



Iranian Research Organization
for Science and Technology
(IROST)



Optimization of coagulation–flocculation pretreatment of palm oil mill effluent using cassava peel as a natural coagulant

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ARTICLE INFO

Document Type:
Research Paper

Article history:
Received 15 March 2025
Received in revised form
12 August 2026
Accepted 20 August 2026

Keywords:
Cassava peel
Coagulation–flocculation
Optimization
Palm oil mill effluent
Response surface methodology

ABSTRACT

This study aims to optimize the coagulation–flocculation pretreatment of palm oil mill effluent (POME) using cassava peel as a natural coagulant. The raw effluent exhibited a high pollution load, with a chemical oxygen demand (COD) of 105200 mgO₂/L and a turbidity of 21450 NTU. Optimization experiments were conducted using response surface methodology (RSM) based on a Box–Behnken design to evaluate the effects of coagulant dosage, pH, and stabilization time. The optimal conditions were determined as pH 9, a coagulant dose of approximately 3000 mg/L, and a stabilization time of 21.11 min. Under these conditions, removal efficiencies reached 97.09% for turbidity and 96.25% for COD. These results indicate that using cassava peel enables the valorization of agro-industrial waste while reducing reliance on chemical coagulants.

1. Introduction

Agro-industrial effluents are a major source of environmental pollution due to their high organic load and their impact on aquatic ecosystems. Among them, palm oil mill effluent (POME) is recognized as particularly problematic due to its high organic content, elevated turbidity associated with suspended particles, acidic nature, and high temperature [1,2]. In Côte d'Ivoire, the rapid expansion of the palm oil industry has led to a significant increase in POME generation, posing serious environmental challenges. In the absence of adequate treatment, its discharge can result in

dissolved oxygen depletion, eutrophication, and degradation of aquatic ecosystems [3]. In addition, the decomposition of organic matter generates strong odors and may pose health risks to nearby populations. To address these issues, various treatment approaches have been developed for POME, including biological processes (anaerobic or facultative digestion), physical treatments such as sedimentation and filtration, and physicochemical methods [4,5]. Advanced technologies, such as adsorption and membrane processes (ultrafiltration and nanofiltration), have also been explored to improve treatment efficiency [6,7]. In the context of increasingly stringent environmental

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DOI: 10.22104/aet.2026.7461.2076

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regulations, the development of more efficient and sustainable treatment processes has become essential to ensure compliance with discharge standards. Among these approaches, coagulation–flocculation is considered an effective pretreatment step due to its short treatment time, operational simplicity, and relatively low cost [8,9]. This process plays a key role in removing major pollutants from POME, particularly suspended solids, turbidity, and chemical oxygen demand (COD). Coagulation destabilizes colloidal particles by reducing electrostatic repulsion forces, while flocculation promotes their aggregation into larger and settleable flocs. The efficiency of this process strongly depends on operating conditions, especially pH, which influences particle destabilization mechanisms and floc formation [10,11]. However, conventional chemical coagulants, particularly aluminum and iron salts, present several limitations, including high sludge production, potential residual toxicity, and relatively high operational costs associated with chemical consumption and sludge management. These limitations have led to increased interest in developing sustainable alternatives based on renewable natural resources, particularly plant-based biocoagulants [8,12]. Various materials, such as *Moringa oleifera*, rice starch, and different agro-industrial residues, have demonstrated promising performance in coagulation–flocculation processes [13–15].

Among these materials, cassava peel represents an abundant agro-industrial residue in Côte d'Ivoire, where cassava is a major staple crop. In addition to its low cost, this material offers significant environmental advantages. It is widely available, non-toxic, and requires minimal processing, making it a promising sustainable alternative to conventional chemical coagulants. Its richness in polysaccharides and functional groups (hydroxyl and carboxyl groups) enhances particle destabilization through adsorption and bridging mechanisms [16–18]. Furthermore, its valorization requires minimal processing, reinforcing its potential as an economical and sustainable alternative for wastewater treatment, in line with circular economy principles [19]. Despite these advances, the application of cassava peel for POME treatment remains insufficiently explored,

particularly in terms of optimizing operating conditions and simultaneously evaluating turbidity and COD removal. Therefore, the objective of this study is to evaluate the effectiveness of cassava peel as a natural biocoagulant for the pretreatment of POME. RSM, based on a Box–Behnken design, was applied to optimize the main operating parameters, namely coagulant dosage, initial pH, and stabilization time, with respect to turbidity and COD removal efficiencies. This study also aims to propose an efficient, economical, and sustainable treatment approach for agro-industrial effluents in tropical regions.

2. Materials and methods

2.1. POME sampling

The POME samples were collected from a production facility located in Divo, central-western Côte d'Ivoire. The samples were collected in clean plastic containers and immediately transported to the laboratory under refrigerated conditions. Upon arrival, they were stored at 4 °C to minimize biological and physicochemical changes prior to analysis and treatment experiments. The main physicochemical characteristics of the raw effluent were determined immediately after sampling to assess its pollution load.

