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Evaluation of Coagulation Functional Parameters of *Chrysophyllum albidum* Seeds in Turbidity Removal from Surface Water

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Abstract

Coagulation–flocculation is essential for removing turbidity-causing colloids from surface water yet concerns over conventional inorganic coagulants have driven interest in sustainable alternatives. This study evaluates the coagulation functional parameters of Chrysophyllum albidum seed in turbidity removal from surface water. The effects of pH, coagulant dosage, and settling time on removal efficiency and coagulation kinetics were examined. Surface water samples were collected from River Ezu, Anambra State, Nigeria, while Chrysophyllum albidum seeds were processed and extracted using ethanol solvent extraction prior to jar test coagulation experiments. Jar test experiments were conducted at varying pH values (3–9), coagulant dosages (0.8–2.2 g/L) and settling times (10–50 min). Perikinetic data generated were fitted to specific kinetic models for the determination of coag-flocculation reaction order α, coag-flocculation rate constant K, and coagulation period $\tau_{1/2}$. The best coag-flocculation activity was recorded at dosage of 1.0g/L, pH of 3, yielding over 75% turbidity removal, with coagulation rate constant $K = 7.4733x10^{-4}m^3/kg.s$, and coagulation period $\tau_{1/2} = 4.58$ Secs, while the least was recorded at a dosage of 2.2g/L ($K = 1.1129x10^{-5}S^{-1}$ and $\tau_{1/2} = 307.12$ Secs). Kinetic analysis revealed low coagulation periods, high collision efficiencies, and maximum coagulation rate constants at the optimal dosage. The coag–flocculation process predominantly followed second-order reaction kinetics (>83%), indicating that particle removal was governed mainly by inter-particle collisions. Chrysophyllum albidum seed extract demonstrated strong potential as an effective green coagulant for surface water treatment. Despite the requirement for acidic operating conditions, its high turbidity removal efficiency and favorable coagulation kinetics support its applicability as a low-cost, biodegradable, and environmentally sustainable alternative to conventional chemical coagulants.

Keywords: Coag-flocculation, Kinetics, Turbidty, *Chrysophyllum albidum*, Coagulation constants

Introduction

Coagulation is a fundamental physicochemical process widely employed in water and wastewater treatment for the removal of suspended and colloidal particles responsible for turbidity. Colloidal particles are typically stable in aqueous systems due to their small size and the presence of similar surface electrical charges, which generate electrostatic repulsion and prevent natural aggregation. This stability is commonly quantified using the zeta potential, a key parameter that reflects the magnitude of repulsive forces between particles. Effective turbidity removal therefore requires the destabilization of these colloids through the addition of a suitable coagulant capable of reducing or neutralizing their surface charges (Qiu et al., 2021). The addition of a coagulant alters inter-particle forces by compressing the electrical double layer and promoting charge neutralization, thereby enhancing particle collisions, aggregation, and subsequent floc formation. These interactions lead to the formation of larger, settleable flocs through mechanisms such as particle bridging and sweep flocculation, which significantly improve clarification efficiency (Konkobo et al., 2023). Beyond conventional performance indicators such as turbidity removal efficiency, the evaluation of coagulation functional parameters, including coagulation period, collision efficiency, coagulation rate constant, and reaction order, provides deeper insight into the kinetics and dominant mechanisms governing the coagulation process.

In practical water treatment operations, coagulation is often enhanced by controlled mixing, which increases particle collision frequency and promotes aggregation. Such mixing is typically achieved through mechanical or hydraulic means and plays a critical role in determining coagulation efficiency (Sharghi and Davarpanah, 2022). The coagulation–flocculation process generally proceeds through three sequential stages: rapid dispersion of the coagulant, destabilization of suspended particles through charge neutralization, and subsequent aggregation into larger flocs via particle collisions (Pillai and Thombre, 2023; Sonal and Mishra, 2021; Shammas et al., 2021). Most conventional coagulants are positively charged substances, often polymeric in nature, which interact with negatively charged colloidal particles to induce floc formation and settling (Moud, 2022). Beyond turbidity removal efficiency, the effectiveness of this process is governed by coagulation functional parameters such as coagulation period, collision efficiency, coagulation rate constant, and reaction order, which collectively describe the kinetics and dominant mechanisms of particle aggregation.

Despite the effectiveness of conventional inorganic coagulants such as aluminum sulfate (alum), increasing concern has been raised regarding their long-term environmental and public health implications. Prolonged exposure to alum-treated water has been associated with potential neurological risks, including a possible link to Alzheimer's disease (Koul et al., 2022; Badawi et al., 2023). Additionally, the generation of chemically laden sludge and the persistence of residual metal ions pose environmental challenges. These concerns have stimulated growing interest in natural coagulants derived from plant-based materials, which are generally biodegradable, non-toxic, locally available, and cost-effective (Gautam and Saini, 2020; Nimesha et al., 2022; Benalia et al., 2024). As a result, the exploration of sustainable green coagulants has become a priority in contemporary water treatment research.

