

Utilization of Banana Peel Biopolymer as a Natural Coagulant for Wastewater Treatment: A Sustainable Approach to Bio-Composite Applications

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Abstract

This study explores an eco-innovative approach to wastewater treatment by utilizing banana peel powder (BPP) as a sustainable, low-cost bio-coagulant. Although effective, conventional chemical coagulants like aluminum sulfate and synthetic polymers are often non-biodegradable, toxic, and economically burdensome, particularly in decentralized or low-resource settings. In contrast, BPP—an agro-waste material rich in bioactive functional groups such as hydroxyl, carboxyl, and phenolic compounds—provides a renewable and environmentally friendly alternative. To enhance its surface area and reactivity, banana peels were processed through washing, shade drying, grinding, and sieving to achieve a particle size below 150 μm. Wastewater samples were collected from domestic drainage systems and analyzed for parameters such as pH, turbidity, TSS, TDS, COD, BOD, chlorides, sulfates, and oil and grease. A standard jar test protocol was employed to assess the coagulation performance of BPP at varying dosages (50–150 mg/L). The optimal dosage resulted in significant reductions in turbidity (by 84.6%), TSS (59.8%), COD (73.4%), and BOD (79.4%), with minimal changes to pH, indicating its suitability for maintaining water chemistry stability. Furthermore, scanning electron microscopy (SEM) demonstrated a highly porous and irregular surface morphology of BPP, which facilitates strong adsorptive interactions with suspended pollutants. The treatment efficiency exhibited by BPP is comparable to that of conventional coagulants, validating its technical feasibility. Additionally, the valorization of banana peels into functional coagulants aligns with circular economy principles and promotes waste-to-resource strategies for environmental sustainability. This research reinforces the potential of banana peel powder as a green alternative for wastewater treatment, especially in rural or decentralized systems. It also contributes to the development of sustainable water purification technologies in support of global water security and SDG goals.

Keywords: Banana peel powder, natural coagulation, turbidity reduction, flocculation, cost-effectiveness

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Received Date: May 12, 2025

Accepted Date: June 04, 2025

Published Date: June 16, 2025

Citation: Vignesh M, Dhamothiran N, Bhuvaneshwaran E, Srinivasan A, Parameshwaran P, Dinesh S. Utilization of Banana Peel Biopolymer as a Natural Coagulant for Wastewater Treatment: A Sustainable Approach to Bio-Composite Applications. *Journal of Polymer & Composites*. 2025; 13(4): 106–115p.

INTRODUCTION

The increasing demands driven by urbanization, industrialization, and population growth have escalated the global need for accessible clean water. Conventional water purification methods rely heavily on chemical coagulants such as aluminum sulfate and ferric chloride, which, despite their effectiveness, pose environmental and health concerns. These include the generation of non-biodegradable sludge and potential health risks such as Alzheimer's disease due to prolonged exposure to aluminum [1]. These challenges underscore the necessity for sustainable, eco-friendly alternatives

