	100 mg/L			62.13 ± 2.36 ***			
	150 mg/L			41.70 ± 2.15 ***			
	200 mg/L			41.71 ± 2.00 ***			
Turbidity	Control	76.74 ± 3.69	4.80	10.88 ± 2.00 ***	2	5	NTU
	50 mg/L			6.52 ± 1.15 ***			
	100 mg/L			5.35 ± 1.15 ***			
	150 mg/L			4.27 ± 1.05 ***			
	200 mg/L			4.28 ± 1.25 ***			
Biochemical oxygen demand (BOD)	Control	147.45 ± 12.87	8.72	144.40 ± 4.28 ^{ns}	30	30	mg/L
	50 mg/L			76.28 ± 2.75 ***			
	100 mg/L			55.83 ± 2.55 ***			
	150 mg/L			46.12 ± 2.05 ***			
	200 mg/L			46.22 ± 3.16 ***			
Chemical oxygen demand (COD)	Control	474.18 ± 10.09	2.12	448.18 ± 3.45 **	120	60	mg/L
	50 mg/L			237.28 ± 3.00 ***			
	100 mg/L			204.30 ± 1.50 ***			
	150 mg/L			200.88 ± 2.52 ***			
	200 mg/L			201.00 ± 2.50 ***			
Electrical conductance (EC)	Control	402.44 ± 1.27	0.31	401.01 ± 0.03 ^{ns}	700	400	µS/cm
	50 mg/L			429.09 ± 0.05 ***			
	100 mg/L			438.41 ± 0.05 ***			
	150 mg/L			447.55 ± 0.01 ***			
	200 mg/L			447.76 ± 0.05 ***			
Alkalinity	Control	385.00 ± 1.85	0.48	383 ± 1.26 ^{ns}	50–150	-	mg/L
	50 mg/L			311.85 ± 0.95 ***			
	100 mg/L			327.25 ± 0.09 ***			
	150 mg/L			329.95 ± 1.06 ***			
	200 mg/L			330.05 ± 0.28 ***			
Total hardness (TH)	Control	128.50 ± 4.36	3.38	125.25 ± 1.25 ^{ns}	-	-	mg/L
	50 mg/L			111.36 ± 0.12 ***			
	100 mg/L			104.96 ± 1.00 ***			
	150 mg/L			101.12 ± 1.05 ***			
	200 mg/L			98.56 ± 1.28 ***			

^{ns}: not significant; *, **, ***: Statistically significant at $p < F$ values of 0.05, 0.01, and 0.001, respectively. MO is *Moringa oleifera*; CV is Coefficient of variation; USEPA is United States Environmental Protection Agency; NESREA is National Environmental Standards and Regulations Enforcement Agency (Establishment) Act.

The turbidity and TSS measure the suspended particulate matters in the wastewater and can also describe the extent of wastewater pollution. Before the treatment, TSS and turbidity parameters (111.93 ± 15.23 and 76.74 ± 3.69) exceeded allowable national standard limits of 25 mg/L and 5 NTU [32], respectively, for wastewater discharge. However, after treatment with MO biomass coagulant, the TSS value was significantly reduced while the turbidity fell within the acceptable national limit of wastewater discharge. The initial high turbidity and TSS levels could be attributed to the presence of inorganic particulate matter in the wastewater.

The initial BOD and COD values before treatment with MO biomass (147.45 ± 12.87 and 474.18 ± 10.09 mg/L, respectively) were remarkably higher than the permissible discharge levels in Africa and Asia [32]. Although the values of both BOD and COD after treatment with 200 mg/L of MO dosage (46.22 ± 3.16 and 201.00 ± 2.50) were above the permissible limit for wastewater reuse in agriculture [30] and wastewater discharge [31]. However, there was a statistically significant difference ($p < 0.001$) between before treatment and after treatment with MO dosage. The BOD and COD indicate the extent of organic pollution in the wastewater and the high levels of these pollutants could be detrimental to the plant, animal, and human health when discharged into the environment, especially without proper treatment.