Chrysophyllum albidum, commonly known as African star apple, is a fruit-bearing tree belonging to the Sapotaceae family and is indigenous to tropical Africa. The plant is widely recognized for its nutritional, medicinal, and socioeconomic value across West Africa. It is locally referred to as "agbalumo" among the Yoruba, "udara" among the Igbo, and "agwaluma" among the Hausa ethnic group in Nigeria (Ujam et al., 2024). In southern regions of the Benin Republic, it is known as "azongogwe," "azongbobwe," or "azonbebi" (Laurent et al., 2012). Beyond its traditional uses, recent studies have begun to explore the potential of *Chrysophyllum albidum* seeds as a natural coagulant due to their bioactive constituents and surface functional groups capable of enhancing particle destabilization and aggregation.

Although several studies have reported the application of plant-based coagulants for surface water treatment, there remains a notable gap in the literature regarding the coagulation kinetics and functional parameters governing the performance of *Chrysophyllum albidum* seed extracts. In particular, limited information exists on the rate of coagulation, collision efficiency, reaction order, and dominant aggregation mechanisms associated with this natural coagulant. Addressing this gap is essential for understanding the mechanistic basis of its performance and for optimizing its application in water treatment systems. Consequently, the present study evaluates the coagulation functional parameters of *Chrysophyllum albidum* seeds in turbidity removal from surface water, with the objective of analyzing both the coagulation kinetics and the key functional parameters that influence their effectiveness, in view to advancing its development as a safe, low-cost, and environmentally sustainable alternative to conventional chemical coagulants.

Coagulation Kinetics Theory and Model Development

The percentage turbidity removal efficiency is given as

$$E(\%) = \left[\frac{Co - C1}{Co}\right] \times 100 \qquad (1)$$

Where C_0 = initial turbidity in NTU

C_1= residual turbidity in NTU

A function of the particles (count) concentration C, and the intensity of Brownian motion characterized by the diffusivity D, gives the rate of flocculation. In a mono dispersed system toward a particle of radius ‘a’ (taken as the central one), considering the particle diffusion flux on the basis of Fick’s equation gives an expression for the rate of decrease in the particle number in equation 2 (Sun et al., 2019).

$$\frac{dC}{dt} = -KC^{\infty} \qquad (2)$$

Integrating Eq. (2) gives

$$\mathrm{I}n\left(-\frac{dC}{dt}\right) = \mathrm{I}nK + \alpha \mathrm{I}nC \qquad (3)$$

From which K and α can be determined from a plot of $\left(\mathrm{I}n\frac{dC}{dt}\right)$ against $\mathrm{I}nC$.

In eq. (3), K is coagulation rate constant/collision frequency

α = the order of coagulation reaction

C = the concentration of the particles (TSS), mg/l

It has been revealed by Von Smoluchowski (1917) that for the conditions described above,

$$\mathrm{K}_R = 8\pi R' D \qquad (4)$$

Where $R' = 2a$

From Einstein’s equation (Naruka et al. 2021); $D = \mathrm{K}_{\mathrm{B}}\left(\frac{\mathrm{T}}{\mathrm{B}}\right)$ (5)

Where B is the friction factor, T is the absolute temperature (^{0}K) and KB is the Boltzman constant (Molar gas constant per particle). For the simplest case of a smooth spherical particle of radius ‘a’ immersed in a fluid of viscosity (η), B is given by Stoke’s relation (Nwabanne and Obi, 2019) as;

$$B = 6\pi\eta a \qquad (6)$$

Putting Eq. (6) into Eq. (5) gives

$$D = \mathrm{K_B}\left(\frac{\mathrm{T}}{6\pi\eta a}\right) \quad (7)$$

But $R' = 2a$, therefore

$$D = \left(\frac{2\mathrm{K_B T}}{6\pi\eta R'}\right) = \left(\frac{\mathrm{K_B T}}{3\pi\eta R'}\right) \quad (8)$$

Putting eq. (8) into eq. (4), yields

$$\mathrm{K}R = 8\pi R'\left(\frac{\mathrm{K_B T}}{3\pi R'\eta}\right) = \frac{8}{3}\left(\frac{\mathrm{K_B T}}{\eta}\right) \quad (9)$$

But the appropriate value of β for Brownian transport is given by Okey-Onyesolu et al. (2020) as;

$$\beta_{\mathrm{B}R} = \frac{8}{3}\varepsilon_p \frac{\mathrm{K_B T}}{\eta} \quad (10)$$

And $\mathrm{K} = \frac{1}{2}\beta_{\mathrm{B}R}$ (11)

Where β_{BR} is collision factor for Brownian transport

Also, $\beta_{\mathrm{B}R} = \varepsilon_p \mathrm{K}_R$ (12)

According to Obiora-Okafo et al. (2022), it has been shown generally from an empirical standpoint that $1 \le \alpha \le 2$

Putting eq. (9) into eq. (2) when $\alpha = 2$ yields

$$\frac{dC}{dt} = -\frac{8}{3}C^2\left(\frac{\mathrm{K_B T}}{\eta}\right) \quad (13)$$

