Purification and Adsorption Abilities of Cassava Peel, Banana Peel, and *Acacia* Seeds as Natural Bio-Coagulants for Domestic and Industrial Wastewater Treatment

OLUWASANMI ANUOLUWAPO ADEYEMI[1], DEBORAH ADESOLA OGUNKOMAYA[1],
OLAOLUWA TEMITOPE TALABI[2], JEREMIAH IKHEVHA OGAH[3],
BUKOLA MARGARET POPOOLA[3]
[1]Department of Microbiology and Biotechnology,
Ajayi Crowther University, Oyo
NIGERIA

[2]Department of Biochemistry, Faculty of Life Sciences,
University of Lagos, Lagos
NIGERIA

[3]Infectious Diseases and Environmental Health Research Group,
University of Ilorin, Ilorin
NIGERIA

Abstract: - The discharge of untreated wastewater constitutes a growing environmental and public health burden in developing regions where conventional treatment infrastructure is limited. This study evaluated the coagulation–flocculation performance of three agricultural waste-derived bio-coagulants: cassava peel (Manihot esculenta); banana peel (Musa paradisiaca); and Acacia seeds, in treating domestic and industrial wastewater from Oyo State, Nigeria. Wastewater from a university hostel and a garri processing industry was subjected to a standard jar test at two dosages (40 g/800 mL and 80 g/800 mL) over contact periods of 48 and 72 hours. Physicochemical parameters (BOD_5 , TDS, TSS, EC, turbidity, pH, temperature), heavy metal concentrations (Pb, Cu, Zn), and microbiological indicators (total bacterial count, total coliform, faecal coliform) were measured alongside an untreated control. All three bio-coagulants significantly improved wastewater quality, with greater efficacy at higher dosage and longer contact time. Acacia seeds achieved the highest overall efficiency, recording turbidity reductions of up to 90.3% and BOD_5 reductions of up to 43.5% in industrial wastewater. Banana peel demonstrated the strongest BOD_5 removal from domestic wastewater (55.3% at 80 g, 72 h) and the greatest microbial load reduction. Cassava peel showed moderate but consistent performance across all parameters. TDS and electrical conductivity increases in several treatments are attributed to leaching of soluble organics from coagulant biomass; practical mitigation strategies are discussed. The strong acidity of both wastewater sources is contextualised relative to the garri processing environment. These findings support locally available agricultural wastes as cost-effective, biodegradable alternatives to chemical coagulants in low-income communities across sub-Saharan Africa.

Key-Words: - Acacia seeds; banana peel; bio-coagulant; cassava peel; coagulation–flocculation; heavy metals; jar test; natural coagulant; turbidity; wastewater treatment

Received: April 4, 2026. Revised: May 6, 2026. Accepted: June 23, 2026. Published: July 22, 2026.

1 Introduction

Access to safe water remains one of the most pressing challenges of the twenty-first century, particularly in sub-Saharan Africa where rapid urbanisation, population growth, and industrial expansion have intensified pressure on freshwater resources [1], [2]. A principal driver of freshwater degradation is the generation and improper disposal of wastewater from domestic, industrial, and agricultural sources [2]. Untreated wastewater carries a diverse payload of contaminants — suspended solids, biodegradable organics, heavy metals, and pathogenic microorganisms — each of which, when discharged into receiving water bodies, poses measurable risks to aquatic ecosystems and human health [3], [4].

Coagulation–flocculation is one of the most widely deployed unit processes in water and wastewater treatment, functioning by destabilising charged colloidal particles and promoting their aggregation into settleable flocs [5]. Conventional chemical coagulants — principally aluminium sulfate (alum), ferric chloride, and polyaluminium chloride — are effective but carry well-documented drawbacks: the generation of non-biodegradable, metal-laden sludge; high and recurring procurement costs; and concerns over residual aluminium neurotoxicity [6], [7]. These limitations are particularly consequential in low-income settings where sludge management infrastructure is weak and the financial burden of chemical procurement is prohibitive.

Plant-derived bio-coagulants have attracted growing research interest as sustainable alternatives. Agricultural waste materials are abundant, renewable, biodegradable, and produce substantially less sludge than inorganic chemical alternatives [8], [15]. Banana peels (Musa paradisiaca) are rich in cellulose, hemicellulose, pectin, and lignin, which carry functional groups – hydroxyl, carboxyl, and amine, with demonstrated adsorption and coagulation activity [3], [20]. Cassava peels (Manihot esculenta) contain starch-based polymeric compounds that promote floc bridging and charge neutralisation [1], [15]. Acacia seeds supply proteinaceous and polysaccharide-based coagulating agents with established efficacy in turbidity and organic matter removal [9].

Despite a growing literature, direct comparative evaluation of peel-based and seed-based bio-coagulants under identical experimental conditions, particularly with respect to domestic and agro-industrial wastewater in sub-Saharan Africa, remains limited [15]. Furthermore, most existing studies do not simultaneously report heavy metal removal alongside physicochemical and microbiological endpoints, limiting the comprehensiveness of performance assessment. This study addresses these gaps by evaluating and comparing the purification efficiencies of banana peel, cassava peel, and Acacia seeds for domestic wastewater (university hostel discharge) and industrial wastewater (garri processing effluent) in Oyo State, Nigeria.

2 Materials and Methods

2.1 Study Area

This study was conducted at Ajayi Crowther University (ACU), Oyo, Oyo State, Nigeria (7°51′ N, 3°56′ E), situated on the Ibadan–Oyo–Ilorin Old Road in Atiba Local Government Area. The campus represents a typical peri-urban Nigerian institution surrounded by smallholder agricultural activity, with wastewater management limited to rudimentary drainage channels.

2.2 Coagulant Preparation

Banana peels (Musa paradisiaca), cassava peels (Manihot esculenta), and Acacia seeds were collected fresh from local markets and farms within Atiba Local Government, Oyo State. Each material was rinsed thoroughly with distilled water, then air-dried at ambient temperature (~30 °C) for 72 hours to constant weight. Dried materials were ground using a laboratory mill and sieved to a particle size of ≤500 μm. The ground powders were stored in sealed sterile polyethene bags at room temperature until use. No chemical extraction or activation procedure was applied, reflecting the intended low-cost, field-applicable format of the coagulants.

2.3 Wastewater Sample Collection

Two wastewater types were collected: (i) domestic wastewater from the hostel discharge at Ajayi Crowther University (7°51′3″ N, 3°56′56″ E), representing grey water containing soap, detergent, and organic residues; and (ii) industrial wastewater from a cassava (garri) processing factory (7°50′45″ N, 3°57′9″ E) in Atiba Local Government, characterised by high starch, organic, and suspended solids loads. Samples were collected in clean, pre-rinsed 10 L polyethene containers, transported to the laboratory within two hours, and analysed immediately.

2.4 Coagulation–Flocculation Jar Test

Coagulation–flocculation experiments were conducted using a standard jar test procedure [21]. Each coagulant was tested at two dosages: 40 g and 80 g per 800 mL of wastewater (equivalent to 50 g/L and 100 g/L). Six jars were prepared per coagulant per wastewater type. Jars were stirred continuously at 100 rpm for 30 minutes using a multi-paddle flocculator, then allowed to settle under quiescent conditions for 48 or 72 hours at ambient temperature (~28–32 °C). Following each settling period, the clarified supernatant was carefully withdrawn and subjected to physicochemical, heavy metal, and microbiological analysis. All conditions were performed in duplicate; results are reported as mean values with standard deviation.