2.2. Preparation of the coagulant

Cassava peels, used as a natural biocoagulant, were collected from a local attiéké production unit in Daloa (Côte d'Ivoire). The samples were thoroughly washed with tap water followed by distilled water to remove surface impurities. After washing, the peels were dried in a ventilated oven at 105 °C for 5 h until constant weight was achieved. The dried material was then ground and sieved to obtain a fine powder with an average particle size of 75 µm. The resulting powder was stored in airtight containers at room temperature until use [17,20].

2.3. Coagulation–flocculation process

Before each experiment, the POME samples were allowed to reach room temperature (25 ± 2 °C) and gently homogenized. A volume of 400 mL of POME was transferred into a 600 mL beaker for each experiment. The pH was adjusted to the desired value (5–9) using a 90 g/L lime solution. The

coagulant was then added according to the experimental design. The mixture was rapidly stirred at 150 rpm for 3 min using an IKA C-MAG HS 7 magnetic stirrer to ensure proper dispersion of the coagulant, followed by slow mixing at 30 rpm for 30 min to promote floc formation. These conditions were selected to ensure effective dispersion and optimal floc formation, in accordance with common practices reported in the literature [21].

After mixing, the samples were allowed to settle for 20–30 min. Approximately 10 mL of supernatant was then collected at about 2 cm below the surface for analysis.

COD was measured using a HACH DR3900 spectrophotometer based on the dichromate method, while turbidity was determined using a HACH 2100Q turbidimeter. The pH was measured using a HANNA HI2211 pH meter. All analyses were performed in triplicate, and the results are expressed as mean values. Instruments were calibrated prior to each measurement series, and analyses were carried out according to standard methods [22]. Removal efficiency was calculated using the following equation (1):

$$Y(\%) = \frac{(C_i - C_f)}{C_i} \times 100 \quad (1)$$

where Y is the removal efficiency (%), and C_i and C_f are the initial and residual concentrations of the COD parameters and turbidity, respectively.

2.4. Experimental design and statistical analysis

RSM based on a Box–Behnken design was used to optimize the coagulation–flocculation process. Three independent variables were considered: coagulant dose (X_1), initial pH (X_2), and settling time (X_3). The ranges of these variables were defined based on preliminary experiments and literature data in order to cover representative operating conditions [21,23]. The coded levels and natural values of the factors used in this statistical analysis are presented in Table 1.

Table 1. Independent variables and experimental levels.

Independent variables	Code units	Coded level		
		-1	0	1
Dosage (mg/L)	X_1	3000	4500	6000
pH	X_2	5	7	9
Stabilization time (min)	X_3	20	25	30

The experimental design consisted of 15 runs, including replicates at the center point to estimate experimental error and evaluate reproducibility. The responses studied were turbidity and COD removal efficiencies. Experimental data were analyzed using Minitab software (version 19). The relationship between the independent variables and the response is described by the quadratic model given in Equation 2:

$$y = b_0 + \sum_{i=1}^k b_i X_i + \sum_{i=1}^k b_{ii} X_i^2 + \sum_{i=1}^{i < j} \sum_j b_{ij} X_i X_j \quad (2)$$

where y is the predicted response (turbidity or COD removal efficiency), b_0 is the intercept term, b_i are the linear coefficients, b_{ii} are the quadratic coefficients, b_{ij} are the interaction coefficients, and X_i and X_j represent the coded independent variables.

Model significance was evaluated at a 95% confidence level ($p < 0.05$) using ANOVA. Model adequacy was assessed using the coefficient of determination (R^2) and adjusted R^2 , while statistical validity was verified using the Fisher test [24,25]. The predictive accuracy of the model was evaluated using the coefficient of variation, as defined in Equation 3:

$$CV = \frac{1}{n} \left[\sum_{i=1}^n \left| \frac{ER_{exp} - ER_{cal}}{ER_{exp}} \right| \right] \times 100 \quad (3)$$

where n is the number of experiments, and ER_{exp} and ER_{cal} represent the experimental and predicted removal efficiencies, respectively. A model is considered satisfactory when the CV is lower than 5% [26]. Optimal conditions were determined from response surface plots and contour plots using the desirability function.

3. Results and discussion

3.1. Characterization of palm oil effluents

The physicochemical characteristics of the raw POME are presented in Table 2. The effluent exhibited an acidic pH (4.2 ± 0.03) and a high temperature (80.7 ± 0.1 °C), which are typical of freshly generated POME. This acidity is generally attributed to the formation of volatile fatty acids during the degradation of organic matter, while the elevated temperature results from sterilization

and extraction processes used in palm oil mills [1,27].

Very high turbidity (21450 ± 30 NTU) and suspended solids (76110 ± 38 mg/L) were observed, indicating a high concentration of colloidal particles, oil residues, and plant fibers. The stability of these particles limits their natural settling, which justifies the application of coagulation–flocculation as a pretreatment step to enhance particle destabilization and aggregation [28,29]. The organic load was particularly high, as indicated by COD (105200 ± 15 mgO₂/L) and BOD₅ ($50\,580 \pm 10$ mgO₂/L) values. The BOD₅/COD ratio was approximately 0.48, indicating a significant biodegradable fraction and suggesting the potential for complementary biological treatment [2,4]. Overall, these results confirm the highly polluted nature of the studied POME and highlight the necessity of implementing an efficient pretreatment prior to any further treatment or environmental discharge.