Using the method of separable variable and integrating eq. (2) within the limits (at t = 0, C = Co at t = t, C = C), yields

$$-\frac{dC}{dC^2} = \mathrm{K}dt \quad (14)$$

Integration eq. (14) gives,

$$\frac{1}{C} = \frac{1}{C_0} + \mathrm{K}t \quad (15)$$

Multiplying both sides of Eq (15) by Co, gives

$$\frac{C_0}{C} = 1 + C_0\mathrm{K}t \quad (16)$$

Making 'C' the subject of the formula, gives

$$C = \frac{C_0}{1 + C_0\mathrm{K}t} = \frac{C_0}{\left[1 + \frac{t}{\frac{1}{C_0\mathrm{K}}}\right]} \quad (17)$$

Let

$$\frac{1}{C_0\mathrm{K}} = \tau \quad (18)$$

Substituting eq. (18) into eq. (17), yields

$$C = \frac{C_0}{1+\frac{t}{\tau}} = \tau \tag{19}$$

When t = τ, eq. (19) becomes

$$C = \frac{C_0}{1+1} = \frac{C_0}{2} \tag{20}$$

Thus, at t = τ, $C = \frac{C_0}{2}$. This quantity is known as the coagulation period, which is defined as time where the initial concentration of particles is halved.

Therefore, as $C_0 \rightarrow 0.5C_0; \tau \rightarrow \tau_{1/2}$

Hence, $\tau_{1/2} = \frac{1}{0.5C_0\mathrm{K}}$ (21)

Where $\tau' = 2\tau$

For Brownian (perikinetic) aggregation at early stages ($t \leq 30$ minutes), Holthof (1996) had stated the generic expression as;

$$\frac{C_{m(t)}}{C_0} = \frac{\left[\frac{t}{2}\left(\frac{1}{\mathrm{K}C_0}\right)\right]^{m-1}}{\left[1+\frac{t}{2}\left(\frac{1}{\mathrm{K}C_0}\right)\right]^{m+1}} \tag{22}$$

Hence, for singlets $(m = 1)$

$$C_1 = C_0\left(\frac{1}{1+\frac{t}{\tau}}\right) \tag{23}$$

For doublets *(m=2)*

$$C_2 = C_0\left(\frac{\frac{t}{\tau'}}{\left(1+\frac{t}{\tau'}\right)^3}\right) \tag{24}$$

For triplets *(m=3)*

$$C_3 = C_0\left(\frac{\left(\frac{t}{\tau'}\right)^2}{\left(1+\frac{t}{\tau'}\right)^4}\right) \tag{25}$$

And the overall concentration of the particles is given by

$$\sum C_m = C_1 + C_2 + C_3 \tag{26}$$

There is however, a reasonable relationship between Turbidity and total suspended solid for the settled effluent. The general form of the relationship is as follows:

$$TSS(mgL^{-1}) = TSS_f \times T \tag{27}$$

Where;
TSS = total suspended solid (mgL^{-1})
TSS_f = a factor used to convert turbidity reading to total suspended solids (Vishali *et al.*, 2022)
T = turbidity (NTU)

Materials and Methods

Seed sample collection

The *Chrysophyllum albidum* seeds used for the study were collected from Ifite in Awka South Local Government Area of Anambra State, Nigeria. The identification of the collected seed samples was done at the Botany Department of the Nnamdi Azikiwe University, Awka, Anambra State.

Water sample collection

Water sample used in this study was collected from River Ezu, located between Ebenebe and Amansea (6°15′ N, 7°08′ E), within Awka North Local Government Area, Anambra State, Nigeria. Prior to sampling, 1-L polyethylene bottles were thoroughly washed and sun-dried. On the day of collection, each bottle was rinsed with the river water, filled, properly labeled, and transported to the laboratory in ice-packed coolers for subsequent analysis.

Extraction

The seeds were cleaned, and air dried at room temperature for five days, after which they were de-shelled and the total seed kernels which weighed 1 kg were grinded using an electric grinding machine. Solvent extraction was performed using standard method described by Hayuningtyas et al. (2024). In this procedure, the ground seed sample was transferred into a clean extraction thimble, after which 700 mL of ethanol was added. The mixture could stand to facilitate solvent–solute interaction and was subsequently filtered through a muslin cloth. The resulting filtrate was collected and designated as the crude extract for further analysis. The extract was stored in the refrigerator until required for testing.

Coagulation studies

The pH was observed using an electronic pH meter (Hanna 8320). It was calibrated using distilled water before use. 50ml of water sample was put into a glass beaker and the instrument was immersed in it from the top through the node. The reading was taken directly from the display after it stabilized. The coagulation study was done using a conventional jar test apparatus. In this method, six 1 Litre beakers containing raw water were arranged on the apparatus. The water samples were mixed homogeneously before being apportioned into the beakers each containing 400mL of suspension. Then the samples were measured for turbidity and initial concentration. Varying doses of extract (0.8, 1.0, 1.8, 1.8, 2.0 and 2.2 g/L) were added to each beaker, before stirring began, then the beakers were agitated at varying mixing time and speed, the first being the rapid for 3 minutes at 350 revolutions per minute, and the second being the slow mixing for 20 minutes at 30 revolutions per minute following immediately. The reasons for the rapid and slow mixing are for the destabilization of the particles and formation of flocs respectively. After this period of agitation, the suspension was allowed to settle by gravity and the supernatants were collected at different settling times (10, 20, 30, 40, and 50 minutes). At the end, these withdrawn supernatants were tested for turbidity which represents the final concentration.