Similarly, the electrical conductivity of the wastewater, both before and after treatment, was found to be within the permissible limit of USEPA guidelines [30], and there was a significant difference between the before treatment and after treatment with MO biomass. Other measured parameters including alkalinity and total hardness exceeded the national standard value range of 50–100 mg/L for alkalinity whereas the standard limit for the hardness is yet to be established, revealing an indication of polluted wastewater. The three parameters, turbidity, BOD, and COD that represent both the particulate and organic pollution of the wastewater were therefore used to investigate the kinetics of the pollutant removal process.

3.2. Effect of MO Dose on Turbidity, BOD and COD Removal

The effect of MO biomass on turbidity, BOD, and COD removal is shown in Figure 1. The removal of all the three investigated pollutants increased with the increase in the MO biomass dosages under 250 min settling time. The result depicts that turbidity removal reached a maximum of 94.44% with the MO biomass dosage of 150 mg/L, which slightly decreased to 94.42% by increasing the dosage to 200 mg/L. Therefore, there was no significant difference for turbidity removal between 150 and 200 mg/L of MO.

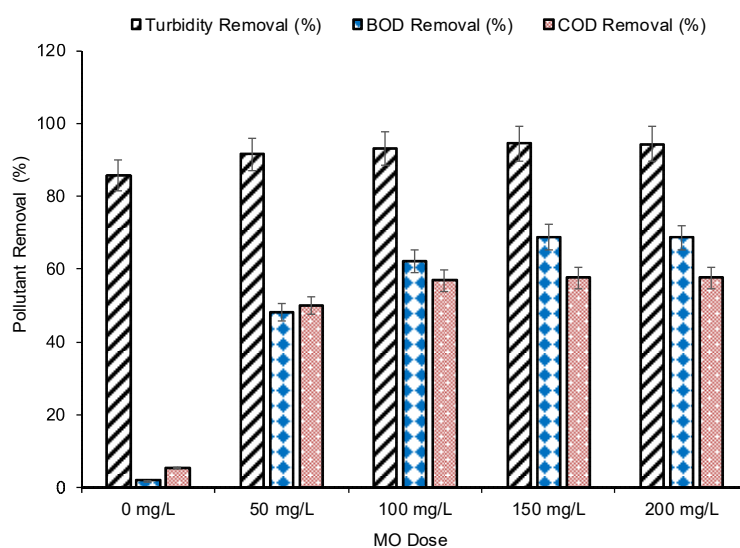


Figure 1. Effect of MO biomass coagulant dosage on turbidity, BOD, COD removal of municipal wastewater.

These results are similar to those obtained by Kayode et al. [32], Kane et al. [33], and Boulaadjoul et al. [34] for municipal wastewater and paper mill effluent, respectively. Dotto et al. [35] also confirmed an improved COD removal with increasing settling time using MO coagulant in textile wastewater. The further decrease in turbidity removal could be explained by the absence of opposite charged colloidal particles needed by the excess MO biomass to react with, which have been exhaustively neutralized and precipitated with the optimum biomass dosage. The maximum BOD and COD removal of 68.72% and 57.64%, respectively, was achieved at 150 mg/L of MO biomass dosage. The removal of the two pollutants is associated with the reduction of turbidity and organic suspended materials in wastewater [10] and as a result, the removal of both BOD and COD followed the same trend as that of turbidity removal. These results are in agreement with those obtained by Al-gheethi et al. [36] and Rosmawanie et al. [37].

3.3. Kinetics of Turbidity, BOD, and COD Removal

In this regard, the kinetics study of turbidity, BOD, and COD removal from municipal wastewater using MO biomass exhibited that the pollutant removal process in this study followed the reaction trend of the first-order kinetic model. The results of the first-order model for removal of turbidity, COD, and BOD are presented in Table 2.

Table 2. First-order kinetic variables for percent turbidity, BOD, and COD removal.

