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Studies on kinetics and settling behavior of flocs formed using a sustainable coagulant in sewage water treatment

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ABSTRACT

This study was focused on the evaluation of the settling behavior of flocs formed during the treatment of sewage water using a green coagulant *Strychnos potatorum*. The batch mode coagulation–flocculation studies were performed to study the effect of experimental parameters. The proposed case to treat a liter of sewage water was 800 mL of eluate made from 1% (wt./vol) of *S. potatorum* and 4 N NaCl, at its own initial pH (6.8–7.4). The presence of protein, an active component, responsible for coagulation was confirmed by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) method. The results were contrasted with chemical coagulant alum. The kinetic studies have suggested the suitability of the natural coagulant for the pollutant removal, heterogeneity behavior and the non-occurrence of chemisorption reaction. The final sludge volume produced was 35 mL/L (*S. potatorum*) and 430 mL/L (alum). The sludge volume index was found to be 64.85 mL/g which indicated that the sludge has very good settling properties. The thickener area required for the settling process was also found. Based on the higher removal efficiency and lower sludge volume, and is an eco-friendly, biodegradable, low-cost natural coagulant, *S. potatorum* could act as a better substitute for chemical coagulant in the sewage water treatment.

Keywords: Sewage water; *S. potatorum;* Coagulation; Settling; Kinetics

1. Introduction

One of the essential things on earth is water. On earth there would not be any life for living beings without water. It is well known that only 2.5% of Earth's water is fresh water. The availability of fresh water is getting depleted and simultaneously the production of polluted water is rising. Sanitation problem is increasing day by day, because of (i) industrialization, (ii) active population growth and (iii) urbanization which threatens the health of living beings. Many diseases are associated with the generation of a huge volume of polluted water throughout the world. The motivation for this work was attained by knowing that 21% of the communicable diseases, in India, are water-related, which was estimated by World Bank [1].

Sewage, which is also known as municipal wastewater, consists of water-carried waste, detergents, microorganisms, pathogens, etc. It also contains a large amount of organic matter which could be treated and reused for other purposes. As a result of realizing the environmental concerns, major attempts were taken to improve the quality of the treated water [2].

The environmental researchers have summarized the available techniques and their effectiveness in the treatment of sewage water. The methods include coagulation, chemical precipitation, carbon adsorption, ion exchange, evaporations

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membrane processes and biological treatment. From the results, the research directions were also identified [3].

Among the variety of conventional methods, coagulation plays a vital role in the sewage water treatment; the impediments observed were conquered by the substitution of green materials. A coagulant obtained from the plant origin is termed as green coagulant or plant-based coagulant. The large volume of sludge formations, changes in the treated water pH and the high operating cost experienced in the usage of chemical coagulant was forced to think about the alternate sustainable green coagulant [4–7].

From the research findings, it was observed that most of the natural coagulants are obtained from fungi, bacteria, plants and animals. The efficiency of the following plant-based coagulants viz., *Strychnos potatorum* Linn, *Moringa oleifera, guar gum, Cassia fistula, Plantago ovate, Trigonella foenum-graecum* and *Opuntia ficus-indica* are proved in the bench-scale testing [8,9].

By scanning the literature, the existence of *Strychnos potatorum* seeds in the water and wastewater treatment was clearly understood. The coagulant chosen for the treatment was a natural and a plant-based one that does not affect the pH of the treated water. The *S. potatorum* was widely used as a coagulant for the treatment of turbid water as well as industrial wastewater. It is abundant in the southern part of India [10].

The objective of the present study is to (i) understand the kinetic mechanism of the coagulant process and (ii) a settling behavior of the flocs produced during coagulation. Laboratory tests have shown the successful removal of physical particulate matters, color and turbidity. The performance of the green coagulant *S. potatorum* was compared with chemical coagulant alum.

2. Materials and methods

2.1. Materials

Sewage water collected from an inlet of SRM Institute of Science and Technology treatment plant was used as an effluent. The physico-chemical properties are given in Table 1. The *Strychnos potatorum* seed powder sieved through 0.5 mm sieve was utilized as a green coagulant. Aluminum sulfate, 16 $Al_2(SO_4)_3 \cdot 16H_2O$, commonly known as alum, a hydrolyzing ferrous metallic salt, was taken as a chemical based coagulant.

Table 1
Physico-chemical properties of sewage water

Parameters	Concentration (mg/L) (except color, pH and turbidity)
Color	Black
Initial pH	6.8–7.4
Dissolved oxygen demand (DO)	0.3
Salinity	1,120
Total dissolved solids (TDS)	1,210
Absorbance, nm	1.181
Turbidity, NTU	50–190
Chemical oxygen demand (COD)	1,400
Total solids (TS)	10,000
Total suspended solids (TSS)	8,790

2.2. Methods

2.2.1. Formulation of coagulant–eluate

A specified amount (1–5 g) of *S. potatorum* seed powder was mixed with 100 mL of solvent (water, NaCl, KCl), for about 15 min at 200 rpm. After 10 min of settling period, a known volume of this extract was taken and utilized as a coagulant for further treatment [11]. Throughout this work, the solvent used is termed as an 'eluent', and the prepared extract is termed as an 'eluate'.