Results and Discussion

Effect of pH and coagulation time on turbidity removal

The analyses of the Ezu river water employed in this work showed that its initial turbidity and pH was 249NTU and 3.1 respectively. The level of pH in water has been widely recognized as an important factor that affects the effectiveness of the coagulation process. This is because each coagulant works best within a specific pH range, where it can properly interact with suspended particles in the water (Sheng *et al.,* 2023). Based on this understanding, this study adopted a pH range between 3 and 9 to investigate the performance of *Chrysophyllum albidum* seed extract as a natural coagulant in treating turbid surface water. Results of these experiments, particularly on how the pH of the treated water (effluent) influenced turbidity removal, are shown in Figure 1. During the tests, the settling time (a period allowed for the particles to settle after treatment) was varied between 10 and 50 minutes. The findings clearly showed that the most effective settling time for this coagulant was 50 minutes. At this point, the turbidity of the treated water from the Ezu River was reduced to 62 Nephelometric Turbidity Units (NTU), resulting in a maximum turbidity removal efficiency of over 75 percent. These results indicate that longer settling times allowed more particles to settle out of the water, improving clarity. This observation agrees with the findings of Alnawajha et al. (2024), who reported that increasing the detention time improved turbidity removal when using water extracted *Leucaena leucocephala* seeds as a coagulant for turbid water treatment. In addition, the gradual decrease in turbidity over time suggests that the number of particles available for coagulation reduced as the process continued. This pattern also implies that turbidity reduction depends greatly on the number of particles in the water and that these particles tend to combine into larger ones as the reaction progresses (Yuan *et al.,* 2025). This explains why longer settling periods often lead to better water clarity.

Effect of coagulant dose on turbidity removal efficiency

As shown in Figure 2, the influence of coagulant dosage was evaluated while maintaining constant effluent pH and initial concentration. The optimum coagulant dose was established to be 1.0g/L. It can also be seen that the residual turbidity at this point was 62NTU with a turbidity removal efficiency of 75.1% when the already estimated optimum pH, coagulation time and surface water initial concentration were applied. These results are in consonance with the work of Bazzo et al. (2022) who reported about 80% turbidity removal efficiency with *Ceratonia Siliqua* L. (carob) seed extract on surface water with initial turbidity of 83.7 NTU. The results also shows that increasing the coagulant dose beyond 1.0g/L resulted in a corresponding increase in the residual turbidity of the water at all times, thus reducing the respective turbidity removal efficiencies.