Parameter	Model Variable	MO Treatment Dose				
		Control	50 mg/L	100 mg/L	150 mg/L	200 mg/L
Turbidity	R^2	0.8432	0.8534	0.8386	0.8335	0.8399
	r	2.2216	2.8276	3.1608	3.6531	3.6472
	y	$-0.0042x + 1.8143$	$-0.0051x + 1.8256$	$-0.0056x + 1.82$	$-0.0062x + 1.8265$	$-0.0062x + 1.8266$
BOD	R^2	0.8064	0.9774	0.9623	0.9638	0.9697
	r	1.0664	1.2234	1.3184	1.3841	1.3833
	y	$-0.0005x + 2.1667$	$-0.0012x + 2.1557$	$-0.0018x + 2.1478$	$-0.0022x + 2.146$	$-0.0022x + 2.1462$
COD	R^2	0.9912	0.8755	0.8534	0.8675	0.8696
	r	0.8686	0.9696	0.9969	0.9999	0.9999
	y	$-0.0001x + 2.6760$	$-0.0013x + 2.6357$	$-0.0016x + 2.6262$	$-0.0016x + 2.6269$	$-0.0016x + 2.6261$

R^2 : coefficient of determination; r : first-order rate constant; y : linear fitness equation of $\log(C)$ versus time t (x).

The data were best fitted in Equation (2) and gave satisfactory results for the applicability of the model in turbidity, BOD, and COD removal. The plot of logarithms of turbidity, BOD, and COD versus settling time (t) showed the good fitness of data points derived from experimental observations (Figure 2). It was evidenced that the coefficient of determination (R^2) values for time course turbidity, BOD, and COD removal ranged from 0.8335–0.8534, 0.8064–0.9774, and 0.8686–0.9999, respectively. Besides this, the rate constant (r) was encountered in control treatment for turbidity (2.2216 NTU min^{-1}), BOD (1.0664 $\text{mg/L}\cdot\text{min}^{-1}$), and COD (0.8686 $\text{mg/L}\cdot\text{min}^{-1}$) removal, correspondingly (Figure 3). Though, there was a variation in the k values of 150 mg/L and 200 mg/L MO treatments. However, the overall maximum removal of turbidity, BOD, and COD in a total of 250 min of settling allowance was achieved in 150 mg/L of MO dose along with a reasonable k value.

The pollutant removal rate in a reaction-based system depends on numerous internal and external factors such as temperature, dose, and particle of plant biomass, agitation, aeration, retention period, and characteristics of wastewater itself [38]. The plant biomass has both physical and chemical binding sites that capture the pollutant particles and forms a complex. As the reaction initiates, the pollutant particle starts attaching to these sites, and the net weight of plant biomass particles is increased [39]. The reaction lasts until the complete saturation of the free sites, and finally, the rapid settling of the particle occurs. The reaction is largely dependent on solute and solvent properties which determines the net pollutant removal efficiency of such systems. Previously, Viotti et al. [20] investigated the adsorption kinetic removal of diclofenac from wastewater using MO biomass. Their results indicated an adsorption capacity of 60.805 mg/g for MO biomass with a significant efficiency as compared to the activated carbon with a maximum adsorption capacity of 71.150 mg/g.

Adsorption of nonylphenol in wastewater using kinetics study was also investigated by Dai et al. [40], and the adsorption process fitted well into the Elovich kinetics. Similarly, Sacher et al. [41] compared three classical kinetic models including zero-, first-, and second-order kinetics to determine the removal of monochloride in Loire river water. The only first-order model fitted well into their kinetic data under the applied experimental conditions, while other forms of kinetic models showed significant random variations. Chen et al. [42] studied the kinetics of zinc removal from wastewater using the first-order model. They confirmed that zinc removal was significantly affected by the initial dose of zinc ions during the electrocoagulation process. Similarly, Kumar et al. [28] conducted lab-scale experiments of phyto-treatment of sugar mill effluent using water hyacinth plants in the CSTR system assisted with direct current (DC). They analyzed the kinetics of BOD and COD reduction in the CSTR system and found the maximum BOD and COD rates of 0.54 mg/L week⁻¹ and 0.90 mg/L week⁻¹, respectively, using the first-order model.