2.2.2. Experimental procedure

A jar test apparatus containing six stirrers and base light up was used for the batch coagulation–flocculation process. A measured volume of coagulant–eluate was added with a liter of sewage water and controlled at 200 rpm for rapid mixing (5 min), 80 rpm for slow mixing (15 min), followed by settling for 60 min. The top layer of the clear solution was used for the analysis [11]. All the experiments were repeated at least thrice for consistency and the results were averaged. All graphs were plotted using the averaged values.

2.2.3. Performance assessment

Using the standard methods, the parameters given in Table 1 were measured [12]. Color was measured using SL 218 double UV visible spectrophotometer (Elico, Chennai, India) at λ_{max} 300 nm. Turbidity was measured using digital nephelo-turbidity meter 132 (Elico, India) and was expressed in nephelometric turbidity units (NTU). The pH was adjusted using a digital pH meter MK. V.I (Elico, India).

3. Results and discussion

3.1. Characterization of S. potatorum

Using the FTIR analysis, the chemical functional groups present in the *S. potatorum* was assessed (Fig. 1a). At 3,417.47 cm^{-1}, an intense peak was viewed, which is due to the existence of OH stretching vibration of water and stretching vibration of amine. The peak at 1,156 cm^{-1} confirmed the presence of C–N stretching. The presence of H_2O was also confirmed by its bending vibration at 1,651 cm^{-1}. $-CH_2$ vibration of alkyl group was noticed by the peak at 2,926.05 cm^{-1}. The CH_2 bending vibration occurred at 1,431 cm^{-1}. Stretching vibration of ether groups, that is, –CO was affirmed by the peak at 1,021.48 cm^{-1}. So, the FTIR spectra reveal that the seed mainly carries aliphatic grouping with ether linkages and amine groups [10].

3.1.1. Identification and estimation of protein

Sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) method is used to find the molecular

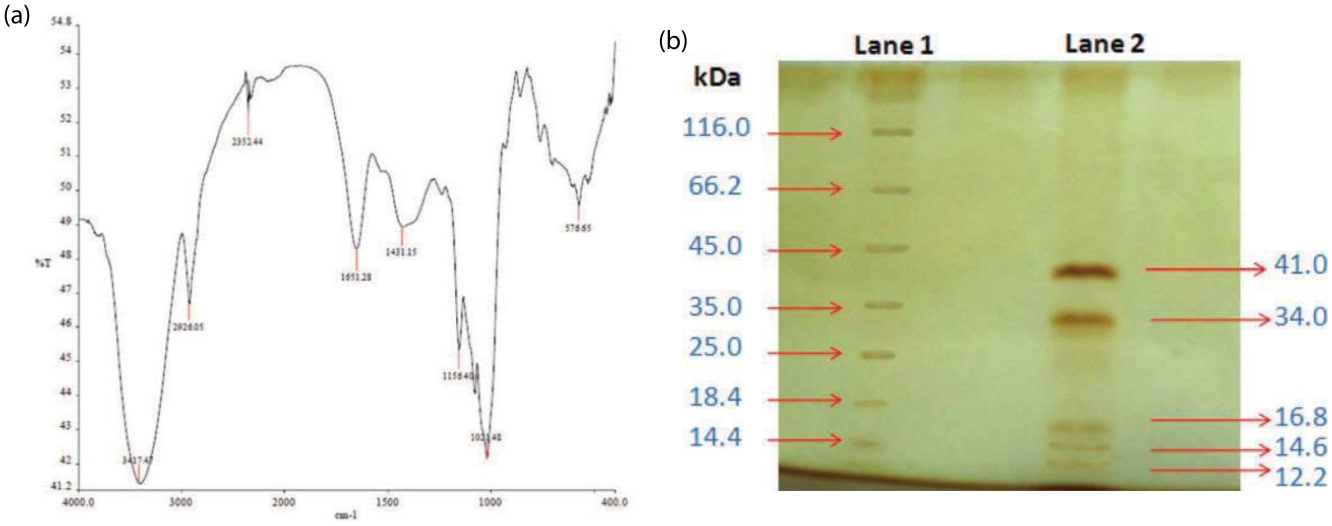

Fig. 1. (a) Fourier transform infrared spectroscopy *(FTIR)* spectrum of *S. potatorum*. (b) SDS PAGE pattern for *S. potatorum*. *Lane 1*: protein marker, *Lane 2*: *S. potatorum* seeds.

protein weight and its profile. The protein content of the extracts prepared using 4 N NaCl was estimated before the treatment process using the Bradford method. Protein bands from SDS-PAGE were excised (Fig. 1b). From the Bradford method, the estimated protein concentration was 72.17 and 80.58 mg/mL before and after the dialysis. The percentage of concentration was 10.5. From the various protein bands, the observed higher intensities with a molecular weight range of 32–41 kDa could possess coagulation activity [10].

3.2. Green coagulant Strychnos potatorum

3.2.1. Change in eluent type and concentration

The existence of protein in a green coagulant *S. potatorum* is evident for its coagulation behavior. The coagulation ability depends on how efficiently, it could be unbound from *S. potatorum* with the help of an eluent.