3.2. Optimization using response surface methodology and Box–Behnken design

3.2.1. Regression analysis and model fitting

Preliminary experiments were conducted to evaluate the influence of the main operating parameters involved in the coagulation–flocculation treatment of POME. Turbidity and COD were considered as response variables due to their relevance in representing colloidal and organic pollution removal during the coagulation–flocculation process. The effects of coagulant dose (X_1), initial pH (X_2), and settling time (X_3) on removal efficiencies were investigated using RSM. A Box–Behnken experimental design consisting of 15

runs, including replicates at the center point, was applied, as presented in Table 3. The results showed that COD removal efficiency varied from 15.97 to 85.94%, while turbidity removal ranged from 75.57 to 96.20%, indicating a strong influence of the operating parameters on process performance.

The highest removal efficiencies were obtained under alkaline conditions, particularly at pH 9, highlighting the dominant role of pH in particle destabilization and floc formation.

A multiple regression analysis was performed to establish the relationship between the responses and the operating variables using a second-order polynomial model.

The quadratic models describing turbidity and COD removal efficiencies are given in Equations 4 and 5, respectively.

$$\begin{aligned} \text{Turbidity} = & 86,79 - 0,729 X_1 + 2,971 X_2 \\ & - 1,620 X_3 + 0,45 X_1^2 + 5,84 X_2^2 \\ & - 5,15 X_3^2 - 0,65 X_1 X_2 \\ & + 5,20 X_1 X_3 + 1,13 X_2 X_3 \end{aligned} \quad (4)$$

$$\begin{aligned} \text{COD} = & 46,96 - 2,26 X_1 + 11,63 X_2 - 2,92 X_3 \\ & + 6,05 X_1^2 + 17,54 X_2^2 \\ & - 13,80 X_3^2 - 1,51 X_1 X_2 \\ & + 20,70 X_1 X_3 + 2,14 X_2 X_3 \end{aligned} \quad (5)$$

where X_1 , X_2 , and X_3 represent the coded values of coagulant dose, initial pH, and settling time, respectively. The linear coefficients represent the individual effects of the variables, while the quadratic and interaction terms describe curvature effects and interactions between variables. Positive coefficients indicate a synergistic effect, whereas negative coefficients indicate antagonistic interactions [15]. The statistical significance and adequacy of the models were evaluated using ANOVA [30–32], as summarized in Tables 4 and 5.

Table 2. Physico-chemical characterization of POME samples.

Parameter	Measured value	Discharge standard*
pH	4.2 ± 0.03	5–9
Temperature (°C)	80.7 ± 0.1	< 40
Electrical conductivity (µS/cm)	10010 ± 9.2	–
TSS (mg/L)	$76\,110 \pm 38$	< 50
Turbidity (NTU)	$21\,450 \pm 30$	–
TDS (mg/L)	4260 ± 7	–
COD (mgO ₂ /L)	$105\,200 \pm 15$	< 500
BOD ₅ (mgO ₂ /L)	$50\,580 \pm 10$	< 100
Oil and grease (mg/L)	8000 ± 30	< 50

Note: Values are expressed as mean $\pm$ standard deviation ($n = 3$). *Discharge standards are provided for comparison based on international guidelines (DOE Malaysia, WHO).

Table 3. Results of COD and turbidity removal using the Box-Behnken design.

N°	Factors			Responses	
	Dosage (mg/L) X_1	pH X_2	Stabilization time (min) X_3	Turbidity removal (%)	COD removal (%)
1	3000	5	25	87.29	51.90
2	6000	5	25	91.21	63.40
3	3000	9	25	95.19	79.66
4	6000	9	25	96.20	85.94
5	3000	7	20	93.22	74.81
6	6000	7	20	77.18	15.97
7	3000	7	30	75.57	20.44
8	6000	7	30	80.35	44.30
9	4500	5	20	85.13	40.97
10	4500	9	20	88.56	58.65
11	4500	5	30	84.11	37.93
12	4500	9	30	91.07	63.87
13	4500	7	25	83.61	42.59
14	4500	7	25	86.62	42.39
15	4500	7	25	88.63	54.19

Table 4. ANOVA results for turbidity removal.

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	907.95	100.883	12.02	0.000
Linear	3	191.75	63.916	7.62	0.001
X_1	1	8.51	8.514	1.01	0.326
X_2	1	141.22	141.224	16.83	0.001
X_3	1	42.01	42.009	5.01	0.037
Square	3	485.90	161.966	19.30	0.000
X_1^2	1	1.47	1.470	0.18	0.680
X_2^2	1	251.67	251.669	29.99	0.000
X_3^2	1	196.01	196.013	23.36	0.000
2-factor interaction	3	230.30	76.768	9.15	0.001
$X_1 \times X_2$	1	3.40	3.398	0.40	0.532
$X_1 \times X_3$	1	216.66	216.659	25.82	0.000
$X_2 \times X_3$	1	10.25	10.248	1.22	0.282
Error	20	167.83	8.392		
Lack of fit	3	135.74	45.247	23.97	0.000
Pure error	17	32.09	1.888		
Total	29	1075.78			

The models were found to be statistically significant ($p < 0.05$), with Fisher values of 12.02 for turbidity removal and 20.89 for COD removal.