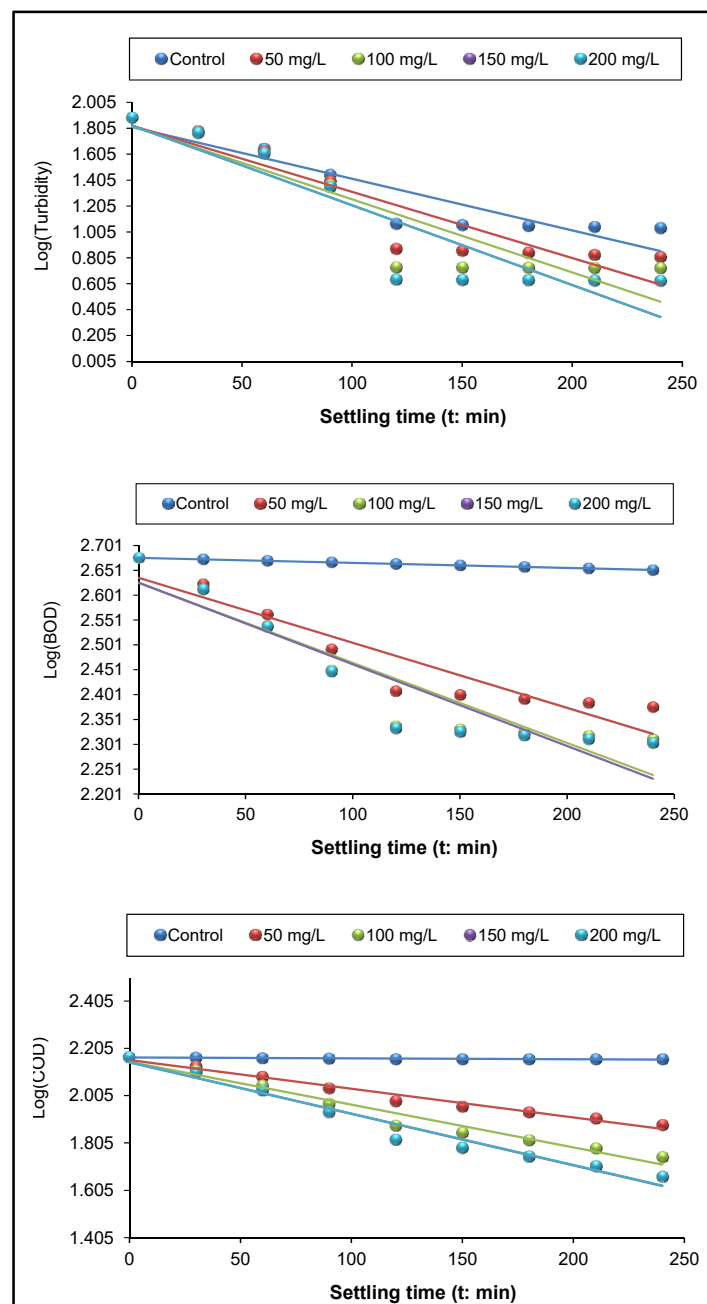


Figure 2. Log(C) versus time (t: min) plots of turbidity, BOD, COD removal of municipal wastewater.