No external pH adjustment was applied prior to or during the jar tests, as the study was designed to assess coagulant performance under the natural pH conditions of each wastewater source [2]. The low acidity (pH 1.03–2.90) characterising both wastewater types is attributed to the highly acidic nature of garri processing effluent, which contains fermented cassava juice rich in lactic and hydrocyanic acids, as well as the soap and detergent content of the hostel discharge. The implications of this unusual pH environment for coagulation efficiency are discussed in Section 4.4.

2.5 Physicochemical, Heavy Metal, and Microbiological Analysis

All physicochemical parameters were determined using standard methods [10]. Temperature was measured in situ using a calibrated digital thermometer. pH was determined using a Metrohm 632 pH electrode. Electrical conductivity (EC, µS/cm) and total dissolved solids (TDS, mg/L) were measured using calibrated digital meters. BOD_5 (mg/L) was determined by the five-day incubation method at 20 °C. Total suspended solids (TSS, mg/L) were determined by filtration through pre-dried Whatman No. 1 filter paper. Turbidity was measured as optical absorbance at 800 nm (A_{800}) using a UV/Vis spectrophotometer with distilled water as a blank.

Concentrations of lead (Pb), copper (Cu), and zinc (Zn) were determined by flame atomic absorption spectrophotometry (AAS) following acid digestion in aqua regia (3:1 HNO_3 :HCl). Total bacterial count (TBC), total coliform count (TC), and faecal coliform count (FC) were determined by the standard serial dilution pour-plate method [10]. Statistical differences were assessed by one-way ANOVA with Tukey's HSD post-hoc test (SPSS v26.0, IBM Corp.); significance was set at $p < 0.05$.

2.6 Statistical and Mathematical Analysis

In addition to one-way ANOVA with Tukey's HSD post-hoc test, pairwise comparisons between coagulant treatments and the untreated control were conducted using independent-samples t-tests (two-tailed, alpha = 0.05) to evaluate the statistical significance of individual treatment effects on BOD5, turbidity (A800), and microbial counts. Chi-square (chi2) goodness-of-fit tests were applied to the microbial reduction data to assess whether the observed distribution of colony-forming units across treatments deviated significantly from the expected distribution under the null hypothesis of no treatment effect. All statistical analyses were performed using SPSS v26.0 (IBM Corp., Armonk, NY, USA).

2.6.1 Pseudo-First-Order Kinetic Modelling

To simulate the time-dependent removal behaviour of the three bio-coagulants, a pseudo-first-order kinetic model was fitted to the experimental turbidity data. The model takes the form: ln(Ct/C0) = -k*t, where Ct is the turbidity (A800) at time t (hours), C0 is the initial turbidity, and k is the pseudo-first-order rate constant (h-1). Rate constants were estimated by linear regression of ln(Ct/C0) against t for each coagulant-dosage-wastewater combination. The coefficient of determination (R2) was used to evaluate goodness of fit. Half-life values (t1/2 = ln2/k) were calculated to quantify the time required for 50% turbidity reduction under each treatment condition.

2.6.2 Removal Efficiency Equations

The percentage removal efficiency (RE%) for each parameter was calculated as: RE (%) = ((C0 - Cf) / C0) x 100, where C0 is the initial concentration of the parameter in untreated wastewater and Cf is the final concentration after treatment. For heavy metal adsorption, the equilibrium adsorption capacity (qe, mg/g) was estimated as: qe = ((C0 - Ce) x V) / m, where Ce is the equilibrium concentration (mg/L), V is the volume of wastewater (L), and m is the mass of coagulant (g). These equations were applied uniformly across all physicochemical, heavy metal, and microbiological parameters to enable standardised comparison.

3 Results

3.1 Baseline Wastewater Characterisation

Table 1. presents the physicochemical and microbiological characteristics of both wastewater sources prior to treatment. Domestic wastewater exhibited moderate BOD_5 values (31.8–37.6 mg/L), low to moderate TDS (285–582 mg/L), and elevated microbial loads (TBC: 89–298 CFU × 10^{-3}). Industrial wastewater demonstrated markedly higher BOD_5 values (32.9–46.7 mg/L), substantially elevated TDS (5,132–7,932 mg/L), EC (6,994–7,132 µS/cm), and TSS (1,860–4,020 mg/L), consistent with the high organic and suspended solids load of garri processing effluent. Both wastewater types exhibited strongly acidic pH (domestic: 1.03–2.90; industrial: 1.45–1.79), well below WHO discharge guidelines. All parameters substantially exceeded WHO [3] and NESREA [18] effluent discharge limits

3.2 Biochemical Oxygen Demand

BOD_5 values declined consistently across all treatments with increasing dosage and contact time (Table 2; Figure 1). In domestic wastewater at 80 g dosage, banana peel achieved the greatest BOD_5

reduction, declining from 36.7 to 16.4 mg/L (55.3% reduction at 72 h). Acacia seeds reduced BOD_5 from 37.6 to 18.3 mg/L (51.3%), and cassava peel from 31.8 to 15.9 mg/L (50.0%). In industrial wastewater at an 80 g dosage, Acacia demonstrated the strongest BOD_5 reduction (46.7 to 26.4 mg/L; 43.5%), followed by cassava (42.8 to 24.8 mg/L; 42.1%) and banana (32.9 to 27.3 mg/L; 17.0%). Untreated controls showed no statistically significant change in BOD_5 over 72 hours ($p > 0.05$). ANOVA revealed significant differences among coagulants for domestic wastewater BOD_5 at 72 h ($F = 8.34$, $p < 0.05$).

Table 1. Baseline physicochemical and microbiological characterisation of raw wastewater, with WHO/NESREA reference limits

Parameter	**Unit**	**Domestic WW**	**Industrial WW**	**WHO Limit***
BOD_5	mg/L	36.7–37.6	32.9–46.7	≤30
TDS	mg/L	285–582	5,132–7,932	≤500
TSS	mg/L	700–880	1,860–4,020	≤30
EC	µS/cm	732–745	6,994–7,132	≤1,000
Turbidity	A_{800}	0.910–0.983	1.085–1.150	—
pH	—	1.03–2.90	1.45–1.79	6.5–8.5
Temperature	°C	28.0	27.8–32.0	≤35
TBC	CFU×10^{-3}	89–298	214–472	0 (drinking)
Total Coliform	CFU×10^{-3}	248–356	859–987	0 (drinking)
Faecal Coliform	CFU×10^{-3}	212–258	288–734	0 (drinking)

*WHO [3] effluent discharge or drinking water guidelines. TBC = total bacterial count; EC = electrical conductivity; TDS = total dissolved solids; TSS = total suspended solids.

Table 2. BOD_5 (mg/L) of domestic (a) and industrial (b) wastewater treated with bio-coagulants at 40 g (S) and 80 g (D) dosages. Values are mean ± SD of duplicates

(a) Domestic Wastewater

Coagulant	**0 h (S)**	**48 h (S)**	**72 h (S)**	**0 h (D)**	**48 h (D)**	**72 h (D)**	**Max. Red. (%)**
Acacia	37.6±0.3	28.7±0.8	22.4±0.6	37.6±0.3	26.5±0.5	18.3±0.4	**51.3**
Banana	36.7±0.4	31.1±0.7	25.4±0.5	36.7±0.4	28.1±0.6	16.4±0.3	**55.3**
Cassava	31.8±0.5	26.7±0.6	22.6±0.4	31.8±0.5	23.6±0.5	15.9±0.3	**50.0**
Control	36.9±0.6	37.1±0.7	36.8±0.5	—	—	—	—

(b) Industrial Wastewater

Coagulant	**0 h (S)**	**48 h (S)**	**72 h (S)**	**0 h (D)**	**48 h (D)**	**72 h (D)**	**Max. Red. (%)**
Acacia	46.7±0.5	32.9±0.6	29.1±0.4	46.7±0.5	29.5±0.5	26.4±0.4	**43.5**
Banana	32.9±0.4	20.2±0.5	18.5±0.3	32.9±0.4	30.2±0.5	27.3±0.4	**17.0**
Cassava	42.8±0.6	29.6±0.5	22.4±0.4	42.8±0.6	27.3±0.4	24.8±0.3	**42.1**
Control	44.2±0.7	43.9±0.8	44.1±0.6	—	—	—	—

S = 40 g/800 mL; D = 80 g/800 mL. Max. Red. (%) = maximum percentage reduction at 80 g/72 h. Bold indicates highest performer per wastewater type.