For turbidity removal (Table 4), the initial pH (X_2) was identified as the most influential parameter ($F = 16.83$, $p < 0.05$), followed by the settling time (X_3). The quadratic terms X_2^2 and X_3^2 were also significant, confirming the non-linear behavior of the process and the existence of optimal conditions. In addition, the interaction between coagulant dose and settling time ($X_1 \times X_3$) had a significant effect on clarification performance. For COD removal (Table 5), pH remained the dominant factor, with the highest Fisher value ($F = 40.31$, $p <$

0.05). The significant quadratic terms (X_1^2 , X_2^2 , and X_3^2) indicate a non-linear relationship between the variables and the removal efficiency. The interaction between coagulant dose and settling time ($X_1 \times X_3$) was also highly significant, highlighting the importance of the combined effect of these parameters in the removal of organic matter.

The coefficients of determination were $R^2 = 0.8440$ and adjusted $R^2 = 0.7738$ for turbidity removal, and $R^2 = 0.9038$ and adjusted $R^2 = 0.8606$ for COD removal, indicating good agreement between experimental and predicted values. In general, R^2 values above 0.80 confirm the satisfactory predictive ability of the model [33].

Although the lack of fit was statistically significant ($p < 0.05$), the model was considered acceptable for describing the process and predicting responses, as supported by its high R^2 values and low deviations between experimental and predicted results. This behavior may be attributed to the complex and heterogeneous nature of POME [33]. Similar behavior has been reported in response surface methodology studies applied to complex wastewater systems [34,35]. Furthermore, the coefficient of variation (CV) remained low, indicating good experimental precision and limited data dispersion. The average deviations between experimental and predicted values were 2.18% for turbidity and 0.58% for COD, confirming the reliability of the developed models. These values are well below the commonly accepted threshold of 5%, indicating satisfactory model reproducibility.

3.2.2. Effects of process variables on removal efficiency

The model equations were used to generate contour plots and three-dimensional response surface curves, providing a better visualization of the effects of the operating parameters on turbidity and COD removal efficiencies during the coagulation–flocculation process.

Effect of coagulant dose and initial pH

Figures 1 and 2 illustrate the combined effects of coagulant dose (X_1) and initial pH (X_2) on turbidity and COD removal, respectively, at a fixed settling time of 25 min.

An increase in pH led to a significant improvement in removal efficiencies, with optimal conditions observed around pH 9 and coagulant doses ranging from 3000 to 6000 mg/L.

Under these conditions, turbidity removal exceeded 96%, while COD removal reached approximately 80%. This confirms the dominant influence of pH, as also indicated by the ANOVA results (Tables 4 and 5). In alkaline conditions, the reduction of electrostatic repulsion enhances particle destabilization and aggregation. The active compounds present in cassava peel coagulant interact more effectively with suspended particles, promoting the formation of larger and denser flocs. Beyond the optimal region, excessive coagulant dosage resulted in a decrease in removal efficiency. This behavior can be attributed to colloidal restabilization or saturation of active sites, which limits floc formation. These observations are consistent with classical coagulation–flocculation mechanisms reported in the literature [13].

Table 5. ANOVA results for COD removal.

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	10090.4	1121.15	20.89	0.000
Linear	3	2382.2	794.06	14.79	0.000
X_1	1	81.7	81.75	1.52	0.232
X_2	1	2164.0	2164.03	40.31	0.000
X_3	1	136.4	136.42	2.54	0.127
Square	3	4226.6	1408.86	26.24	0.000
X_1^2	1	270.5	270.48	5.04	0.036
X_2^2	1	2271.5	2271.53	42.31	0.000
X_3^2	1	1406.6	1406.61	26.20	0.000
2-factor interaction	3	3481.6	1160.54	21.62	0.000
$X_1 \times X_2$	1	18.2	18.24	0.34	0.567
$X_1 \times X_3$	1	3426.7	3426.66	63.83	0.000
$X_2 \times X_3$	1	36.7	36.72	0.68	0.418
Error	20	1073.6	53.68		
Lack of fit	3	870.2	290.07	24.24	0.000
Pure error	17	203.4	11.97		
Total	29	11164.0			