To optimize the type of eluent suitable to unbind the protein, 100 mL each of distilled water, 1 N NaCl and 1 N KCl solutions were used to dissolve 5 g of *S. potatorum* seed powder, for the preparation of coagulant–eluate. Hence the proteins were not dissolving in water, poor outcome was observed for water eluent. The removal showed by KCl was 49.47% color, and 50.68% turbidity, whereas NaCl showed 66.32% color, and 54.51% turbidity removal. This could be because of the ion exchange property of NaCl solution that has the greatest ability to liberate the protein from *S. potatorum* rather than KCl (Fig. 2). Thus NaCl was chosen as a better eluent because of higher removal efficiency. No removal was noticed when NaCl solution alone was used as an eluent in the absence of *S. potatorum*. Similar results were found in the treatment of paint industry effluent using guar gum seeds [13].

The liberation of protein from its source leans on the ionic strength of the NaCl solution. Concentrations of NaCl used for elution were in the range of 1–5 N. The removal efficiencies were comparatively good for 4 N NaCl, such as 76.17% and 88.34% for color and turbidity, respectively (Fig. 3). The protein eluted by the gradual increase in ionic strength showed different coagulation efficiency when applied in the same dose. The results indicate that 4 N NaCl is an optimum eluent concentration, which liberates the maximum amount of protein from 5 g of *S. potatorum*. At the higher concentrations, the protein denaturation increases the residual turbidity. The results coincided with the work done on the extraction and partial purification of coagulation active components from common bean seeds [14].

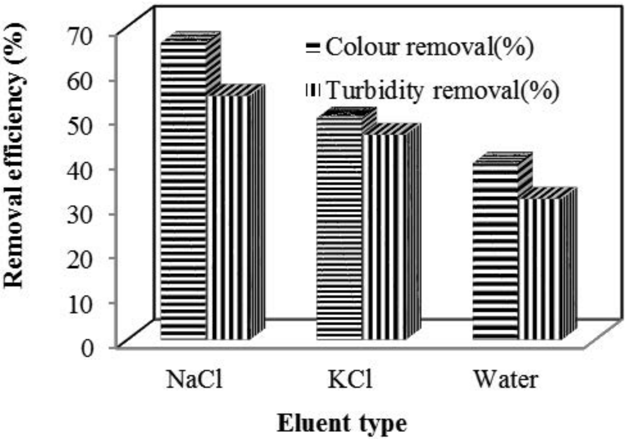

Fig. 2. Effect of change in eluent type eluent: water, 1 N NaCl, 1 N KCl; *S. potatorum* dose: 5 g; Coagulant-eluate volume: 100 mL; initial pH: actual effluent pH (6.8–7.4).

3.2.2. Change in coagulant dose

Inadequate or surplus dose of coagulant leads to the unbalance of the charged particles. Therefore, to find the optimum dose of coagulant to treat a liter of effluent, experiments were repeated by varying the coagulant amount from 1 to 5 g/L of effluent, by keeping other parameters constant. From Fig. 4, the maximum removal was found as 75.26% for color and 81.82% for turbidity when 1 g of *S. potatorum* was used.

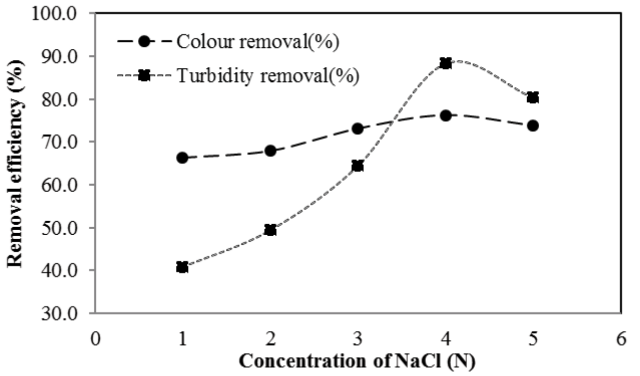

Fig. 3. Effect of change in eluent concentration eluent: 1–5 N NaCl; *S. potatorum* dose: 5 g; coagulant–eluate volume: 100 mL; initial pH: actual effluent pH (6.8–7.4).

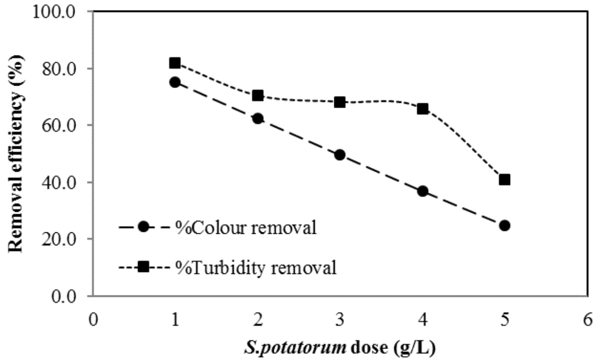

Fig. 4. Effect of change in coagulant dose eluent: 4 N NaCl; *S. potatorum* dose: 1–5 g; coagulant–eluate volume: 100 mL; initial pH: actual effluent pH (6.8–7.4).

The increase in the coagulant dose results in the fall of the treatment efficiency in reverse of rising. There are two believed mechanisms behind that: (i) the larger dose may lead to charge reversal and (ii) the eluent volume was not concurrently raised with coagulant dose to liberate the available protein. Akin outcomes were observed when the plant-based coagulant *Cactus opuntia* was used in the industrial wastewater treatment [15].