in wastewater treatment. Among various natural options explored, banana peel powder has gained significant attention due to its abundance, biodegradability, and inherent functional properties that favor coagulation and adsorption mechanisms [2]. Banana peels, typically discarded as agricultural waste, contain high amounts of biopolymers such as pectin, cellulose, hemicellulose, and lignin, which provide hydroxyl and carboxyl functional groups. These groups facilitate pollutant binding by forming aggregates that settle out of solution, thereby improving water clarity [3]. Several studies have validated the ability of banana peel powder to significantly reduce turbidity, chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals such as lead, cadmium, copper, and zinc [4]. The turbidity removal rate has been reported to be as high as 90% when using finely ground, microwave-treated peel powders, which is attributed to increased surface area and enhanced adsorption kinetics [5]. Moreover, studies employing Langmuir and Freundlich isotherm models confirm monolayer adsorption behaviors, revealing that surface modification can further enhance the powder's capacity to bind specific pollutants [6]. A comprehensive review of the literature demonstrates consistent findings across various experimental setups. One study reported up to 88% turbidity removal with dried banana peel powder at pH 6.5–7.5, highlighting the presence of natural polysaccharides and proteins responsible for coagulation [7-8]. Another study showed that banana peel powder could remove heavy metals with over 90% efficiency in acidic environments, aligning with adsorption theories based on active functional groups [9-10]. Significant reductions in turbidity (82%), COD (70%), and BOD (75%) have been observed using untreated banana peel powder [11]. Comparative studies found banana peel powder to outperform other agro-wastes, such as coconut shell and orange peel, in removing turbidity and metals [12]. In further developments, chemically modified banana peel powder achieved 95% turbidity and 80% color removal from industrial wastewater, suggesting its suitability for scaled applications [13-14]. Additional investigations emphasized its dual function as a coagulant and adsorbent for dye and organic pollutant removal from industrial effluents [15]. Despite these promising results, several challenges must be addressed before banana peel powder can be adopted widely [16]. Factors such as pH tolerance, coagulation dosage, storage stability, particle size optimization, and synergistic effects with other natural coagulants require further investigation. Standardization of powder preparation methods is also critical to ensure reproducibility and scalability [17-19]. Addressing these limitations will be vital for transitioning banana peel powder from laboratory research to full-scale wastewater treatment operations. This research aims to evaluate the coagulation performance of banana peel powder for treating synthetic industrial wastewater, with a particular focus on turbidity and heavy metal removal. The study further explores the effects of pH, dosage optimization, and particle size on treatment efficiency, while also examining the potential of microwave pretreatment in enhancing surface reactivity. This work contributes to developing a cost-effective, sustainable, locally available natural coagulant that supports environmental conservation and promotes circular economy principles through agro-waste valorization.

MATERIALS AND METHODS

In response to growing concerns over the environmental hazards posed by chemical coagulants in wastewater treatment, this study explores a sustainable, low-cost alternative using banana peel powder—a biodegradable agricultural waste rich in lignin, cellulose, and pectin compounds known for their natural adsorptive and coagulating properties. The selection of banana peel as a natural coagulant was motivated by its abundant availability, high organic content, and proven affinity for binding pollutants via flocculation and sedimentation mechanisms, offering a green approach to wastewater purification. Figure 1 shows the Methodology for treating wastewater using banana peel powder [20-21].

Materials Collection and Preparation

Fresh ripe bananas were procured from a local market, and the peels were separated post-consumption. The peels were washed thoroughly under running tap water to remove adhering dirt and organic residues. They were then chopped into smaller segments to facilitate uniform drying. A two-step drying method was adopted—initial sun-drying for two weeks to reduce moisture through natural

desiccation, followed by oven-drying at 105°C for 24 hours to ensure complete removal of residual moisture. This dual-phase drying process was chosen to preserve the fibrous matrix's structural integrity and enhance the adsorption surface area [22]. The dried banana peels were ground using a mechanical grinder into fine powder and stored in air-tight, contamination-free containers. The granular texture was optimized to improve the contact efficiency between the coagulant and suspended pollutants during treatment. Figure 2 shows the raw banana peel, while Figure 3 depicts the powdered form of the raw banana peel.