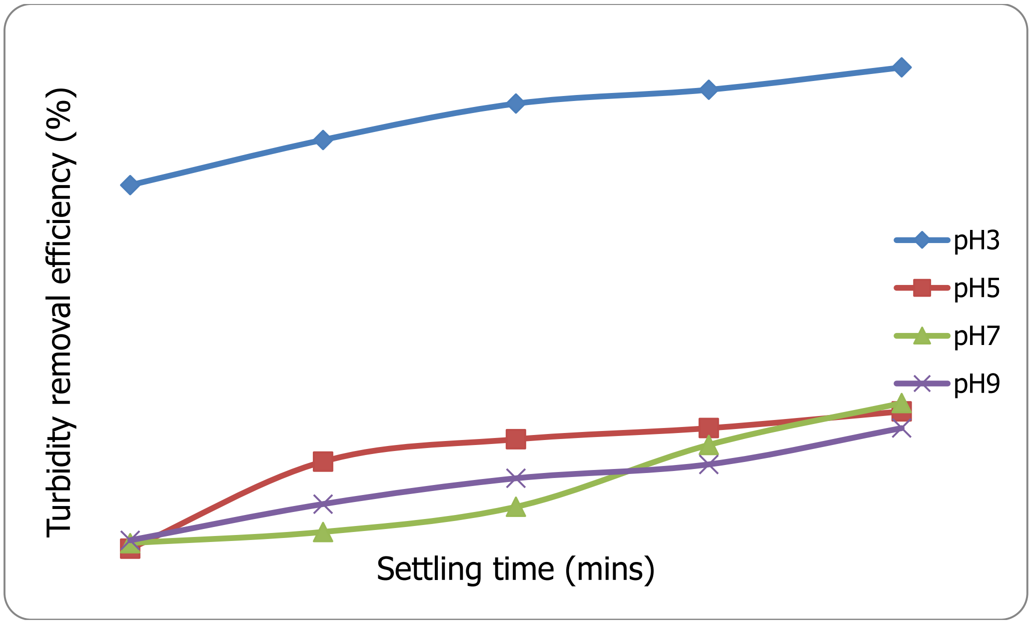

Figure 1: Effect of pH on turbidity removal

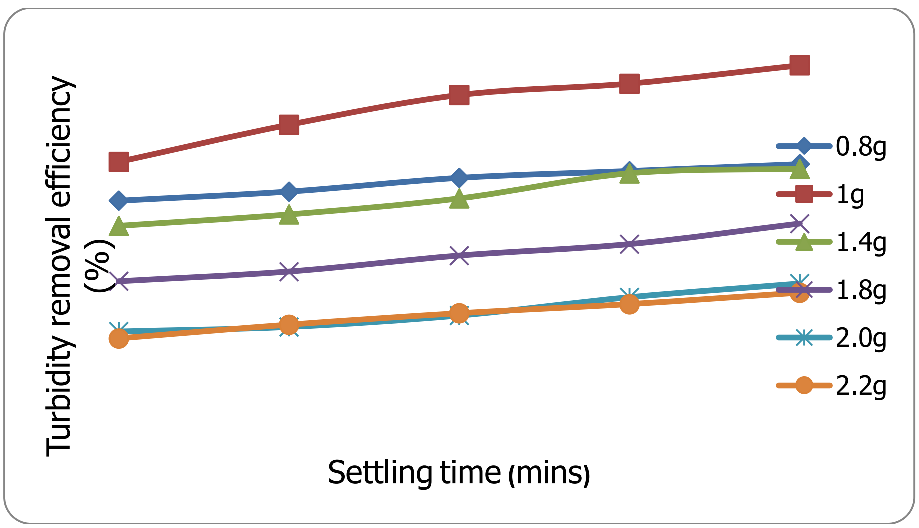

Figure 2: Effect of coagulant dosage on Turbidity removal

It can be seen that the trend for the turbidity removal efficiency was consistent at all dosages, which is in agreement with the report of (Owodunni *et al.*, 2024).

Coagulation kinetic parameters

To effectively study the coagulation kinetics, the results gotten for the turbidity of sample in NTU, with the use of the turbidimeter were first converted to the respective concentrations (mg/L). A summary of the coag-flocculation functional parameters at optimum conditions with varying coagulant dose as obtained in this study is shown in Table 1. In this study, the regression coefficient (R^2) was employed to measure the level of accuracy of fit of the experimental data, and the result presented in Table 1. In the scenario where α = 1(as presented in table 1), it is a diversion from the expectations in theory, but it is however, in agreement with the evidence from empirical studies

(Alazaiza *et al.*, 2025). In general, the value of K is inversely proportional to the value of α. Hence, with a lower K value, a higher value of α can be obtained (Iloamaeke *et al.*, 2024). Consequently, the values of K and α obtained in this study agrees with recent works involving Brownian Coagulation (Adimachukwu *et al.*, 2025). It can be seen from Table 1 that the value of K is almost less sensitive to the variation in the *Chrysophyllum albidum* seed coagulant dosage. This however shows that coag-flocculation is more sensitive to changes in effluent pH than that of coagulant dosages (Okey-Onyesolu *et al.*, 2022). Also, the variation in K_R value as presented in table 1 can be seen to be negligible. This trend can be attributed to the fact that K_R is a function of room temperature (T), and the viscosity of the effluent medium, both of which did not vary greatly throughout the course of the experiment which was conducted under room temperature. In the event of such negligible variations, ε_p confirms its direct relationship with β_{BR}, which is in consonant with previous works (Nweke *et al.*, 2022).

In line with these facts, it can be seen from the result in Table 1 that the best coag-flocculation is recorded at dosage 1.0g/L. This is supported by the highest value of K= $7.4733\text{x}10^{-4}\text{m}^3$/kg.S, and the lowest value of τ' (ie $\tau_{1/2}$) = 4.58 Secs. However, the high value of $\tau_{1/2}$ = 307.12 Secs., with a corresponding low value of K=$1.1129\text{x}10^{-5}\text{S}^{-1}$ indicates aversion in the system (Adimachukwu *et al.*, 2025). Finally, the coag-flocculation reaction rate equations are evaluated as a dependent function of K, C and α, and is presented in Table 1.

Summary: The values of K_R, β_{BR}, ε_p, τ and $\tau_{1/2}$ were calculated from equations 9, 10, 12, 18, and 21 respectively.

Table 1: Coag-flocculation functional parameters for varying coagulant dose at optimal pH and settling time