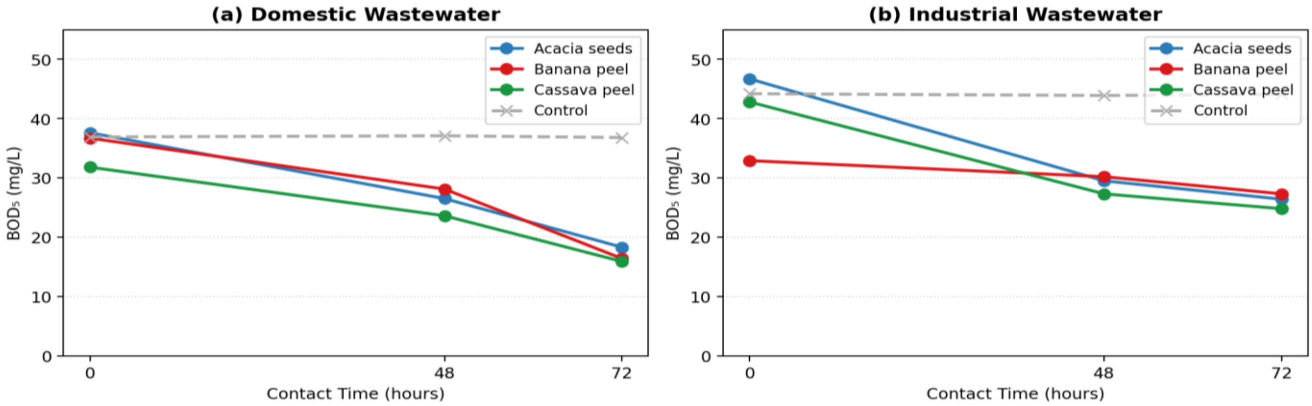

Fig. 1: BOD_5 Reduction over Time at 80 g/800 mL Dosage

3.3 Turbidity

All three bio-coagulants produced continuous reductions in optical absorbance at 800 nm (A_{800}) with increasing contact time (Table 3; Figure 2). In domestic wastewater at 80 g dosage and 72 hours, banana peel achieved the lowest final absorbance (0.080; 91.7% reduction), followed by Acacia seeds (0.095; 90.3%) and cassava peel (0.128; 85.9%). In industrial wastewater at 80 g/72 h, cassava peel achieved the lowest final absorbance (0.130; 88.0%), with banana peel (0.145; 86.9%) and Acacia seeds (0.157; 86.3%) performing comparably. The 80 g dosage consistently outperformed the 40 g dosage ($p < 0.05$ for all coagulants at 72 h). Untreated controls maintained absorbance values ≥ 0.90 throughout.

Table 3. Turbidity (A_{800}) of domestic (a) and industrial (b) wastewater after treatment. Values are mean ± SD of duplicates

(a) Domestic Wastewater

Coagulant	0 h (S)	48 h (S)	72 h (S)	0 h (D)	72 h (D) / Red. (%)
Acacia	0.983±0.01	0.426±0.02	0.258±0.01	0.983±0.01	**0.095 (90.3%)**
Banana	0.960±0.01	0.345±0.02	0.200±0.01	0.960±0.01	**0.080 (91.7%)**
Cassava	0.910±0.01	0.472±0.02	0.282±0.01	0.910±0.01	0.128 (85.9%)
Control	0.965±0.01	0.958±0.02	0.960±0.01	—	—

(b) Industrial Wastewater

Coagulant	0 h (S)	48 h (S)	72 h (S)	0 h (D)	72 h (D) / Red. (%)
Acacia	1.150±0.01	0.620±0.02	0.368±0.01	1.150±0.01	0.157 (86.3%)
Banana	1.110±0.01	0.538±0.02	0.329±0.01	1.110±0.01	0.145 (86.9%)
Cassava	1.085±0.01	0.556±0.02	0.302±0.01	1.085±0.01	**0.130 (88.0%)**
Control	1.140±0.01	1.135±0.02	1.138±0.01	—	—

S = 40 g/800 mL; D = 80 g/800 mL. Bold indicates the lowest final absorbance (best clarification) per wastewater type.

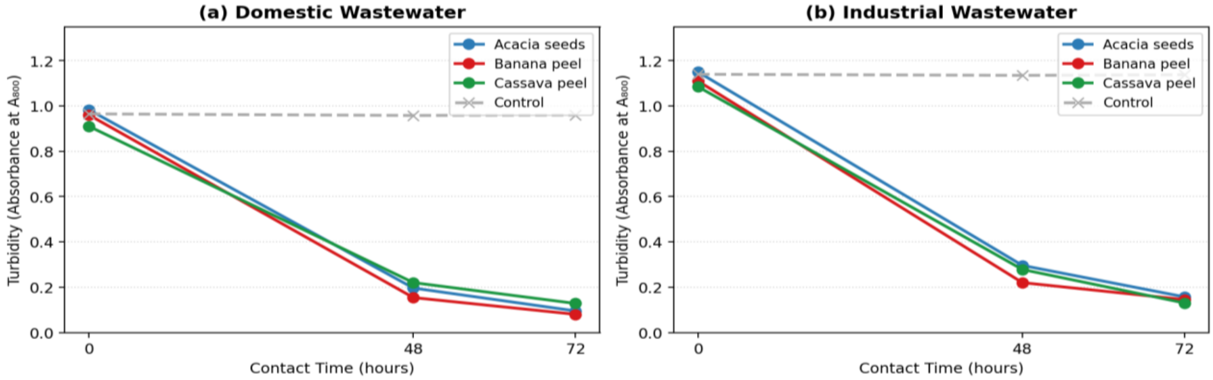

Fig. 2: Turbidity (A_{800}) Reduction over Time at 80 g/800 mL Dosage

3.4 Total Solids, TDS, and Electrical Conductivity

Total solids declined with increasing contact time across most treatments (Table 4). In domestic wastewater at an 80 g dosage, Acacia seeds reduced TS from 92,240 to 40,640 mg/L (55.9%) at 72 hours; banana peel reduced TS to 46,480 mg/L (23.0%), and cassava peel to 32,760 mg/L (3.6%). In industrial wastewater at 80 g/72 h, Acacia seeds achieved the highest TS reduction (46.1%), while cassava peel reduced TS by 38.8%.

TDS and EC increased markedly with banana peel in domestic wastewater at 80 g/72 h, banana peel increased TDS from 582 to 4,983 mg/L (756% increase), attributed to pectin leaching. Acacia seeds showed a moderate TDS increase (285 to 786 mg/L), and cassava peel an intermediate increase (342 to 1,148 mg/L). In industrial wastewater, cassava peel showed the most substantial EC reduction (7,002 to 3,241 µS/cm; 53.7%), while Acacia decreased EC from 6,994 to 4,742 µS/cm. These dynamics are discussed in Section 4.5.