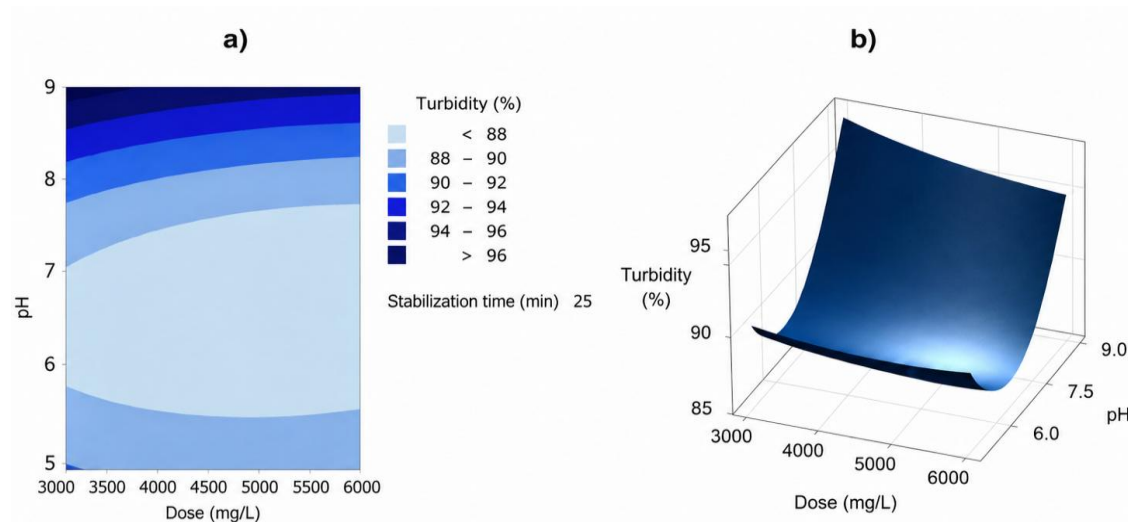


Fig. 1. Effect of coagulant dose and pH on turbidity removal efficiency.

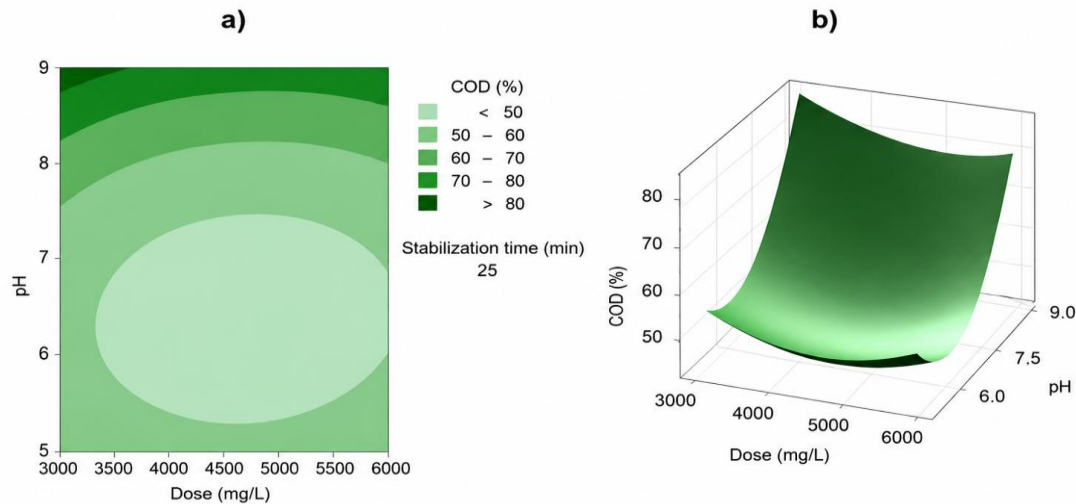


Fig. 2. Effect of coagulant dose and pH on COD removal efficiency.

Effect of coagulant dose and settling time

Figures 3 and 4 present the combined effects of coagulant dose (X_1) and settling time (X_3) on turbidity and COD removal efficiencies at a constant pH of 7. The contour plots showed curved and non-linear response patterns, indicating a significant interaction between coagulant dose and settling time, in agreement with the ANOVA results, where the interaction term X_1X_3 was found to be significant. Increasing the settling time initially improved pollutant removal, with optimal performance observed between 20 and 25 min for coagulant doses within the range of 3000–6000 mg/L, where turbidity removal reached 85–90%, and COD removal ranged from approximately 60 to

75%. At shorter settling times, floc formation remained incomplete, limiting clarification efficiency. However, at longer settling times combined with higher coagulant doses, a decrease in performance was observed. This behavior may be attributed to floc destabilization or particle redispersion, indicating an overdosing effect [11]. Thus, the interaction between coagulant dose and settling time reflects a balance between floc formation kinetics and floc stability. Moderate conditions favor optimal aggregation, whereas extreme conditions may disrupt floc structure.

Effect of initial pH and settling time

Figures 5 and 6 illustrate the combined effects of initial pH (X_2) and settling time (X_3) on removal

efficiencies at a fixed coagulant dose of 4500 mg/L. Removal efficiencies increased with settling time, particularly under alkaline conditions. Optimal performance was observed around pH 9 and settling times between 21 and 24 min, where turbidity removal exceeded 95%, and COD removal ranged from 70 to 80%.

At shorter settling times, removal efficiencies remained limited due to incomplete aggregation

and insufficient sedimentation of flocs. Increasing the settling time enhanced floc growth and settling until equilibrium conditions were reached. Under alkaline conditions, pH adjustment reduces electrostatic repulsion between colloidal particles, facilitating aggregation and the formation of compact flocs with improved settling properties [23,36].