3.2.3. Change in coagulant–eluate volume

The different volume of coagulant–eluate (20–120 mL) prepared using 1 g of *S. potatorum* in 100 mL of 4 N NaCl solution was applied in a liter of effluent. The concentration of *S. potatorum* differed between jars (Table 2). It was calculated as below:

$$V_1N_1 = V_2N_2 \tag{1}$$

where V_1 = volume of coagulant–eluate, mL; V_2 = volume of effluent with coagulant–eluate, mL; N_1 = concentration of *S. pototarum*, g/mL; N_2 = concentration of *S. potatorum* in the effluent, g/mL

When the coagulant–eluate volume was raised, the removal of color and turbidity was also hiked due to the presence of increasing concentration of coagulant. The equilibrium values were observed at 80 mL, where the corresponding concentration of the coagulant was 0.7407 g/L. The results were 77.89% and 51.02% for color and turbidity, respectively (Fig. 5). Identically results were noticed in work performed on the extraction of proteins from common bean, which was used as a coagulant in the water turbidity removal [16].

3.2.4. Change of initial pH of effluent

The basic mechanism behind the coagulation process is charge neutralization. The charge of the particles present in the effluent could be altered by changing its initial pH. The initial pH of the effluent varied from 5 to 10 by adding HCl/NaOH solution accordingly. The actual pH of the sewage water ranged from 6.8 to 7.4, that is, nearer to neutral.

It was marked that the treatment was good at pH 8 (experiment could not be carried out below pH 5 due to precipitation) and the results were 92.34% color and 80.77% turbidity, respectively. Almost similar results were obtained at the actual pH likely (6.8–7.4); 91.65% of coloring matter removal and 78.68% of turbidity removal (Fig. 6). Therefore, by considering the removal efficiency and economic facts, it was preferred to conduct the treatment at the actual pH of the effluent itself. Thus, the believed mechanism could be described as adsorption and charge neutralization. The presence of positive ions might perform well in the basic region. Similarly, maximum removal was obtained at the actual pH of the olive mill and winery wastewaters treatment, using chitosan as a coagulant [17].

Table 2
Concentration of *S. potatorum* in jars

Jar number	Volume of coagulant–eluate (mL) (1 g coagulant: 100 mL eluent)	Concentration of *S. potatorum* in a liter of effluent (g/L)
1	20	0.1961
2	40	0.3846
3	60	0.5660
4	80	0.7407
5	100	0.9091
6	120	1.071

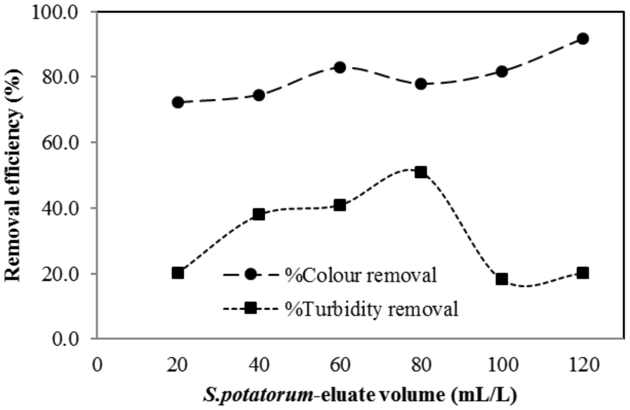

Fig. 5. Effect of change in S. potatorum-eluate volume eluent: 4 N NaCl; *S. potatorum* dose: 1 g; Coagulant-eluate volume: 20–120 mL; initial pH: actual effluent pH (6.8–7.4).

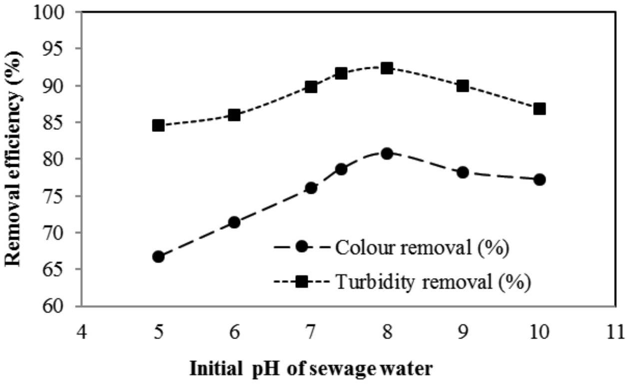

Fig. 6. Effect of change in initial pH of sewage water (*S. potatorum*) eluent: 4 N NaCl; *S. potatorum* dose: 1 g; coagulant–eluate volume: 80 mL; initial pH: 5–10.

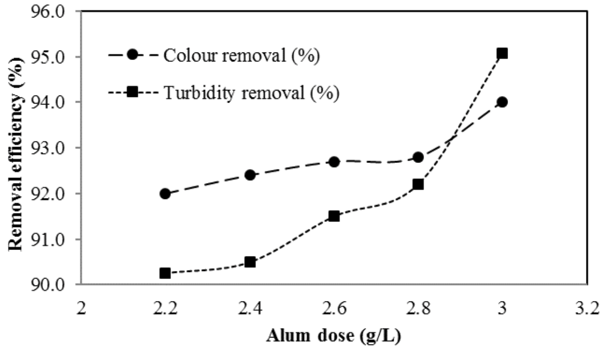

Fig. 7. Effect of change in alum dose. Alum dose: 2.2–3 g; initial pH: actual effluent pH (6.8–7.4).