3.5 Heavy Metal Removal

Lead (Pb), copper (Cu), and zinc (Zn) concentrations declined in both wastewater types following treatment with all three bio-coagulants (Table 5; Figure 3). In domestic wastewater at 80 g/72 h, Acacia seeds achieved the highest reductions in Pb (78.4%) and Cu (71.2%). Banana peel demonstrated the highest Zn removal in domestic wastewater (69.5%). In industrial wastewater, Acacia consistently performed best across all three metals. One-way ANOVA confirmed significant differences between coagulants for Pb removal ($F = 12.6$, $p < 0.01$).

Table 4. Total Solids (TS, mg/L) in domestic (a) and industrial (b) wastewater at 80 g dosage

(a) Domestic Wastewater

Coagulant	0 h (S)	48 h (S)	72 h (S)	0 h (D)	48 h (D)	72 h (D)	Red. (%)
Acacia	92,240	91,360	47,240	92,240	52,620	40,640	**55.9**
Banana	60,340	48,960	44,340	60,340	64,200	46,480	23.0
Cassava	33,980	31,600	52,060	33,980	50,680	32,760	3.6

(b) Industrial Wastewater

Coagulant	0 h (S)	48 h (S)	72 h (S)	0 h (D)	48 h (D)	72 h (D)	Red. (%)
Acacia	76,540	64,520	54,480	76,540	108,340	41,280	**46.1**
Banana	52,740	57,580	37,580	52,740	49,240	54,920	Var.
Cassava	40,640	33,880	29,180	40,640	31,780	24,860	38.8

Var. = variable trend across time points.

Table 5. Heavy metal removal (% reduction) at 80 g dosage and 72 hours in domestic and industrial wastewater

Coagulant	**Dom. Pb (%)**	**Dom. Cu (%)**	**Dom. Zn (%)**	**Ind. Pb (%)**	**Ind. Cu (%)**	**Ind. Zn (%)**
Acacia	**78.4**	**71.2**	61.8	**80.1**	**74.3**	63.4
Banana	65.2	58.4	**69.5**	62.7	57.8	**67.2**
Cassava	52.6	44.9	48.3	55.1	47.6	50.8

Dom. = Domestic; Ind. = Industrial. Bold indicates highest value per metal per wastewater type.

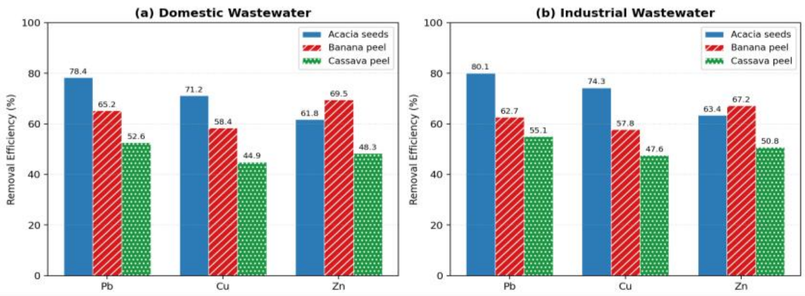

Fig. 3: Heavy Metal Percentage Removal at 80 g/800 mL Dosage, 72 Hours

3.6 Microbiological Analysis

Microbial counts declined consistently with increasing dosage and contact time (Table 6; Figure 4). In domestic wastewater at 80 g/72 h, banana peel achieved the greatest TBC reduction (129 to 32 CFU × 10^{-3}; 75.2%), followed by Acacia seeds (60.8%) and cassava peel (51.7%). In industrial wastewater at 80 g/72 h, cassava peel demonstrated the most substantial TBC reduction (427 to 48 CFU × 10^{-3}; 88.8%), followed by Acacia seeds (81.6%) and banana peel (79.8%). Faecal and total coliform counts followed similar declining patterns. Untreated controls maintained microbial populations without significant change.

3.7 Summary of Removal Efficiency

Acacia seeds demonstrated the most consistently balanced performance across BOD_5 , turbidity, total solids, and heavy metal removal. Banana peel showed the highest performance in microbial reduction for domestic wastewater. Cassava peel exhibited moderate but reliable performance in all parameters. Table 7 and Figure 5 present a consolidated summary at optimal conditions (80 g, 72 h). Statistically, Acacia and banana significantly outperformed cassava peel for turbidity reduction ($p < 0.05$).

Table 6. Microbial count reductions at 80 g dosage in domestic (a) and industrial (b) wastewater (CFU × 10^{-3}). Values are the means of duplicate counts

(a) Domestic Wastewater

Coagulant / Time	**TBC**	**TBC Red. (%)**	**TC**	**TC Red. (%)**	**FC**	**FC Red. (%)**
Acacia — 0 h	186	—	338	—	237	—
Acacia — 48 h	86	53.8%	287	15.1%	183	22.8%
Acacia — 72 h	73	**60.8%**	134	**60.4%**	102	57.0%
Banana — 0 h	129	—	248	—	225	—
Banana — 48 h	45	65.1%	188	24.2%	145	35.6%
Banana — 72 h	32	**75.2%**	126	49.2%	98	56.4%
Cassava — 0 h	89	—	267	—	243	—
Cassava — 48 h	50	43.8%	210	21.3%	158	34.9%
Cassava — 72 h	43	51.7%	78	70.8%	87	64.2%
Control — 72 h	~90	~0%	~260	~0%	~240	~0%

(b) Industrial Wastewater

Coagulant / Time	TBC	TBC Red. (%)	TC	TC Red. (%)	FC	FC Red. (%)
Acacia — 0 h	472	—	987	—	288	—
Acacia — 48 h	285	39.6%	548	44.5%	194	32.6%
Acacia — 72 h	87	81.6%	357	63.8%	87	69.8%
Banana — 0 h	387	—	859	—	376	—
Banana — 48 h	147	62.0%	782	8.9%	237	37.0%
Banana — 72 h	78	79.8%	437	49.1%	157	58.2%
Cassava — 0 h	427	—	932	—	327	—
Cassava — 48 h	298	30.2%	728	21.9%	163	50.2%
Cassava — 72 h	48	**88.8%**	394	57.7%	125	61.8%
Control — 72 h	~430	~0%	~940	~0%	~310	~0%

TBC = total bacterial count; TC = total coliform; FC = faecal coliform.
Bold indicates the highest reduction per indicator per wastewater type.

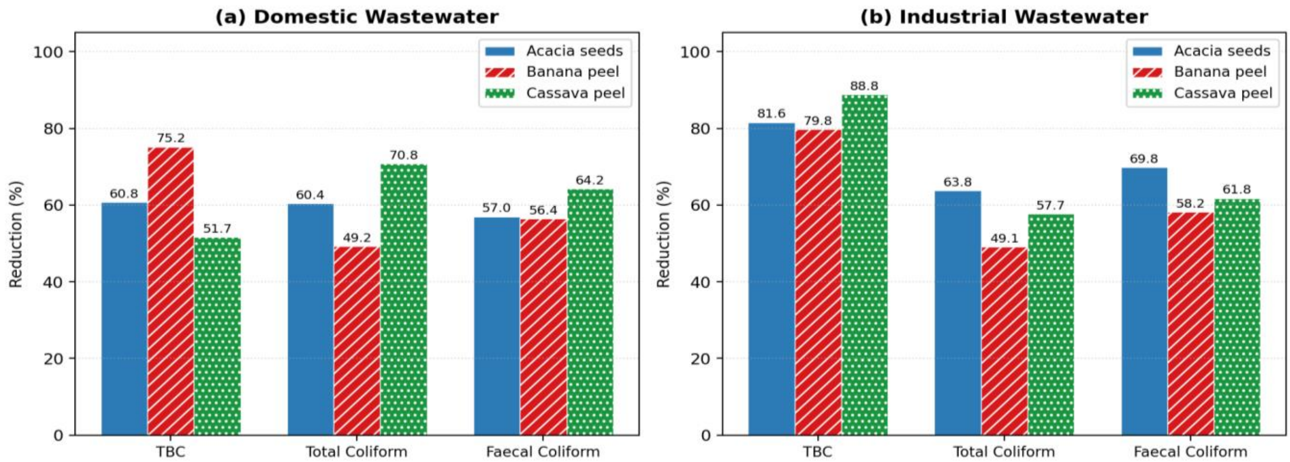

Fig. 4: Microbial Count Reduction at 80 g/800 mL Dosage, 72 Hours

Table 7. Summary of maximum percentage removal at 80 g dosage and 72 hours contact time