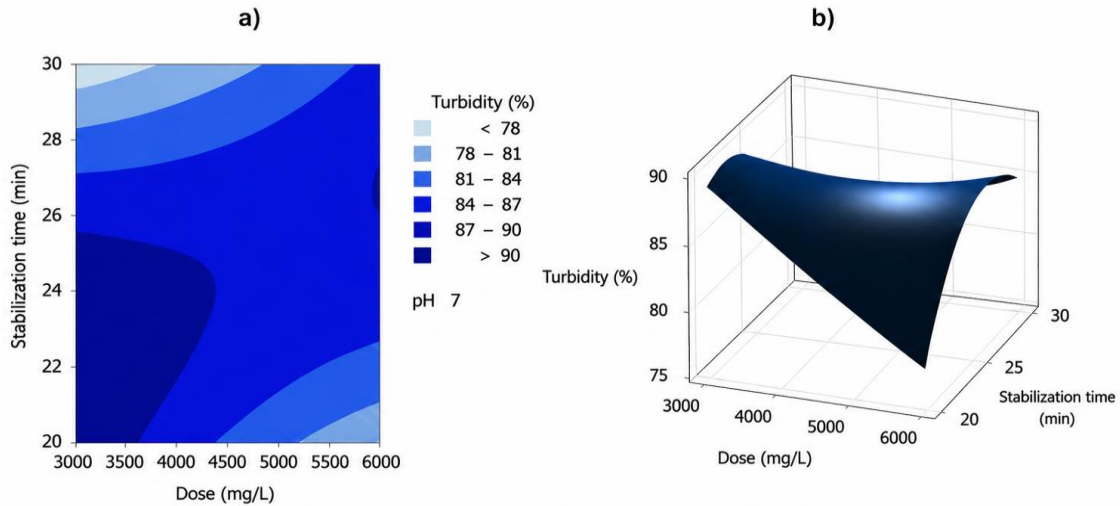


Fig. 3. Effect of coagulant dose and stabilization time on turbidity removal efficiency.

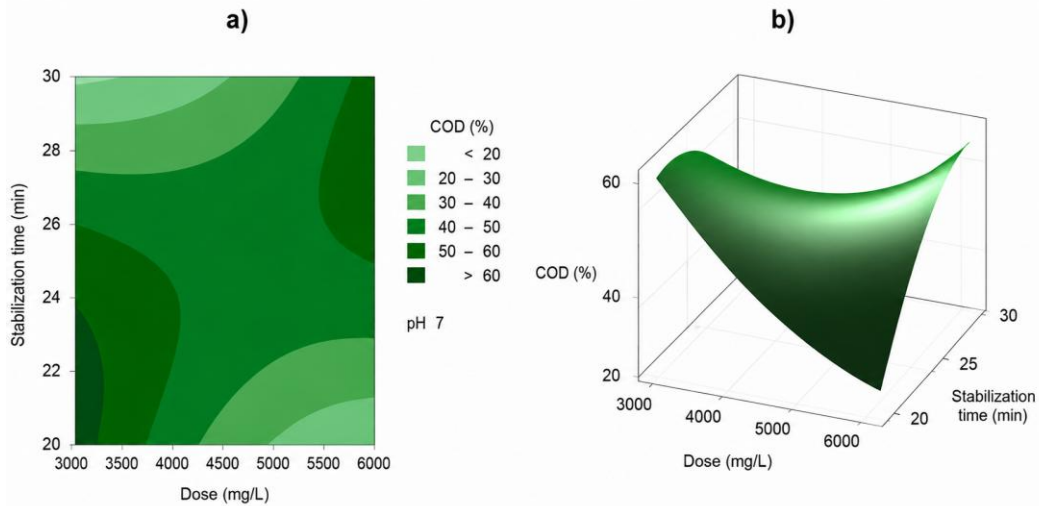


Fig. 4. Effect of coagulant dose and stabilization time on COD removal efficiency.