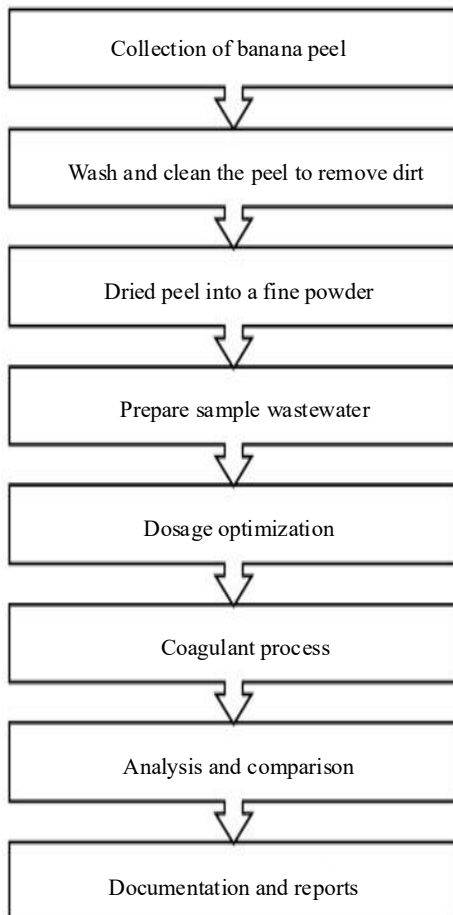


Figure 1. The flowchart of the wastewater treatment methodology using banana peel powder.



Figure 2. Raw banana peel before processing.



Figure 3. Ground banana peel powder used as a coagulant

Wastewater Sample Collection and Characterization

Representative wastewater samples were collected from a laboratory effluent stream using standard grab sampling techniques to ensure consistency in pollutant concentration and sample quality. The selection of this source allowed for a controlled analysis of pollutant removal under laboratory-scale conditions while maintaining relevance to domestic and semi-industrial wastewater types. Water samples were systematically collected using pre-sterilized polyethylene containers to prevent external contamination [22]. To preserve the physicochemical integrity of the samples, they were immediately stored under chilled conditions and transported to the laboratory for prompt analysis. This ensured the minimization of any biological or chemical alterations before testing. A comprehensive baseline characterization was performed to quantify key pollution indicators, including turbidity, total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), pH, alkalinity, acidity, electrical conductivity, sulphates, chlorides, and oil and grease content. These parameters were chosen for their critical roles in defining the pollution profile of the water matrix and serve as essential benchmarks for assessing the performance and efficiency of subsequent treatment methodologies. [23-24].

Coagulation Procedure and Analytical Method

Standardized jar test experiments were conducted using varying concentrations of banana peel powder, ranging from 50 mg/L to 150 mg/L, to emulate practical coagulation scenarios. Each trial commenced with a rapid mixing phase of 2 minutes at 150 rpm to ensure uniform dispersion of the coagulant throughout the suspension. This was followed by a slow agitation phase lasting 20 minutes at 30 rpm to facilitate effective flocculation, and subsequently, a quiescent sedimentation period of 30 minutes to allow the formed flocs to settle. This experimental protocol was meticulously designed in alignment with established coagulation-flocculation procedures to ensure consistency, reproducibility, and accurate comparative analysis of the treatment efficacy. After settling, the supernatant was extracted carefully and subjected to post-treatment analysis for the same parameters assessed initially. The selected methodology ensures systematic evaluation of the banana peel powder's coagulating efficiency across various concentrations, enabling dosage optimization for maximal contaminant removal with minimal material usage. The procedure emphasizes cost-effectiveness, environmental safety, and the valorization of organic waste, positioning banana peel powder as a promising green alternative in sustainable wastewater treatment applications [25].

Figure 4 illustrates the manual collection of a domestic wastewater sample using a sterile container under field conditions. This process ensures representative sampling for subsequent laboratory analysis of key physicochemical parameters. The procedure highlights adherence to proper sample handling protocols to minimize contamination and preserve the integrity of water quality indicators for accurate treatment assessment.



Figure 4. Collection of a water sample.