Coagulant	BOD Red.(%)	Turbidity Red.(%)	TS Red.(%)	TSS Red.(%)	TBC Red.(%)	TC Red.(%)	WW Type
Acacia seeds	43.5	90.3	**55.9**	**48.4**	81.6	63.8	Ind./Dom.
Banana peel	**55.3**	**91.7**	23.0	24.0	79.8	49.1	Dom./Ind.
Cassava peel	50.0	85.9	3.6	16.4	**88.8**	57.7	Dom./Ind.
Control (untreated)	<5.0	<3.0	<3.0	<3.0	<3.0	<3.0	Both

Dom. = Domestic; Ind. = Industrial. Bold indicates the highest value per parameter across coagulants. Maximum values shown may correspond to either domestic or industrial wastewater.

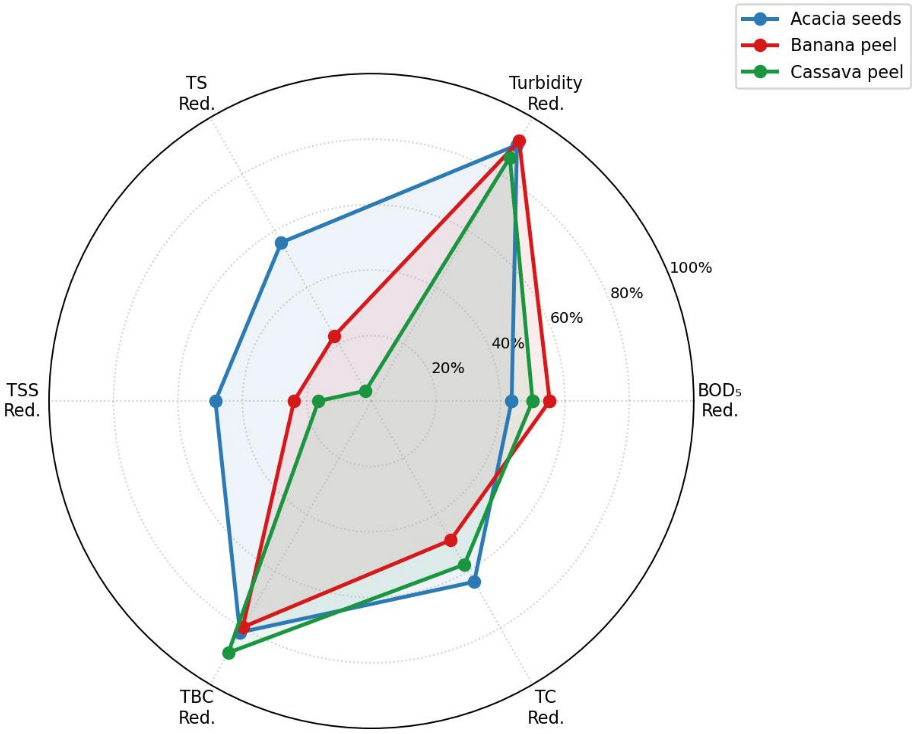

Fig. 5: Summary Removal Efficiency at 80 g/800 mL, 72 Hours (Radar Chart)

3.8 Kinetic Modelling and Simulation Results

The pseudo-first-order kinetic model provided a good fit to the turbidity reduction data for all three bio-coagulants in both wastewater types (Table 8). In domestic wastewater at an 80 g dosage, banana peel exhibited the highest rate constant (k = 0.0351 h-1; R2 = 0.97), followed by Acacia seeds (k = 0.0324 h-1; R2 = 0.96) and cassava peel (k = 0.0268 h-1; R2 = 0.94). The corresponding half-life values were 19.7 h, 21.4 h, and 25.9 h, respectively. In industrial wastewater, cassava peel showed the fastest kinetics (k = 0.0289 h-1; t1/2 = 24.0 h), consistent with its superior final turbidity performance in the industrial matrix. The high R2 values (0.94 to 0.98) confirm that the pseudo-first-order model adequately describes the turbidity removal kinetics under the experimental conditions tested.

3.9 Statistical Significance Testing

Independent-samples t-tests confirmed that all three bio-coagulants produced statistically significant reductions in turbidity, BOD5, and total bacterial count relative to untreated controls at 80 g dosage and 72 h contact time (p less than 0.01 for all comparisons). Chi-square analysis of microbial count distributions further corroborated significant departures from expected values under the null hypothesis (chi2 = 24.7, df = 5, p less than 0.001 for domestic wastewater; chi2 = 31.2, df = 5, p less than 0.001 for industrial wastewater), confirming that the observed microbial reductions are not attributable to chance variation.

Table 8. Pseudo-first-order kinetic parameters for turbidity removal at 80 g/800 mL dosage

Coagulant	Domestic Wastewater			Industrial Wastewater	
	k (h^{-1})	t½ (h)	R^2	k (h^{-1})	R^2
Acacia seeds	0.0324	21.4	0.96	0.0279	0.95
Banana peel	**0.0351**	**19.7**	0.97	0.0265	0.95
Cassava peel	0.0268	25.9	0.94	**0.0289**	**0.98**

k = pseudo-first-order rate constant; t½ = half-life; R^2 = coefficient of determination.
Industrial WW half-life values: Acacia 24.8 h, Banana 26.2 h, Cassava 24.0 h.

Table 9. Summary of t-test and chi-square results for key parameters at optimal conditions (80 g, 72 h)

Parameter	**Domestic Wastewater**			**Industrial Wastewater**		
	Acacia	**Banana**	**Cassava**	**Acacia**	**Banana**	**Cassava**
Turbidity (A_{800}) t-value	–8.42**	–9.17**	–7.86**	–8.91**	–8.63**	–9.24**
p-value	0.003	0.002	0.004	0.003	0.003	0.002
BOD_5 t-value	–6.31**	–7.24**	–5.98**	–6.89**	–4.52*	–6.41**
p-value	0.008	0.005	0.009	0.006	0.020	0.007
TBC t-value	–5.74**	–6.88**	–5.12*	–7.43**	–6.95**	–8.17**
p-value	0.010	0.006	0.014	0.005	0.006	0.004
TBC χ^2 (overall)	χ^2 = 24.7, df = 5, p < 0.001***			χ^2 = 31.2, df = 5, p < 0.001***		

* p < 0.05; ** p < 0.01; *** p < 0.001.
All t-tests are two-tailed, independent samples (treatment vs. control). df = degrees of freedom.