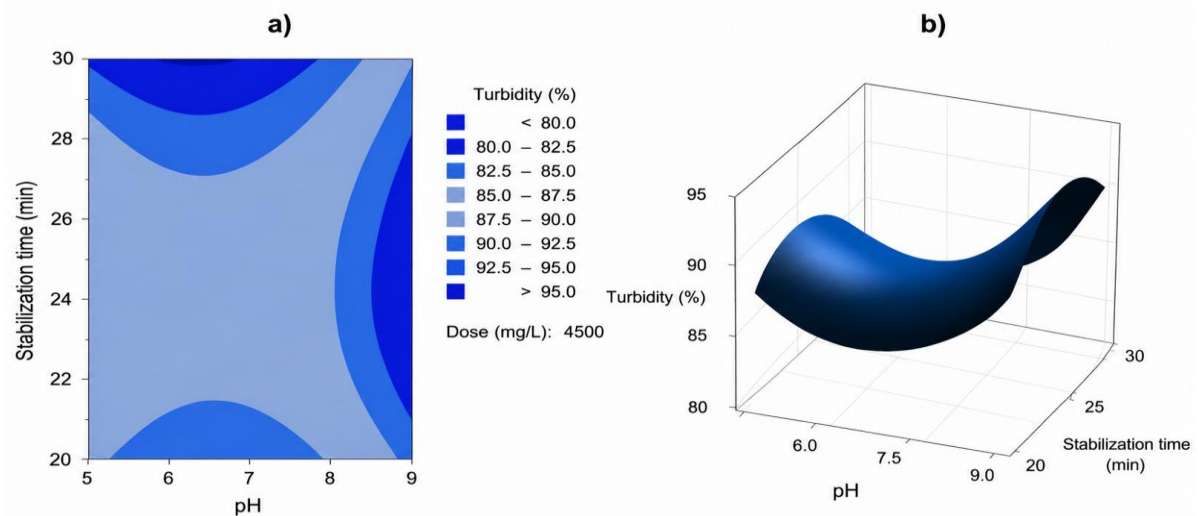


Fig. 5. Effect of pH and stabilization time on turbidity removal efficiency.

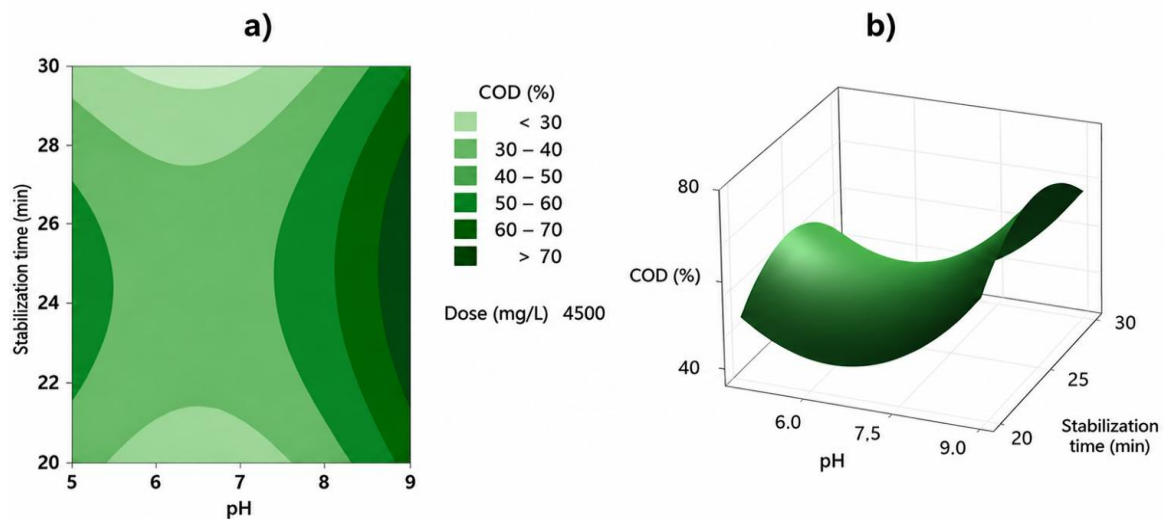


Fig. 6. Effect of pH and stabilization time on COD removal efficiency.

3.2.3. Optimization and model validation

The optimal conditions for the coagulation-flocculation process were determined using the second-order polynomial model developed through RSM.

The optimization was carried out using the desirability function in order to simultaneously maximize turbidity and COD removal efficiencies. The desirability profiles (Figure 7) indicated that a global desirability close to 1 ($D \approx 1.00$) was achieved at a coagulant dose of 3000 mg/L, an initial pH of 9, and a settling time of 21.11 min. These conditions correspond to the optimal operating region of the process.

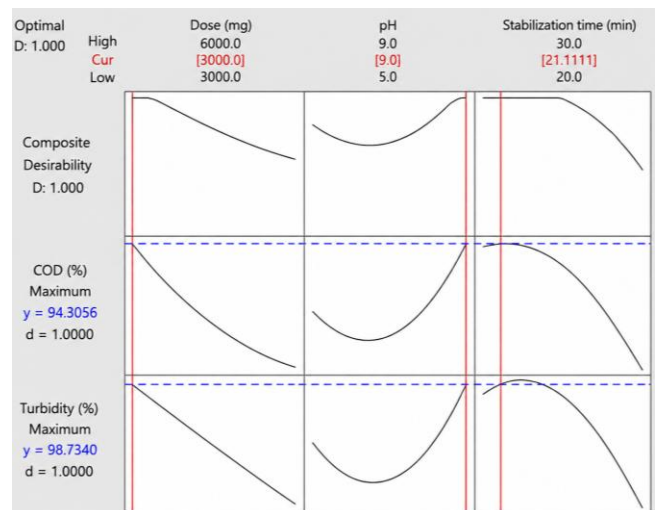


Fig. 7. Desirability profiles for COD and turbidity.

Under these conditions, the model predicted removal efficiencies of 98.73% for turbidity and 94.31% for COD. To validate the reliability of the model, three experimental runs were performed under the identified optimal conditions. The results obtained are presented in Table 6.

The experimental results showed good agreement with the model predictions. The relative deviation between predicted and experimental values remained below 5%, confirming the reliability and robustness of the developed model. These results demonstrate the satisfactory predictive capability of the model under optimized conditions.