EXPERIMENTAL TESTING

The potential of banana peel powder as a sustainable, natural coagulant was evaluated through a modified jar test protocol to identify an environmentally benign and cost-efficient alternative to conventional chemical coagulants. Representative wastewater samples were systematically collected and initially characterized for critical quality parameters, including pH, turbidity, total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) [26]. Owing to its abundance of surface-active functional groups—such as carboxyl, hydroxyl, and phenolic moieties—banana peel biomass was processed via sequential washing, shade-drying, pulverization, and sieving to obtain a homogenous fine powder ($<150\ \mu\text{m}$), ensuring enhanced surface area and effective dispersion in aqueous media. For each experimental run, 1-liter aliquots of wastewater were treated with banana peel powder at 50, 75, 100, 125, and 150 mg/L dosages. The coagulation-flocculation sequence consisted of rapid mixing at 150 rpm for 5 minutes to achieve uniform distribution of the coagulant, followed by gentle agitation at 50 rpm for 15 minutes to facilitate floc formation. Subsequently, the suspension was allowed to settle undisturbed for 30 minutes. The clarified supernatant was then carefully extracted and reanalyzed for the parameters above to assess treatment efficacy and pollutant removal efficiency. The effectiveness of banana peel powder as a natural coagulant was assessed using a customized beaker test method to explore an eco-friendly and cost-effective alternative to conventional chemical coagulants. Wastewater samples were collected and analyzed for key initial parameters, including pH, turbidity, TSS, TDS, COD, and BOD [26]. Banana peels, rich in functional groups such as carboxyl, hydroxyl, and phenolic compounds, were processed by washing, shade-drying, grinding, and sieving to obtain fine powder ($<150\ \mu\text{m}$) for optimal dispersion and interaction. In each trial, 1-liter wastewater samples were treated with banana peel powder at 50, 75, 100, 125, and 150 mg/L. The coagulation process involved rapid mixing at 150 rpm for 5 minutes, followed by slow mixing at 50 rpm for 15 minutes to promote floc formation. After settling for 30 minutes, the supernatant was extracted and reanalyzed for the same parameters [27]. This approach utilizes agricultural waste and reduces chemical dependency in water treatment. The findings may contribute to developing scalable, sustainable treatment technologies for decentralized wastewater systems, with future studies focusing on coagulant blending, pH optimization, and performance in real industrial effluents.

Key chemical parameters of the effluents include pH (ranging from 6.63 to 12.70), specific gravity (approximately $1.52\text{--}1.53\ \text{g/cm}^3$), and constituents such as SiO_2 , Na_2O , Fe_2O_3 , K_2O , P_2O_5 , and MgO . Al_2O_3 was below detectable limits in all samples. To assess the impact of this substitution, a systematic mix design was developed using two alkaline-to-binder ratios ($A1 = 0.4$ and $A2 = 0.5$) and two binder compositions: BG25 (75% bottom ash and 25% GGBS) and BG50 (50% bottom ash and 50% GGBS). Sodium hydroxide (NaOH) was used at three molarities—4 M, 6 M, and 8 M. Effluent was used to replace Na_2SiO_3 in five proportions: 0%, 25%, 50%, 75%, and 100%. This resulted in a total of 60 distinct mix combinations, labeled from 4A1BG25E0 to 8A2BG50E100. All specimens were cast and ambient-cured. Each mix was used to prepare test specimens for compressive strength ($100 \times 100 \times 100$ mm cubes), split tensile strength (100×200 mm cylinders), and flexural strength ($100 \times 100 \times 500$ mm prisms). Three cube specimens were tested at 7, 14, and 28 days for compressive strength, while two specimens each were tested at 28 days for tensile and flexural properties. Material quantities were computed for each batch based on the binder and alkaline liquid proportions, ensuring uniformity across the testing matrix. Table 1 shows that the textile effluents have varied pH levels, consistent specific gravity, and differing concentrations of key oxides like SiO_2 , Na_2O , and MgO , indicating their potential as sodium silicate substitutes in geopolymer production.

RESULTS AND DISCUSSION

The coagulation performance of banana peel powder in treating wastewater was evaluated by comparing the reduction in key physicochemical parameters before and after treatment. Table 2 presents the measured values and corresponding removal efficiencies for each parameter. A significant reduction in turbidity was observed, decreasing from 1.3 mg/L to 0.2 mg/L, representing an efficiency of 84.62%. This indicates excellent clarification potential due to the effective agglomeration of colloidal particles

by the bioactive compounds in the banana peel powder. Total Suspended Solids (TSS) also showed a substantial decrease from 172 mg/L to 69 mg/L (59.88% efficiency), attributed to solid particles' physical entrapment and sedimentation within the flocs formed during slow mixing.