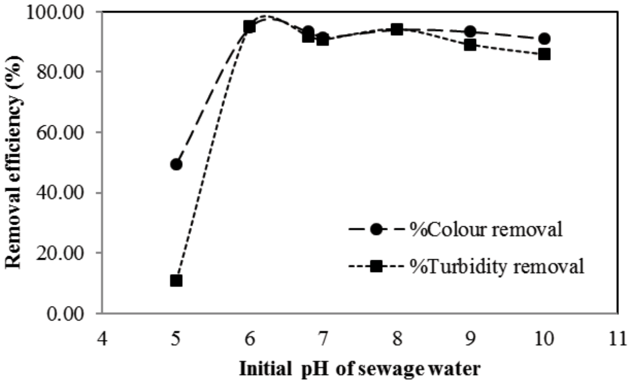

Fig. 8. Effect of change in initial pH of sewage water (alum). Alum dose: 3 g; initial pH: 5–10.

3.3. Chemical coagulant -alum

3.3.1. Change of alum dose and initial pH of sewage water

The change of alum dose was tested by varying the alum amount from 2.2 to 3 g per liter of effluent. The choicest value was 3 g for that the removal efficiency was 94.01% color and 95.07% turbidity, respectively (Fig. 7). Beyond 3 g, there was no further appreciable change in the removal efficiency. To examine the influence of initial pH of the effluent on removal, it was varied from 5 to 10. At neutral pH 6.8, the topmost removal efficiency, that is, 91.72% color and 93.41% turbidity was marked (Fig. 8). The results were matched with the work done on the paint wastewater treatment using alum as a conventional chemical coagulant [10].

The optimum treatment conditions and its performance for both the green coagulant and the alum are consolidated in Table 3.

3.4. Sludge settleability parameters

Completeness of the coagulation process relies on the settling ability of the flocs formed. The settling behavior of a suspension is governed by its concentration and flocculation tendency and it is classified into four regimes discrete non-flocculent settling (class I), discrete flocculent settling (class II), zone settling or hindered settling (class III) and compressive settling (class IV).

3.4.1. Sludge volume index

It is defined as the ratio between the volume (mL) occupied by 1 g of sludge after settling in the tank for 30 min (SV_{30}) and final sludge volume (SV_F).

$$\mathrm{SVI} = \frac{\mathrm{SV}_{30}\left(\frac{\mathrm{mL}}{\mathrm{L}}\right)}{\mathrm{SV}_F\left(\frac{\mathrm{g}}{\mathrm{L}}\right)}, \mathrm{mL/g} \tag{2}$$

The SVI result of the *S. potatorum* was viewed to be 64.85 mL/g which indicated sludge with very good settling properties. The reference value of SVI is ranged between 50 (indicates very good settleability) and 400 mL/g (poor settleability).

SVI is used to describe the settling characteristics of sludge. It is a process control parameter to determine the recycle rate of sludge. It has become the standard measure of the physical characteristics of activated sludge processes [18].

3.4.2. Batch settling curve and the hindered settling velocity

The batch test was performed in a column of 65 mm in diameter and 430 mm deep, and by gently stirring (1 rpm) the sample during settling. The volume of the sludge produced after a fixed settling span is the basis for the measurement of the sludge settleability parameters of the coagulant used. Among these, the SVI is the most known. It is influenced by the dimensions of the settling cylinder. These problems can be significantly reduced by conducting the test under certain prescribed conditions. The initial sludge height was 0.303 m (*S. potatorum*), 0.328 m (alum) and at the end of the 60th min, it was 0.113 m (*S. potatorum*) and 0.287 m (alum). The final sludge volume was 35 mL/L (*S. potatorum*), 875 mL (alum) and the dry weight was 4.17 g for *S. potatorum* [19]. The sludge volume measured when the coagulant was *S. potatorum* is much lower than the alum.

From the batch settling results, the plot was made between the sludge bed heights over time (Figs. 9a and b). Hindered settling velocity (V_{HS}) was calculated from the steepest slope of the three consecutive data points of the batch curve. It governs the determination of the limiting flux and thus the thickener surface area. At higher concentrations, the settling particles will be increasingly hindered by surrounding particles, which slows down the V_{HS}. For *S. potatorum*, the hindered settling velocity was found to be 0.0032 and 0.00057 m/min for alum [20].

3.4.3. Determination of thickener area

To determine the area of the clarifier–thickener, settling data obtained from batch tests were used. To concentrate the sludge from sewage water with an initial concentration of 1.4 kg/m^3 and at the rate of 1,000 L/d, the Kynch theory was used. In the batch settling curve of *S. potatorum* and alum (Fig. 9) tangent was drawn for selected points. The meeting point of the tangent line on the *Y*-axis, that is, sludge bed height was marked as Z_i (m). Corresponding values of the time and a sludge bed height of the selected points were named as (min), Z_L (m), respectively. Based on these three data obtained from Fig. 9, sludge concentration (C_L), under flow sludge concentration (C_U) and settling velocity (V_L) were calculated using the following formulae (Eqs. (3)–(6)) [21]. The plot (Fig. 10) was made between InlineEqn(1) vs. C_L to determine the clarifier–thickener area. At the optimized conditions to treat 1,000 L/d flow of sewage water with the initial concentration of 1.4 kg/m^3, the clarifier–thickener area required was 0.23 m^2 for *S. potatorum* and 4.45 m^2 for alum.