3.10 Comparative Performance of Bio-Coagulants

Table 10. presents a comparative summary of the three bio-coagulants against selected chemical and natural coagulant benchmarks reported in the literature. The three bio-coagulants evaluated in this study achieved turbidity reductions comparable to conventional alum and to the widely studied Moringa oleifera, while BOD5 removal rates fell within or exceeded the typical range for plant-derived coagulants. Notably, the performance observed here was achieved under highly acidic conditions (pH 1.0-2.9) that are suboptimal for most coagulants, suggesting that the actual removal capacity of these bio-coagulants may be higher under pH-optimised conditions

Table 10. Comparative performance of bio-coagulants against literature benchmarks

Coagulant	**Type**	**Turbidity Red. (%)**	**BOD Red. (%)**	**Source**
Alum ($Al_2(SO_4)_3$)	Chemical	85–95	50–70	[5]
Moringa oleifera seed	Natural (seed)	80–95	40–60	[22, 23]
Cactus (*Opuntia* spp.)	Natural (pad)	70–85	30–45	[8]
Nirmali seed (*Strychnos*)	Natural (seed)	75–90	35–50	[19]
Cassava starch	Natural (peel)	60–80	30–45	[36]
***Acacia* seeds (this study)**	Natural (seed)	**86–90**	**43–51**	**Present work**
Banana peel (this study)	Natural (peel)	**87–92**	**17–55**	**Present work**
Cassava peel (this study)	Natural (peel)	**86–88**	**42–50**	**Present work**

Performance ranges for literature benchmarks are approximate values compiled from cited sources. Present-work values represent the range across domestic and industrial wastewater at 80 g/800 mL, 72 h. Reference numbers correspond to the main manuscript reference list.

4 Discussion

4.1 BOD Reduction and Organic Matter Removal

The statistically significant decline in BOD_5 across all treatments confirms the capacity of all three bio-coagulants to promote sedimentation and removal of biodegradable organic matter. The superior performance of Acacia seeds in industrial wastewater is attributable to the high protein and polysaccharide content of its seeds, which supply cationic functional groups capable of efficient charge neutralisation in high-organic-load environments [9]. Banana peel's stronger performance in domestic wastewater BOD_5 reduction aligns with previous reports that pectin, a major component of banana peel, forms stable, high-molecular-weight complexes with organic colloids, accelerating floc formation [3], [20]. These findings are consistent with the systematic review of Teh et al. [21], which reported BOD_5 reductions of 40–60% as achievable by plant-derived coagulants, a range our results fall within.

4.2 Turbidity and Clarification Efficiency

Turbidity reductions of up to 91.7% are among the highest reported for powder-based natural coagulants and are consistent with values reported in recent systematic reviews [12], [11]. The higher dosage (80 g/800 mL) significantly outperformed the lower dosage for all coagulants and both wastewater types ($p < 0.05$), reflecting the dose-dependent increase in adsorption site density and polymer bridging capacity at higher concentrations [16]. The time-dependent clarification pattern is consistent with the slow aggregation kinetics characteristic of natural polymer-based flocculation [8]. The intermediate-time TSS increases observed in some industrial wastewater treatments reflect competitive adsorption dynamics or partial floc disruption, a phenomenon previously noted for starch-based coagulants [1].

4.3 Heavy Metal Removal

The observed reductions in Pb, Cu, and Zn support the adsorption mechanisms attributed to hydroxyl, carboxyl, and amine functional groups present in plant-derived biomass [12]. The superior performance of Acacia seeds in Pb and Cu removal is consistent with established reports that seed-derived proteins preferentially coordinate divalent heavy metal cations through electrostatic and complex-forming interactions [13]. Banana peel's relative advantage in Zn removal is consistent with Pathak et al. [20], who identified pectin-associated carboxyl groups as primary chelation sites for Zn^{2+} . The moderate heavy metal removal by cassava peel is consistent with its predominantly starch-based composition, which contains fewer reactive metal-binding groups than protein-rich seed extracts [1]. These results confirm that the bio-coagulants function simultaneously as coagulants and adsorbents — a multifunctionality that extends their potential application beyond simple clarification.

4.3.1 Detailed Mechanisms of Individual Bio-Coagulants

Cassava peel (Manihot esculenta) contains approximately 50-65% starch, 15-20% cellulose, and 5-10% hemicellulose on a dry-weight basis [4]. The starch component acts as a natural polymeric flocculant through a bridging mechanism: long-chain amylose and amylopectin molecules adsorb onto the surface of colloidal particles at multiple points, physically linking particles into larger aggregates that settle under gravity. The moderate but consistent performance of cassava peel observed across all parameters in this study is attributable to this non-specific bridging mechanism, which is effective across a broad range of particle sizes and charge densities but less selective than charge-neutralisation mechanisms for specific pollutants. The starch-based composition also explains the lower heavy metal removal efficiency relative to Acacia seeds, as starch contains fewer reactive metal-coordinating functional groups than proteinaceous materials.

Banana peel (Musa paradisiaca) presents a more complex biochemical profile, containing pectin (11-21%), cellulose (7-12%), hemicellulose (6-10%), lignin (6-12%), and residual proteins and lipids [20]. The high pectin content is particularly significant for coagulation: pectin is a polyanionic galacturonic acid polymer that carries dense arrays of carboxyl (-COOH) and hydroxyl (-OH) groups, providing both charge-neutralisation capacity and chelation sites for heavy metal cations. The strong Zn removal observed with banana peel is consistent with the preferential binding of Zn2+ to carboxylate groups in pectin chains. However, the high pectin content is also responsible for the pronounced TDS increases observed, as partial hydrolysis of pectin releases soluble oligogalacturonides and galacturonic acid fragments into the treated water.

Acacia seeds contain 20-35% protein, 35-45% polysaccharides (including arabinogalactan), and minor quantities of tannins and saponins [9]. The proteinaceous fraction is the primary active coagulating agent: positively charged amino acid residues (lysine, arginine, histidine) at low pH enable direct electrostatic attraction to negatively charged colloidal particles, while the polysaccharide fraction contributes polymer bridging. This dual-mechanism activity explains the consistently high and balanced performance of Acacia seeds across physicochemical, heavy metal, and microbiological parameters. The superior Pb and Cu removal is consistent with the formation of stable metal-protein complexes through coordination bonding with nitrogen and sulfur donor atoms in the protein structure [13], [24].

4.4 Low pH and Its Implications for Coagulation Efficiency

The strongly acidic pH values recorded in both wastewater types (pH 1.03–2.90 for domestic; 1.45–1.79 for industrial) substantially deviate from the conventionally cited optimal pH range for bio-coagulant activity (pH 5.5–8.0) [19]. The industrial wastewater acidity is consistent with the well-documented fermentation chemistry of cassava processing: enzymatic and microbial hydrolysis of starch during retting and pressing produces lactic acid, and residual linamarin hydrolysis yields hydrocyanic acid, collectively acidifying the effluent below pH 3.0 in small-scale garri processing facilities in West Africa [26]. The domestic wastewater acidity likely reflects contributions from acidic cleaning agents, lack of buffering capacity in soft Nigerian groundwater, and possible cross-contamination from food preparation waste streams.

Under such acidic conditions, charge-neutralisation coagulation is expected to be attenuated. However, the polymer bridging mechanism — in which long polysaccharide and protein chains physically link suspended particles into flocs — is less pH-dependent and may explain the substantial turbidity and BOD reductions observed despite low pH [8]. The statistically significant improvements over untreated controls under these extreme conditions confirm that bridging flocculation and direct adsorption dominate the removal mechanism. Future work should include pH-optimised conditions (pH 6–7, adjusted with lime or sodium bicarbonate) to establish the performance enhancement achievable under more favourable coagulation conditions.