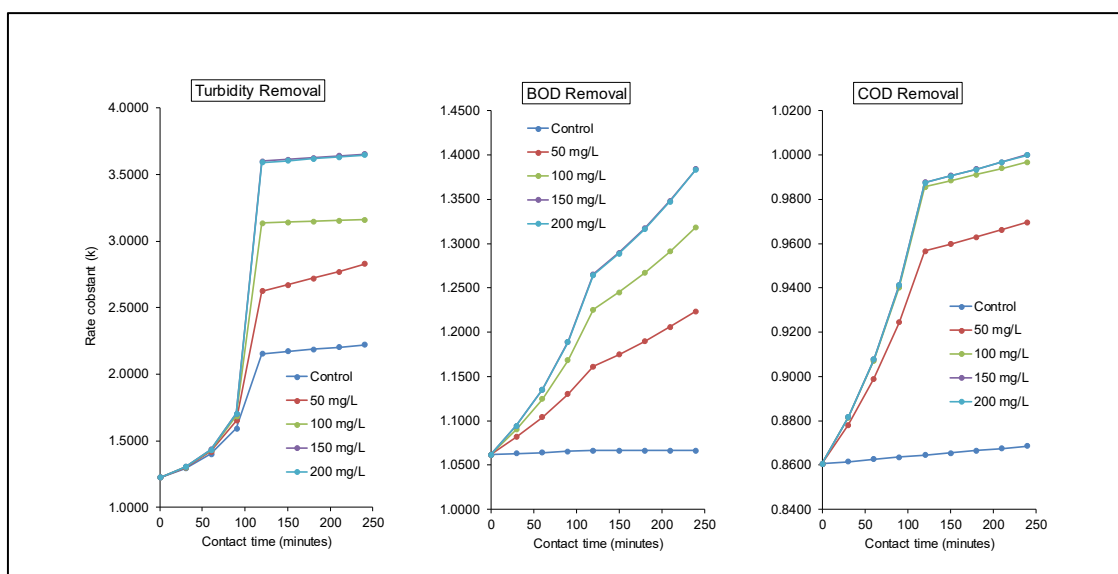


Figure 3. The first-order rate constant (r) of cumulative turbidity (NTU min^{-1}), BOD ($\text{mg/L}\cdot\text{min}^{-1}$), and COD ($\text{mg/L}\cdot\text{min}^{-1}$) removal of municipal wastewater using MO coagulant.

3.4. Prediction and Validation of Model Results

Prediction modeling results of cumulative turbidity, BOD, and COD removal using the modified Gompertz kinetic model are given in Table 3. From the final results, it was evidenced that the model can be successfully implemented for simulation of turbidity, BOD, and COD removal from municipal wastewater using MO biomass. The results showed that the coefficient of determination (R^2) had strong fitness of experimental data, which ranged from 0.98–0.99 for cumulative turbidity, BOD, and COD removal.

Table 3. Measured versus predicted percent (%) removal of turbidity, BOD, and COD with Gompertz model variables.

Parameter	Variable	MO Treatment Dose				
		Control	50 mg/L	100 mg/L	150 mg/L	200 mg/L
Turbidity	RE_m	85.82	91.49	93.02	94.44	94.42
	RE_p	87.50	93.24	95.22	96.97	96.95
	S_E	2.24	2.37	2.51	2.55	2.53
	λ_m	45.94	45.99	45.56	45.57	45.58
	μ	0.0291	0.0290	0.0293	0.0296	0.0294
	R^2	0.98	0.98	0.98	0.98	0.98
BOD	RE_m	2.07	48.26	62.14	68.72	68.65
	RE_p	2.10	46.58	61.71	68.15	68.08
	S_E	0.05	1.64	1.57	1.61	1.62
	λ_m	45.99	63.32	56.82	55.16	55.24
	μ	0.0290	0.0177	0.0205	0.0214	0.0213
	R^2	0.99	0.99	0.99	0.99	0.99
COD	RE_m	5.48	49.96	56.92	57.64	57.61
	RE_p	5.37	50.24	57.38	58.05	58.02
	S_E	0.74	1.10	1.34	1.35	1.34
	λ_m	117.89	48.31	47.15	47.28	47.29
	μ	0.0092	0.0265	0.0277	0.0276	0.0276
	R^2	0.99	0.99	0.99	0.99	0.99

RE_m : Measured removal (%); RE_p : predicted removal (%) using modified Gompertz model; S_E : standard error in prediction; λ_{max} : lag phase in min; μ : specific removal rate per min; and R^2 : coefficient of determination.

Furthermore, the predicted removal in all MO treatments was intensely close to the measured removal. Figures 4 and 5 give graphical representations of comparison of predicted and measured turbidity, BOD, and COD removal. The maximum measured (R_m) versus predicted (R_p) removal of turbidity (RE_m : 94.44 and RE_p : 96.97), BOD (RE_m : 68.72 and RE_p : 68.15), and COD (RE_m : 57.64 and RE_p : 58.05) indicated that the models had an acceptable and small standard error in prediction (<5%). The maximum specific removal rate (μ_m) was maximum in 150 mg/L MO treatment for all the three selected parameters. However, all the model parameters in 200 mg/L MO treatment were slightly less than the parameter values of 150 mg/L MO treatment, therefore, increasing the MO dose after 150 mg/L was not recommended. Also, the medium values of the lag phase (λ_{max}) revealed that the initial settling time of 150 min was the most determining phase in which the maximum specific pollutant removal was achieved. However, the models were developed based on the specific municipal wastewater and the estimated variables may vary according to the water quality. Still, the methodology suggests the good fitness of the models in determining the major factors of the municipal wastewater treatment process.