$$\text{Sludge concentration, } C_L = \frac{C_0 Z_0}{Z_i}, \text{kg / m}^3 \quad (3)$$

$$\text{Under flow concentration, } C_U = \frac{C_0 Z_0}{Z_U}, \text{kg / m}^3 \quad (4)$$

$$\text{Settling velocity, } V_L = \frac{Z_i - Z_L}{\theta_L}, \text{m / s} \quad (5)$$

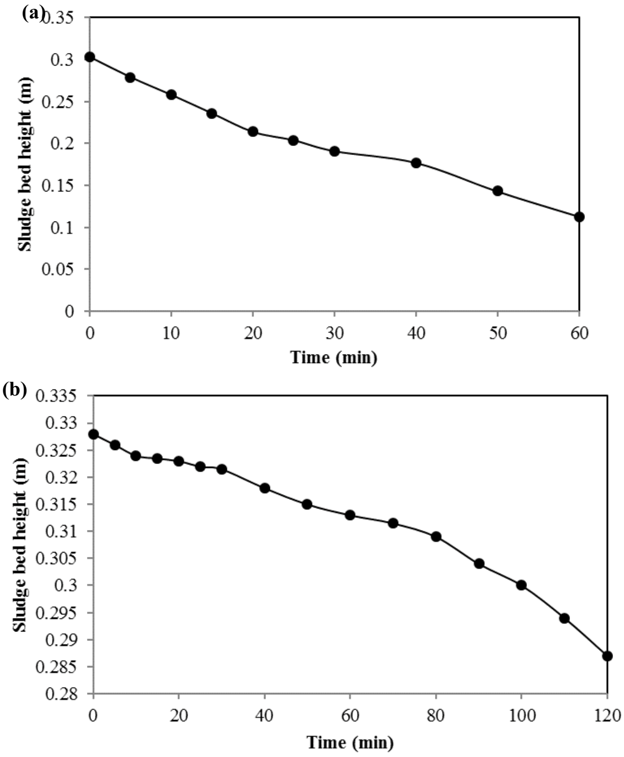

Fig. 9. Batch settling curve of (a) *S. potatorum* and (b) alum.

$$\text{Thickener area, } A = \frac{\dfrac{FC_0}{V_L}}{\left(\dfrac{1}{C_L} - \dfrac{1}{C_U}\right)}, \text{m}^2 \quad (6)$$

where F = rate of feed, m^3/s; C_0 = initial concentration, kg/m^3; C_U = under flow concentration, kg/m^3; Z_0 = initial sludge bed height, m; Z_U = final sludge bed height, m; V_L = settling velocity, m/s.

3.5. Kinetic studies

One of the economic parameter for wastewater treatment is the equilibrium time. Several kinetic models were, therefore, tried and tested during the treatment. Selection of the most suitable model was based on the comparison of the experimental and simulated data, and the evaluation of the correlation between coagulation properties and model theory.

The models investigated were first-order, second order, Bangham, Elovich and Avrami. Excel spread sheets were used to determine the experimentally determined ($q_{e,\text{exp}}$) and calculated ($q_{e,\text{cal}}$) and correlation coefficient (R^2) along with the kinetic constant. The kinetic model equations and the predicted model parameters are tabulated in Table 3.

The plots were made between time and ln (C_0/C) (Fig. 11a), and the model parameters are linear regression coefficient (R^2), rate constant k_1 (1/min). The plot was linear but did not pass through the origin, indicating that the process was not in acknowledgment with the experimental values.

The linear form of second order equation is plotted in Fig. 11b. The second order rate constant k_2 (L/mg. min), and the experimental and graphical $1/C_0$ (mg/L) values were listed. The similarity between the experimental and graphical $1/C_0$ (mg/L) values indicated the suitability of the model. The work was compared with the results obtained from the adsorption of molasses wastewater on activated carbon [22].

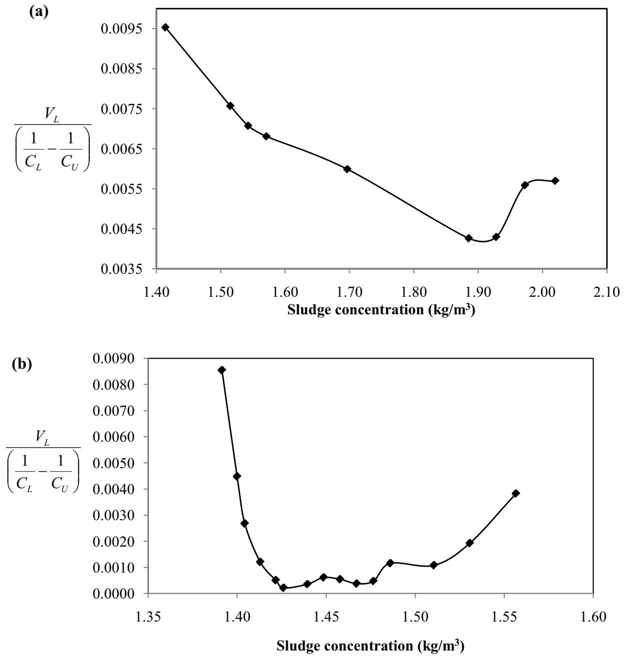

Fig. 10. Clarifier–thickener area determination of (a) *S. potatorum* and (b) alum.