Parameter	**Dosage (g/L)**					
	0.8	**1.0**	**1.4**	**1.8**	**2**	**2.2**
α	1	2	2	2	2	**2**
R^2	0.7012	0.8474	0.7579	0.6805	0.7006	0.7772
K	$1.11\text{x}10^{-5}\text{S}^{-1}$	$7.47\text{x}10^{-4}\text{m}^3$kg.S	$4.22\text{x}10^{-4}\text{m}^3$kg.S	$5.26\text{x}10^{-4}\text{S}^{-1}$	$6.04\text{x}10^{-4}\text{m}^3$kg.S	$2.77\text{x}10^{-4}\text{m}^3$kg.S
β_{BR}	$2.23\text{x}10^{-5}\text{S}^{-1}$	$1.49\text{x}10^{-3}\text{m}^3$kg.S	$8.44\text{x}10^{-4}\text{m}^3$kg.S	$1.05\text{x}10^{-3}\text{S}^{-1}$	$1.21\text{x}10^{-3}\text{m}^3$kg.S	$5.54\text{x}10^{-4}\text{m}^3$kg.S
K_R (m^3/S)	$1.18\text{x}10^{-17}$	$1.05\text{x}10^{-17}$	$1.13\text{x}10^{-17}$	$1.10\text{x}10^{-17}$	$1.08\text{x}10^{-17}$	$1.16\text{x}10^{-17}$
ε_p	$1.86\text{x}10^{12}\text{m}^{-3}$	$1.42\text{x}10^{14}\text{kg}^{-1}$	$7.44\text{x}10^{13}\text{kg}^{-1}$	$9.60\text{x}10^{13}\text{m}^{-3}$	$1.11\text{x}10^{14}\text{kg}^{-1}$	$4.85\text{x}10^{13}\text{kg}^{-1}$
τ (secs)	153.56	2.29	4.06	3.25	2.83	6.17
τ' (secs)	307.12	4.58	8.1	6.5	5.66	12.34
$-r_A$	$1.1129\text{x}10^{-5}$C	$7.4733\text{X}10^{-4}\text{C}^2$	$4.2226\text{X}10^{-4}\text{C}^2$	$5.2611\text{X}10^{-4}$C	$6.0396\text{X}10^{-4}\text{C}^2$	$2.7686\text{X}10^{-4}\text{C}^2$

Nomenclature of parameters in Table 1

K: αth order coag-flocculation rate constant

β_{BR}: Collision factor for Brownian Transport

ε_p: Collision Efficiency

$\tau_{1/2}$: Coagulation Period/ Half life

C: Concentration of particles

R^2: Coefficient of Determination

α: Coag-flocculation reaction order

-rA: Coag-flocculation reaction rate

Particle distribution plots

This was achieved by determining the coag-flocculation reaction constants (K) for the plot of $l_n(-{}^{dC}/_{dt})$ against (l_nC) for the respective coagulant dosage. Then using the K value and the known C_O, the respective values of $\tau_{1/2}$ were obtained from equations 18 and 21. The values of C_1, C_2, C_3, and C_T were obtained using equations 23, 24, 25, and 26 respectively. Then a graph of concentration against time (particle distribution plots), were plotted for the respective coagulant dosages, and are presented in figures 3 to 8.