In our findings, the modified Gompertz model-based variables increased from control treatment to 150 mg/L MO treatment and further decreased to 200 mg/L. The stability of these model variables may be associated with the kinetic factors, i.e., solute (MO biomass) concentration. A high dose of MO may not be kinetically feasible for the pollutant capture reaction, and, therefore, the reaction rate was stabilized. The good fitness of the non-linear curve, as demonstrated in Figure 4, explained the feasibility of the modified Gompertz model in the present study. Recently, Carvajal et al. [43] studied the pollutant removal kinetics and their relative impact of anoxic BTEX biodegradation using the modified Gompertz model. They precisely modeled the BTEX biodegradation and showed that the higher concentration mixture might cause an inhibitory effect on the degradation process. Báez et al. [29] investigated the pollutant load removal efficiency of whey using a modified Gompertz model with validation of the results by specific model verification tools like R^2 , efficiency, and standard error in prediction. Hernández-Martínez et al. [44] performed batch mode experiments in a bubble column reactor for pollutant load reduction petroleum hydrocarbons using microbial biomass. They also modeled the hydrocarbon biosorption process using the modified Gompertz model and explained the model predicted removal was near to the experimental removal.

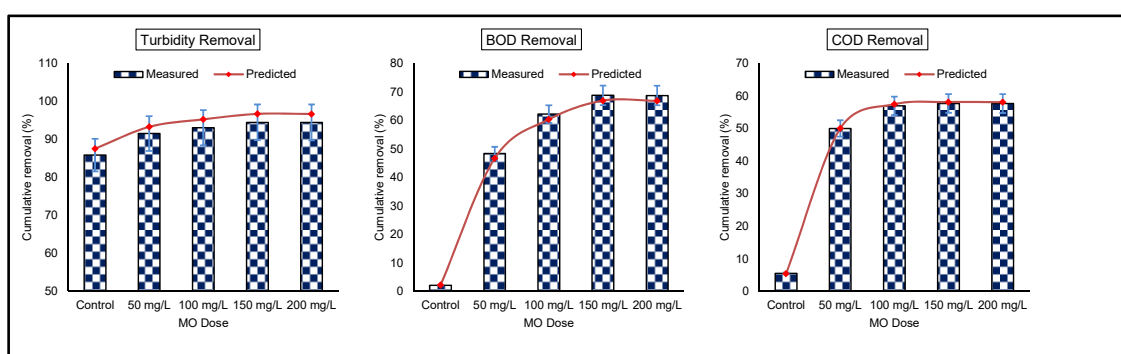


Figure 4. Effect of MO dose with measured versus predicted cumulative removal of turbidity, BOD, and COD of municipal wastewater using MO coagulant.