The Bangham model can be used to calculate k_B and $1/m_B$ and was estimated from the basic plot between log t vs. log q_t (Fig. 11c). The m_B value of the *S. potaturum* is 1.189. Larger values of k_B (>1) were indicative of the suitability of a material for pollutant removal. It may be concluded that film and pores diffusion differed in their degree of importance during the pollutant removal process.

Interpretations of the Elovich equation are usually connected to the heterogeneous surfaces. The large value of α_E (>1) implied that the model was capable of explaining heterogeneity of surface coagulants (Fig. 11d). The trend was supported by the outcomes of study on adsorption of Remazol Brilliant Blue R using ZnO fine powder [23].

The Avrami model might suggest the mechanism of pollutant binding onto the coagulant. The value also made it possible to determine whether the adsorption process is limited by surface reaction ($m_{\mathrm{av}} > 1$) or not (Fig. 11e). Akin results were marked in the paint effluent treatment using five different coagulants namely, *Strychnos potatorum, Cactus opuntia, Moringa oleifera, Cyamopsis tetragonolobus* and *Portunus sanguinolentus* [24].

The growth of flocs formed concerning time was estimated for monomers ($m = 1$), dimmers ($m = 2$) and trimmers ($m = 3$), respectively, using Eq. (7). In the curve nature, it was viewed that the speedy decrease in the monomer particles than that of total particles. The dimmer and trimmer particles formation was enhanced by the declined nature of monomer particles (Fig. 12). The similar report was observed in the kinetic studies of coagulation process for tannery industry effluent treatment using *Moringa oleifera* seeds protein [25].

$$\mathrm{Nm}(t) = 4\mathrm{No}^{m}(\mathrm{kt})^{m-1}\left(2 + k\,\mathrm{Not}\right)^{-m+1} \tag{7}$$

Table 3
Performance comparison of coagulant under optimized conditions (basis: 1 liter of sewage water)

Kinetic models	Model parameters		Inference [24]
First order $\ln(C_0/C_t) = k_1 t$	R^2	0.99	Existence of intercept indicates the non suitability of this model.
	k_1	0.0258	
	Intercept	0.0258	
Second order $(1/C_t) = k_2\, t + (1/C_0)$	R^2	0.95	Similarity between experimental and graphical $1/C_0$ value indicates the suitability of this model.
	k_2	0.0002	
	Graph $(1/C_0)$	0.0033	
	Expt$(1/C_0)$	0.0041	
Bhangam $\log q_t = \log k_B + \frac{1}{mB}\log t$	R^2	0.96	>1 suitability of coagulant
	m_B	1.189	
	k_B	1.72	
Elovich $q_t = \frac{1}{\beta_E}\ln\left(\propto_E \beta_E\right) + \frac{1}{\beta_E}\ln t$	R^2	0.93	
	β_E	12	>1 non-occurrence of the chemisorption reaction.
	α_E	318	>1, heterogeneity of surface coagulants
Avrami $\ln\left(-\ln\left(1-\frac{q_t}{q_e}\right)\right) = \ln\left(k_{\mathrm{av}}\right) + m_{\mathrm{av}}\ln t$	R^2	0.68	
	m_{av}	0.791	$m_{\mathrm{av}} < 1$ adsorption process is not limited by surface reaction alone
	k_{av}	13	