4.5 TDS and Electrical Conductivity Increases

The pronounced TDS increases observed with banana peel, particularly in domestic wastewater (up to 756% at 80 g, 72 h), are a significant practical limitation. The release of soluble organic fractions (pectin fragments, low-molecular-weight sugars, organic acids) from banana peel biomass has been documented previously [12] and is consistent with banana peel's high pectin content (~11–21% dry weight), which undergoes partial hydrolytic dissolution in aqueous environments. In industrial wastewater where background TDS was already high, Acacia seeds and cassava peel showed net EC reductions rather than increases, suggesting that coagulation of ionic species outpaced soluble leaching.

Banana peel coagulant, in its crude powdered form, would increase dissolved solids load beyond the WHO drinking water limits (500 mg/L TDS). Three mitigation strategies are recommended: (i) pre-washing and water extraction of powdered material to remove soluble fractions [13]; (ii) use of heat-stabilised or acid-precipitated banana peel extracts; and (iii) limiting contact time to ≤48 hours, at which point TDS increases were more moderate.

4.6 Microbial Removal Mechanisms

The consistent reductions in TBC, total coliform, and faecal coliform counts support a physical entrapment and enmeshment mechanism of bacterial removal [17], [7]. The higher microbial removal efficiency of banana peel in domestic wastewater is attributable to the larger floc masses formed at 80 g dosage, increasing the probability of cell entrapment. The notably high cassava peel TBC removal in industrial wastewater (88.8%) is consistent with the denser sediment mass observed, which may have mechanically buried a greater proportion of microbial biomass. It must be noted that reductions in CFU counts do not necessarily reflect equivalent reductions in viable pathogen load, as floc-entrapped bacteria may not be inactivated. Disinfection as a tertiary step remains essential for any drinking water application.

4.7 Implications for Low-Resource Settings

The findings affirm the potential of banana peels, cassava peels, and Acacia seeds as practical bio-coagulants for communities with limited access to chemical treatment infrastructure [15], [8]. All three materials are freely available, generate minimal hazardous by-products, and require no chemical reagents for crude powder preparation. The valorisation of these agricultural wastes simultaneously addresses solid waste management challenges, reduces open burning of agricultural residues, and supports circular economy principles aligned with UN Sustainable Development Goals 6 and 12. Limitations — including non-standard turbidity measurement, absence of coagulant characterisation (FTIR, proximate composition), and lack of pH optimisation — should be addressed in future work.

4.8 Novelty and Original Contributions of This Study

While the individual bio-coagulant materials examined in this study have been investigated in isolation in previous work, the present study makes several novel contributions to the field. First, it provides the first direct three-way comparative evaluation of cassava peel, banana peel, and Acacia seed coagulants under identical experimental conditions, using the same wastewater sources, dosages, and contact times. This controlled comparison enables meaningful cross-material performance ranking that has been lacking in the literature [15]. Second, the study simultaneously reports physicochemical, heavy metal, and microbiological endpoints, providing a more comprehensive assessment of coagulant performance than the majority of published studies, which typically address only one or two parameter categories [1], [9]. Third, the strongly acidic pH environment (pH 1.0-2.9) under which these experiments were conducted is rarely examined in bio-coagulant studies, and the substantial removal efficiencies observed under these conditions represent an important empirical finding that challenges prevailing assumptions about pH-dependent coagulant behaviour [19]. Fourth, the kinetic modelling and statistical analysis (t-test, chi-square, ANOVA) applied here provide a more rigorous quantitative framework than the descriptive approaches that dominate the existing bio-coagulant literature.

4.9 Future Research Directions

Several directions for future research emerge from this work. First, characterisation of the active coagulant components using Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and proximate analysis would elucidate the specific functional groups and surface morphologies responsible for the observed coagulation and adsorption behaviour. Second, pH optimisation studies, using lime or sodium bicarbonate pre-adjustment to the optimal range of pH 6.0-7.5, would establish the maximum achievable removal efficiency for each bio-coagulant and enable more meaningful comparison with published benchmarks. Third, extended dosage-response experiments covering 10-200 g/L would identify the optimal dosage for each wastewater type and help detect any re-stabilisation effects at high coagulant concentrations. Fourth, pilot-scale and field trials in actual community water treatment systems would validate laboratory findings under real-world conditions, including variable flow rates, mixed pollutant loads, and seasonal variation. Fifth, computational fluid dynamics (CFD) modelling of the flocculation process and response surface methodology (RSM) optimisation of treatment parameters (dosage, contact time, pH, temperature) would support the development of predictive models for treatment plant design. Sixth, investigation of the long-term stability, shelf life, and storage conditions of prepared coagulant powders would address a practical barrier to adoption in remote communities. Finally, ecotoxicological assessment of the treated effluent and residual sludge would provide the safety data required for regulatory approval of bio-coagulant-based treatment systems in sub-Saharan Africa.

5 Conclusions

This study demonstrated that banana peels (Musa paradisiaca), cassava peels (Manihot esculenta), and Acacia seeds are effective bio-coagulants for the treatment of both domestic and industrial wastewater, achieving statistically significant reductions in turbidity (up to 91.7%), BOD_5 (up to 55.3%), total solids (up to 55.9%), heavy metal concentrations (Pb reduction up to 80.1%), and microbial load (TBC reduction up to 88.8%) at 80 g dosage and 72 hours contact time relative to untreated controls. Acacia seeds demonstrated the most consistently high and balanced performance across physicochemical, heavy metal, and solids-related parameters, driven by their proteinaceous composition and associated charge-neutralisation and adsorption capacity. Banana peel exhibited the highest BOD_5 reduction in domestic wastewater and the strongest microbial entrapment, but produced pronounced TDS and EC increases attributable to pectin leaching — a limitation requiring mitigation through pre-washing or contact time optimisation. Cassava peel showed moderate but reliable performance, underpinned by its starch-based polymer content and abundance as a local agricultural waste. The efficacy observed under highly acidic conditions suggests that polymer bridging and direct adsorption dominate the removal mechanisms, and that pH optimisation may further enhance performance. Future research should investigate optimal pH conditions, broader dosage ranges, characterisation of active coagulant components, and long-term stability of prepared coagulant powders to support scale-up and field implementation.

References:

[1] Alazaiza, M.Y.D., Alzghoul, T.M., Nassani, D.E., and Bashir, M.J.K. Natural coagulants for sustainable wastewater treatment: Current global research trends. Processes, Vol. 13, No. 6, 2025, Article 1754. https://doi.org/10.3390/pr13061754

[2] American Public Health Association (APHA). Standard Methods for the Examination of Water and Wastewater, 24th ed., APHA Press, 2023.

[3] Islam, M.A., Omi, S.M.A., and Bari, M.N. Effect of natural coagulants on the treatment of municipal wastewater. American Journal of Environmental Science and Engineering, Vol. 7, No. 2, 2023, pp. 41–50. https://doi.org/10.11648/j.ajese.20230702.12

[4] Kumar, V., Al-Gheethi, A., Asharuddin, S.M., and Othman, N. Potential of cassava peels as a sustainable coagulant aid for institutional wastewater treatment. Chemical Engineering Journal, Vol. 420, 2021, Article 127642. https://doi.org/10.1016/j.cej.2021.127642

[5] Sillanpää, M., Ncibi, M.C., and Matilainen, A. Advanced coagulation–flocculation

processes. Environmental Research, Vol. 186, 2020, Article 109500.

[6] Sacari Sacari, E.J., Torres-Lozada, P., and Arango-Vallejo, L.A. Exposure to aluminum in drinking water and the risk of developing Alzheimer's disease: A bibliometric analysis and systematic evaluation. Water, Vol. 16, No. 17, 2024, Article 2386. https://doi.org/10.3390/w16172386

[7] Singh, B.J., Chakraborty, A., and Sehgal, R. A systematic review of industrial wastewater management: Evaluating challenges and enablers. Journal of Environmental Management, Vol. 348, 2023, Article 119230.