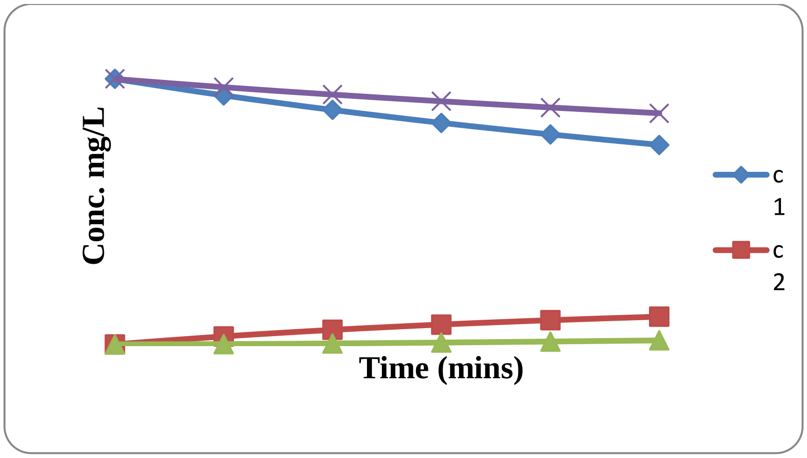

Figure 3: Particle distribution plot for 0.8g/l

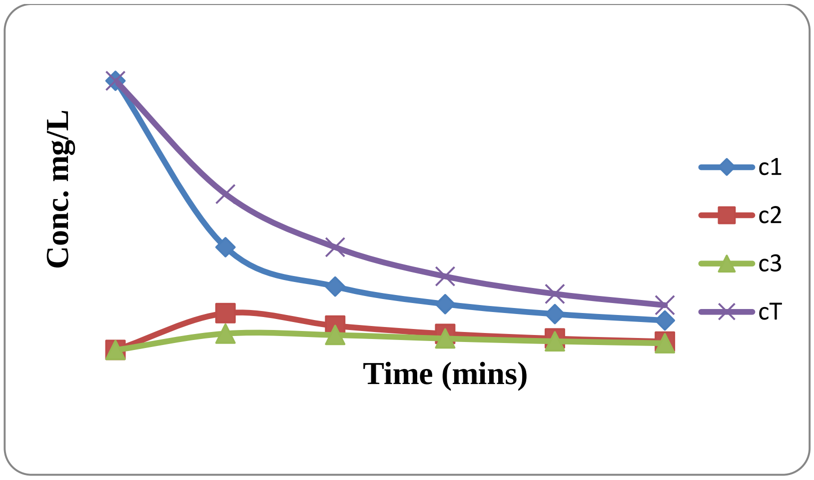

Figure 4: Particle distribution plot for 1.0g/l

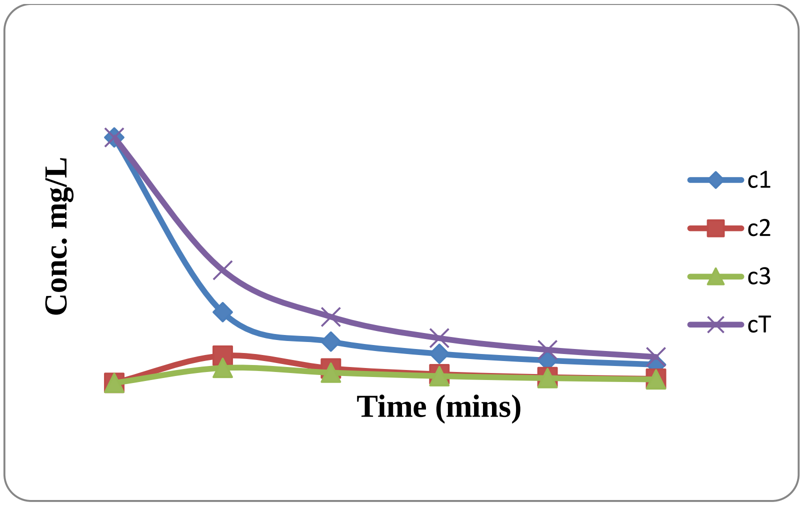

Figure 5: Particle distribution plot for 1.4g/l

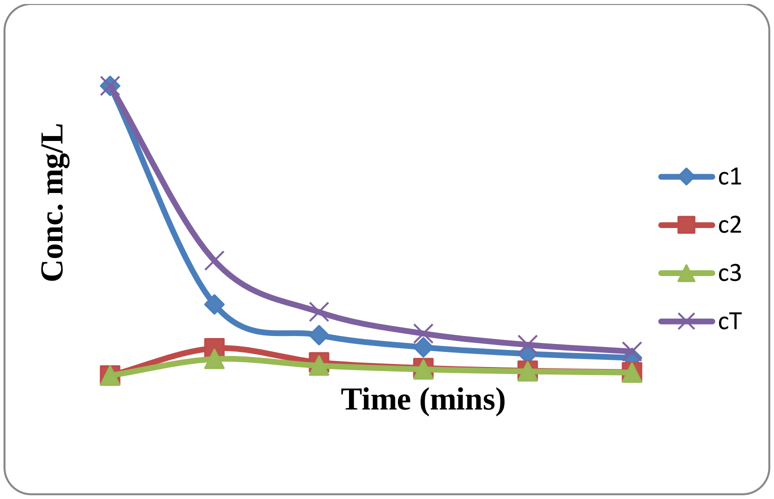

Figure 6: Particle distribution plot for 1.8g/l

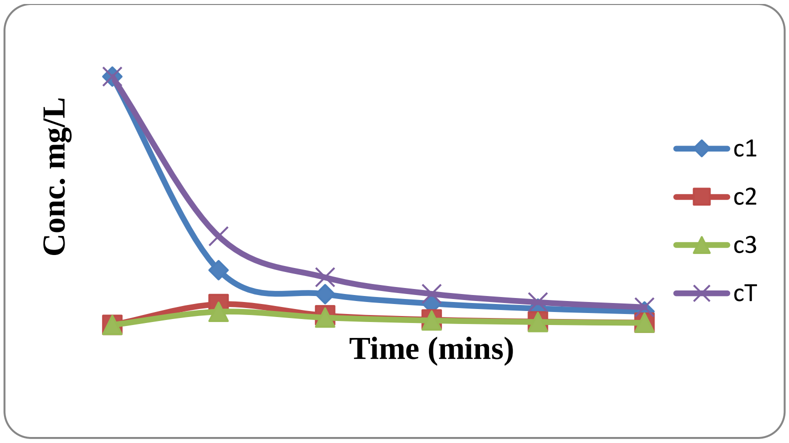

Figure 7: Particle distribution plot for 2.0g/l

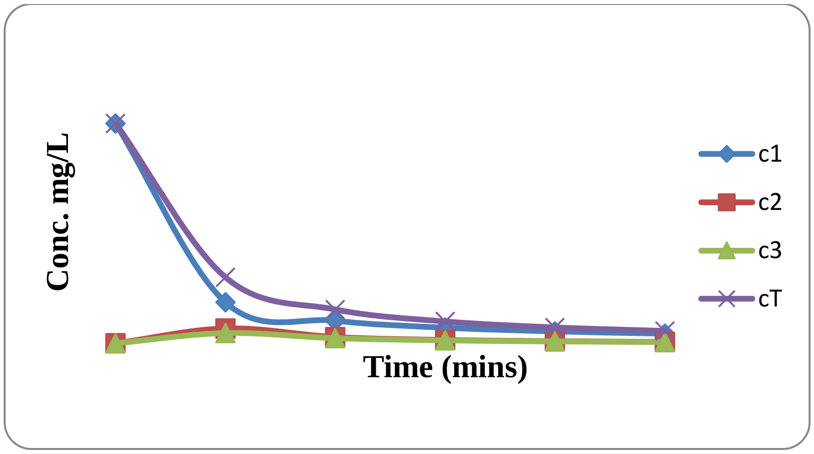

Figure 8: Particle distribution plot for 2.2g/l

The particle distribution plots presented in Figures 3–8 describe the temporal evolution of particle size classes (C_1, C_2, C_3, and C_T) at different dosages of *Chrysophyllum albidum* seed coagulant and provide direct insight into the underlying coagulation kinetics. The predominance of second-order reaction behavior (>83%) indicates that particle removal is governed mainly by inter-particle collisions, consistent with classical perikinetic and orthokinetic coagulation theory. At the lowest dosage of 0.8 g/L (Figure 3), the particle distribution curves show a relatively slow decline in the concentration of primary particles (C_1) and total particle concentration (C_T), accompanied by a modest increase in intermediate aggregates (C_2) and larger flocs (C_3). This trend reflects a comparatively low coagulation rate constant, implying limited collision efficiency due to insufficient active sites for effective particle destabilization and bridging (Patchaiyappan and Devipriya, 2022). Under these conditions, the second-order kinetics suggest that although collisions occur, their frequency and effectiveness are constrained by inadequate coagulant availability.

In contrast, the particle distribution at 1.0 g/L (Figure 4) demonstrates a pronounced and systematic reduction in C_1 and C_T with time, coupled with a sustained increase in C_3. This behaviour corresponds to the highest observed coagulation rate constant among the tested dosages and signifies optimal collision efficiency. The strong second-order kinetic response at this dosage confirms that particle aggregation is dominated by particle–particle interactions, where destabilized colloids rapidly collide and form larger, settleable flocs. The consistency between the kinetic parameters and the particle redistribution trends indicates that sweep flocculation and particle linking mechanisms are maximized at this dosage. As the dosage increases beyond the optimum (1.4–2.2 g/L; Figures 5–8), the particle distribution plots reveal a deviation from the efficient aggregation pattern observed at 1.0 g/L. Although initial reductions in C_1 are still evident, the rate of decline becomes less pronounced, and the growth of C_3 flocs is comparatively subdued. This behaviour is reflected in reduced effective coagulation rate constants, despite the persistence of second-order reaction characteristics. The results suggest that overdosing leads to partial restabilization of particles or excessive coating of colloidal surfaces, which diminishes effective collision efficiency even though collision frequency remains high. The trend as depicted in Figures 3 to 8 shows that, the number of the singlet particles (C_1), decreased in a more rapid state than that of the sum particles (C_T), which is in line with the report of (Patchaiyappan and Devipriya, 2022. This reveals that at the early stage, the coag-flocculation process is not only affected by the destabilization of the colloids, but by rapid sweep as well (Nimesha *et al.