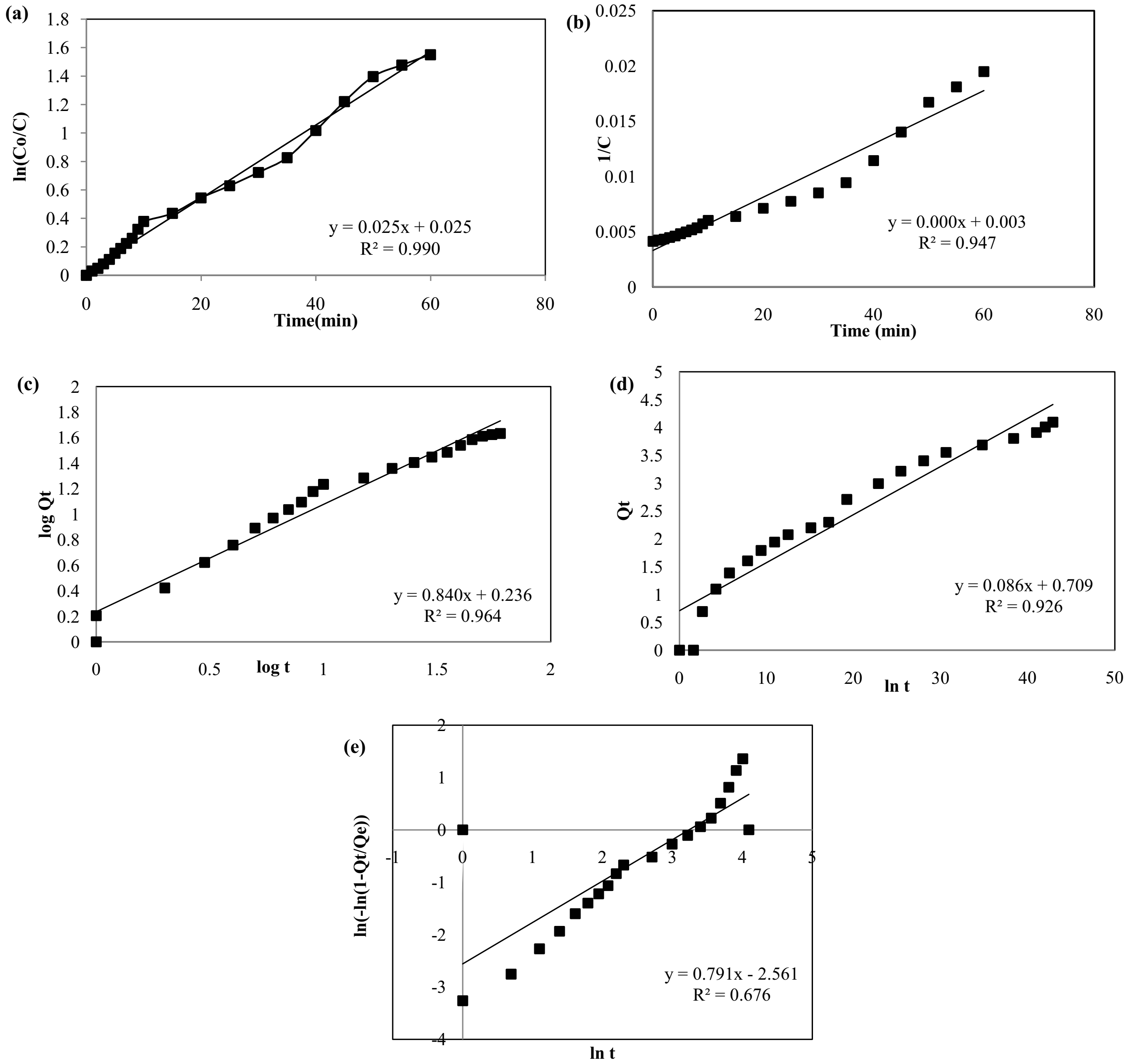

Fig. 11. (a) First order kinetic model, (b) second order kinetic model, (c) Bangham kinetic model, (d) Elovich kinetic model and (e) Avrami kinetic model.

Table 4
Kinetic model equations and parameters

Coagulant	Eluent and conc.	Dose and eluate volume	Initial pH	Color removal efficiency (%)	Turbidity removal efficiency (%)
S. potatorum	4 N NaCl	1 g and 800 mL	6.8–7.4	92.34	80.77
Alum	***	3 g	6.8–7.4	94.01	95.07

4. Conclusions

In this study, the ability of *S. potatorum* in the treatment of sewage water collected from the SRM Institute of Science and Technology treatment plant was examined. The experiments were performed in batch coagulation operation. The optimized conditions for the treatment of liter of effluent were concluded as 800 mL of eluate prepared using 1 g of *S. potatorum* and 4 N NaCl at its own initial pH (6.8–7.4). The dry weight of the final sludge produced

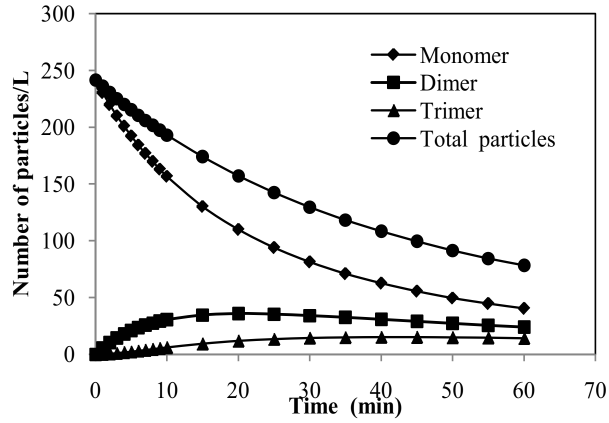

Fig. 12. Cluster size distribution.

using *S. potatorum* was 4.17 g. The SVI value 64.85 mL/g indicated the very good settleability of sludge formed using *S. potatorum*. The thickener area requirement was found to be 0.23 m^2 (*S. potatorum*), 4.45 m^2 (alum) for the flow rate of 1,000 L/d. The kinetic studies suggested the suitability of the natural coagulant for the pollutant removal, heterogeneity behavior and the non-occurrence of chemisorption reaction. Based on the higher removal efficiency and lower sludge volume, lower clarifier–thickener area requirement and being eco-friendly, *S. potatorum* could act as a better substitute for chemical coagulant in the sewage water treatment. This study was in the laboratory prototype stage and still, there is work to be done before use in a real situation.

Symbols

C_0, C_t — Concentration of the solute, at $t = 0$, and time t in the sewage water, mg/L
k_{av} — Kinetic constant in the model Avrami model
k_B — Kinetic constant in the model Bangham model, mg/g min
k_1, k_2 — Kinetic rate constant in the first order model (1/min), second order model, L/mg min
m_{Av} — Avrami model parameter
m_B — Bangham model parameter
n — Order of the coagulation process
N_0 — Initial particle concentration, mg/L
q_t — Total quantity of pollutant adsorbed at time t, mg/g
$q_{e,\exp}$, $q_{e,\text{eqn}}$ — Equilibrium uptake of pollutants from the experiment and model equation, mg/g
R^2 — Correlation coefficient
t — Coagulation process time, min
α_E — Initial adsorption rate in the Elovich model, mg/mg
β_E — Desorption constant in the Elovich model, g/mg

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