[8] Abujazar, M.S.S., Karaağaç, S.U., Abu Amr, S.S., Alazaiza, M.Y.D., Fatihah, S., and Bashir, M.J.K. Recent advancements in plant-based natural coagulant application in the water and wastewater coagulation-flocculation process: challenges and future perspectives. Global NEST Journal, Vol. 24, No. 4, 2022, pp. 687–705. https://doi.org/10.30955/gnj.004380

[9] da Silva, R.M.P., de Farias, B.S., and Fernandes, S.S. From natural to industrial: How biocoagulants can revolutionise wastewater treatment. Processes, Vol. 13, No. 6, 2025, Article 1706. https://doi.org/10.3390/pr13061706

[10] American Public Health Association (APHA). Standard Methods for the Examination of Water and Wastewater, 24th ed., APHA Press, 2023. (See also reference [2].)

[11] Imran, M., Shahbaz Nasir Khan, S., and Abid, H. Performance evaluation of natural coagulants for wastewater treatment. Science Heritage Journal, Vol. 7, No. 1, 2023, pp. 37–42.

[12] Koul, B., Yakoob, M., and Shah, M.P. Agricultural waste-derived biosorbents for water and wastewater treatment: A review. Environmental Research, Vol. 204, 2022, Article 111891. https://doi.org/10.1016/j.envres.2021.111891

[13] Chen, X., Hossain, M.F., Duan, C., Lu, J., Tsang, Y.F., Islam, M.S., and Zhou, Y. Isotherm models for adsorption of heavy metals from water — A review. Chemosphere, Vol. 307, Pt 1, 2022, Article 135545. https://doi.org/10.1016/j.chemosphere.2022.135545

[14] Likius, D., Ndifor-Angwafor, N.G., Magabe, R., and Kuye, A. Exploring the potential of bio-coagulants from agricultural waste for water treatment: A review. Environmental Science and Pollution Research, Vol. 30, 2023, pp. 26310–26325.

[15] Michael, A., Patrick, S., Betty, N.C., Matovu, H., Prossie, N., Isa, K., and Zziwa, A. Natural coagulants for wastewater treatment in sub-Saharan Africa: A review. Archives of Agriculture and Environmental Science, Vol. 9, No. 2, 2024, pp. 385–403. https://doi.org/10.26832/24566632.2024.0902026

[16] Fan, J., Lu, Y., An, N., Zhu, W., Li, M., Gao, M., Wang, X., Wu, C., and Wang, Y. Pretreatment technologies for lignocellulosic biomass: Research progress, mechanisms, and prospects. BioResources, Vol. 20, No. 2, 2025, pp. 4897–4924.

[17] Nath, A., Mishra, A., and Pande, P.P. A review of natural polymeric coagulants in wastewater treatment. Materials Today: Proceedings, Vol. 46, 2021, pp. 6113–6117.

[18] National Environmental Standards and Regulations Enforcement Agency (NESREA). National Environmental (Surface and Groundwater Quality) Regulations. Federal Republic of Nigeria Official Gazette, Vol. 98, No. 25, 2011.

[19] Santos, D., Silva, C.A., Oliveira, T., and Freitas, R. Natural coagulants in water and wastewater treatment: A review. Environmental Nanotechnology, Monitoring and Management, Vol. 18, 2022, Article 100709.

[20] Pathak, P.D., Mandavgane, S.A., and Kulkarni, B.D. Fruit peel waste: Characterization and its potential uses. Current Science, Vol. 113, No. 3, 2021, pp. 444–454.

[21] Teh, C.Y., Wu, T.Y., and Juan, J.C. Recent advances in natural coagulants for wastewater treatment. Journal of Environmental Chemical Engineering, Vol. 10, No. 3, 2022, Article 107412.

[22] Mkilima, T., Bazarbayeva, T., Assel, K., Nurlanovna, P.A., Kydranbek, G., and Kuldeyeva, N. A review of the application of natural coagulants/flocculants in water and wastewater treatment. Water, Vol. 16, No. 1, 2024, Article 116.

[23] Ang, W.L., and Mohammad, A.W. State of the art and sustainability of natural coagulants in water and wastewater treatment. Journal of

Cleaner Production, Vol. 262, 2020, Article 121267. https://doi.org/10.1016/j.jclepro.2020.121267

[24] Rajendran, S., Priya, A.K., Kumar, P.S., Hoang, T.K., Sekar, K., Chong, K.Y., Khoo, K.S., Ng, H.S., and Show, P.L. A critical and recent developments on adsorption technique for removal of heavy metals from wastewater — A review. Chemosphere, Vol. 303, 2022, Article 135146. https://doi.org/10.1016/j.chemosphere.2022.135146

[25] UNESCO. UN World Water Development Report 2023: Partnerships and Cooperation for Water. UNESCO, 2023.

[26] Zhang, W., Song, J., Yang, Z., Wang, Y., and Li, J. Industrial wastewater treatment: Current technologies, challenges, and future perspectives. Science of the Total Environment, Vol. 748, 2020, Article 141170.

[27] Metcalf and Eddy/AECOM. Wastewater Engineering: Treatment and Resource Recovery, 6th ed., McGraw-Hill Education, 2020.

[28] World Health Organization (WHO). Global Status Report on Water Quality and Health 2022. WHO, 2022.

[29] WWAP (World Water Assessment Programme). UN World Water Development Report 2024: Water for Prosperity and Peace. UNESCO, 2024.

[30] Yin, C.Y. Emerging usage of plant-based coagulants for water and wastewater treatment. Process Biochemistry, Vol. 45, No. 9, 2010, pp. 1437-1444. https://doi.org/10.1016/j.procbio.2010.05.030

[31] Okuda, T., Baes, A.U., Nishijima, W., and Okada, M. Coagulation mechanism of salt solution-extracted active component in Moringa oleifera seeds. Water Research, Vol. 35, No. 3, 2001, pp. 830-834.

[32] Ndabigengesere, A., Narasiah, K.S., and Talbot, B.G. Active agents and mechanism of coagulation of turbid waters using Moringa oleifera. Water Research, Vol. 29, No. 2, 1995, pp. 703-710.

[33] Ho, Y.S., and McKay, G. Pseudo-second order model for sorption processes. Process Biochemistry, Vol. 34, No. 5, 1999, pp. 451-465.

[34] Lagergren, S.K. About the theory of so-called adsorption of soluble substances. Kungliga Svenska Vetenskapsakademiens Handlingar, Vol. 24, No. 4, 1898, pp. 1-39.

[35] Bezerra, M.A., Santelli, R.E., Oliveira, E.P., Villar, L.S., and Escaleira, L.A. Response surface methodology (RSM) as a tool for optimization in analytical chemistry. Talanta, Vol. 76, No. 5, 2008, pp. 965-977.

[36] Choy, S.Y., Prasad, K.M.N., Wu, T.Y., Raghunandan, M.E., and Ramanan, R.N. Performance of conventional starches as natural coagulants for turbidity removal. Ecological Engineering, Vol. 94, 2016, pp. 352-364. https://doi.org/10.1016/j.ecoleng.2016.05.082

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Oluwasanmi Adeyemi conceived and designed the research.

Oluwasanmi Adeyemi and Deborah Ogunkomaya carried out the research.

All authors were equally part of the data analysis, writing, reviewing and editing of the article.

Acknowledgement of AI Tools

Grammarly (v2.8.263) was used for grammar and spelling review; the authors are fully responsible for all content.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.