*, 2022). The range of results in the present study corroborates the findings in previous studies (Rasheed et al., 2023; Kitheka et al., 2022; Nhut et al., 2021)

The close agreement between particle distribution trends and coagulation kinetic parameters demonstrates that the clarification process using *Chrysophyllum albidum* seed extract is strongly governed by second-order kinetics. The optimal dosage of 1.0 g/L achieves the highest coagulation rate constant and most favorable redistribution of particles from fine colloids to larger flocs, confirming efficient particle destabilization, collision, and aggregation. At sub-optimal and supra-optimal dosages, reduced rate constants and altered particle distribution patterns highlight the sensitivity of the coagulation process to coagulant concentration. These findings reinforce the suitability of *Chrysophyllum albidum* seed extract as an effective green coagulant and provide a kinetic basis for dosage optimization in surface water treatment applications.

Conclusion

The performance of Udara (*Chrysophyllum albidum*) seed extracts as a potential green coagulant has been established. The process was able to remove over 75% turbidity from the surface water. However, the results of the jar test experiments were sensitive to pH and dosage. A dosage of 1.0 g/L of *Chrysophyllum albidum* seed coagulant and a pH of 3 were found to be the optimal conditions for surface water clarification. The optimal acidic pH indicates that coagulation efficiency is enhanced under conditions where the surface charge of suspended particles is effectively neutralized, thereby reducing electrostatic repulsion and promoting particle destabilization. At low pH, protonation of functional groups present in the seed extract likely increases its positive charge density, improving adsorption, particle bridging, and sweep flocculation mechanisms. The experimental results of low coagulation period, high collision efficiency, and high coagulation rate constant obtained for the functional parameters are satisfactory and consistent with previous studies. Coag–flocculation reaction order was over 83% second order, indicating that the reaction rate is proportional to the square of particle concentration. These findings consolidate that the coagulation process of *Chrysophyllum albidum* seed coagulant relies predominantly on particle linking and sweep flocculation mechanisms. Although the requirement for acidic conditions may necessitate pH adjustment in practical applications, the high turbidity removal efficiency achieved demonstrates that *Chrysophyllum albidum* seed extract is a promising and effective green coagulant for surface water treatment.

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