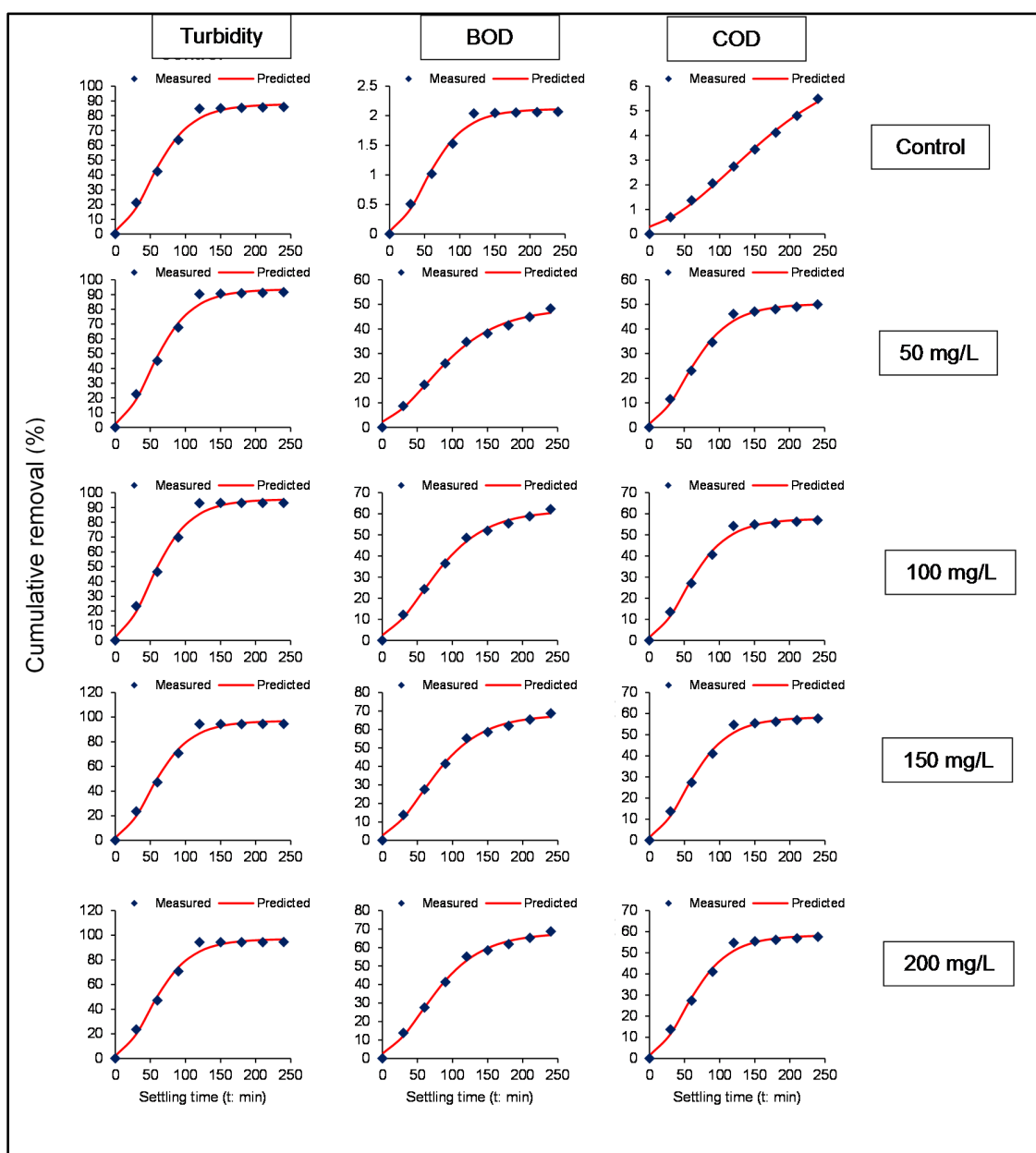


Figure 5. Experimental versus modified Gompertz model predicted cumulative removal (%) of turbidity, BOD, COD of municipal wastewater using MO coagulant.

4. Conclusions

In this study, we deduced that *Moringa oleifera* (MO) seed biomass was an effective coagulant to reduce the pollutant load of municipal wastewater. The results revealed that a significant reduction ($p < 0.05$) of the selected wastewater parameters, viz., turbidity, BOD, and COD was achieved. Also, the kinetic modeling of the reactor system utilizing the first-order and modified Gompertz model helped to enhance the turbidity, BOD, and COD removal process. We found that among the different MO treatments (0–200 mg/L), the maximum measured (R_m) and predicted (RE_p) removal of turbidity (RE_m : 94.44 and RE_p : 96.97), BOD (RE_m : 68.72 and RE_p : 68.15), and COD (RE_m : 57.64 and RE_p : 58.05) were achieved using a MO dose of 150 mg/L after 250 min of settling retention, respectively. However, the models should be tested for the treatment of other wastewaters as the variables may vary according to the water quality. The findings of this study will be essentially useful for low-cost

primary treatment of municipal wastewater employing MO seed biomass and minimize its possible, disposable environmental risks.

Author Contributions: B.A. conceived the idea, conducted the experiment, analyzed the data, and wrote the manuscript. M.S.O. collected the data, performed sampling analysis, and wrote the manuscript. F.O.A. performed the data curation, analyzed the data, and revised the manuscript. T.S.A. analyzed the data and revised the manuscript. H.O.B. collected the data and revised the manuscript. K.S.C. resources and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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