3.2.4. Comparison with previous studies

Table 7 summarizes previous studies on turbidity and COD removal using coagulation–flocculation processes.

Various chemical and natural coagulants have been evaluated for the treatment of different types of wastewater, including industrial effluents and palm oil mill effluent. The results reported in the

Table 6. Model validation under optimal conditions.

Run	Coagulant dose (mg/L)	pH	Time (min)	Turbidity removal (%)	COD removal (%)
				Pred. / Exp.	Pred. / Exp.
1	3000	9	21.11	98.73 / 97.08	94.31 / 96.85
2	3000	9	21.11	98.73 / 96.90	94.31 / 95.70
3	3000	9	21.11	98.73 / 97.30	94.31 / 96.20
Mean ± SD	–	–	–	98.73 / 97.09 ± 0.20	94.31 / 96.25 ± 0.58

Note: Pred.: predicted values; Exp.: experimental values; SD: standard deviation.

Table 7. Comparison of coagulation–flocculation performance for different coagulants.

Material	Effluent	Dose (mg/L)	pH	Turbidity removal (%)	COD removal (%)	References
Alum	Industrial effluent	1000	5	–	68	[37]
Alum	Leachate	8000	5	94.5	69.4	[38]
Ferric sulphate	Leachate	6000	3	72.9	58.9	[38]
Pomegranate seeds	Industrial wastewater	2400	4	94.44	–	[39]
Copperas + Ca(OH) ₂	POME	1000–5000	–	77.6	57	[40]
Okra	POME	~1000	11–12	92.5	34–43	[41]
Cassava peel	POME	3000	9	97.09	96.25	This study

4. Conclusion

This study demonstrated the effectiveness of cassava peel as a natural coagulant for the pretreatment of palm oil mill effluent. The optimization of the coagulation–flocculation

literature indicate that the efficiency of the coagulation–flocculation process strongly depends on operating conditions, particularly pH, which plays a key role in the destabilization of colloidal particles.

Optimal performance is achieved through the combined effect of pH and coagulant dose. Compared to previous studies, the present work achieved higher COD removal efficiency at a relatively moderate coagulant dose. For instance, alum showed COD removals of 68% and 69.4% at doses of 1000 mg/L and 8000 mg/L, respectively, while ferric sulphate achieved 58.9% at 6000 mg/L. Similarly, natural coagulants such as okra exhibited lower COD removal efficiencies ranging from 34% to 43%, despite high turbidity removal. In contrast, the use of cassava peel at 3000 mg/L and pH 9 resulted in 97.09% turbidity removal and 96.25% COD removal. These values are higher than those reported in previous studies, even when higher coagulant doses were applied.

process using a Box–Behnken experimental design resulted in high removal efficiencies, with 97.09% turbidity removal and 96.25% COD reduction achieved under optimal conditions (pH 9, coagulant dose of 3000 mg/L, and a settling time of approximately 21 min). The findings confirmed the

dominant role of pH in the coagulation–flocculation process and highlighted the importance of optimizing operating conditions to enhance treatment performance. From an environmental perspective, the use of cassava peel offers a sustainable alternative to conventional chemical coagulants, contributing to agro-industrial waste valorization while reducing chemical consumption. In addition, the relatively low optimal dose supports the economic feasibility of the process, making cassava peel a practical alternative to conventional coagulants. Despite these advantages, the process primarily acts as an efficient pretreatment step, significantly improving effluent quality through the reduction of turbidity and organic load. However, additional treatment is still required to achieve full compliance with discharge standards. In this context, the integration of this pretreatment with advanced processes, particularly oxidation-based methods, appears to be a promising strategy to further enhance pollutant removal and meet regulatory requirements.

Acknowledgement

The authors gratefully acknowledge the Laboratory of Environmental Sciences and Technologies (LSTE), Jean Lorougnon Guédé University, for providing laboratory facilities and technical support for this research. The authors also sincerely thank the ETRAPCI palm oil mill for facilitating access to the industrial site and the collection of palm oil mill effluent samples.

Author's contribution

Yapo M'besso Edith Christine: Methodology, Field Investigation, Laboratory Analysis, Data Curation, Formal Analysis, Drafting the original draft. **Kouadio David Léonce:** Methodological Validation, Scientific Supervision, Data Interpretation, Review & editing. **Akese Djamatche Paul Valery:** Review & editing. **Yapi Yapo Hermann Aristide:** Review & editing. **Dalogo Kacou Alain Paterne:** Review & editing. **Dibi Brou:** Review & editing. All authors have read and approved the final version of the manuscript.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

Not Applicable.

Funding

Self-funded.

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How to cite this paper:



Yapo, M. E. C., Kouadio, D. L., Akesse, D. P. V., Yapi, Y. H. A., Dalogo, K. A. P. & DIBI, B. (2026). Optimization of coagulation–flocculation pretreatment of palm oil mill effluent using cassava peel as a natural coagulant. *Advances in Environmental Technology*, 12(4), 430–443. DOI: 10.22104/aet.2026.7461.2076