The treatment process reduced Chemical Oxygen Demand (COD) from 248 mg/L to 136 mg/L (45.16% removal) and Biochemical Oxygen Demand (BOD) from 66 mg/L to 28 mg/L (57.58% removal), confirming banana peel powder's capacity to eliminate biodegradable and non-biodegradable organic matter. The functional groups in the powder likely adsorbed dissolved organic compounds, enhancing overall oxygen demand reduction. For oil and grease, a notable reduction from 3 mg/L to 1mg/L (66.67% efficiency) was achieved, suggesting effective hydrophobic interactions between lipid molecules and the fibrous structure of the coagulant. Sulfate concentration dropped from 136 mg/L to 96 mg/L (29.41% reduction). In comparison, chloride showed a relatively lower decrease from 275 mg/L to 240 mg/L (12.73% efficiency), possibly due to the limited ion-exchange capacity of the natural coagulant for these anions. The reduction in alkalinity from 196 mg/L to 132 mg/L (32.65%) indicates partial buffering of the solution, which may support future dosage control and process pH tuning. Overall, the results demonstrate the potential of banana peel powder as a viable, eco-friendly coagulant in primary wastewater treatment. Further optimization, including pH adjustments and composite formulations with other natural or low-toxicity agents, could enhance its efficacy in treating complex industrial effluents.

Figure 5 illustrates the comparative reduction in key wastewater parameters before and after treatment with banana peel powder. Significant decreases were observed in turbidity (from 1.3 to 0.2 NTU), TSS (172 to 69 mg/L), total solids (1946 to 829 mg/L), COD (248 to 66 mg/L), and BOD (136 to 28 mg/L), demonstrating the effective pollutant removal capability of the bio-coagulant. Minor reductions in TDS, chlorides, sulphates, oil & grease, and alkalinity further support the treatment's overall efficacy. The negligible change in pH indicates that the banana peel powder did not adversely affect the water's acid–base balance. The figure supports the data in Table 2, validating the natural coagulant's potential for eco-friendly wastewater remediation. Table 3 outlines the recommended dosage range of banana peel powder for effective wastewater treatment, based on the observed reductions in specific parameters. The data show that lower dosages (50–75 mg/L) suffice for decreasing turbidity, oil, and grease while maintaining pH stability. Moderate dosages (75–125 mg/L) effectively target parameters like TSS, chlorides, sulfates, BOD, and alkalinity. Higher dosages (100–150 mg/L) are necessary for substantial reductions in COD, total dissolved solids (TDS), and total solids, especially when initial concentrations are elevated. The banana peel powder has demonstrated effective treatment potential for various pollutants, with dosage requirements varying according to pollutant load and type.

Table 1. Chemical properties of textile effluent [28-29]

S no	Parameters	Mercerizing - 1 process	Mercerizing- 2 process	Washing process	Wetting process	Bleaching process
1	pH	7.91	12.70	7.07	6.63	8.10
2	Colour	Yellowish	Yellowish	Yellowish	Yellowish	White
3	Specific gravity	1.53g/cm ³	1.53g/cm ³	1.52g/cm ³	1.52g/cm ³	1.52g/cm ³
4	SiO ₂	95.00mg/l	28.73mg/l	38.38mg/l	73.86mg/l	137.80mg/l
5	Na ₂ O	177.93mg/l	1887.15mg/l	103.79mg/l	98.40mg/l	266.90mg/l
6	Fe ₂ O ₃	1.92mg/l	1.11mg/l	1.02mg/l	2.24mg/l	0.33 mg/l
7	Al ₂ O ₃	BDL [D.L:0.01]	BDL [D.L:0.01]	BDL [D.L:0.01]	BDL [D.L:0.01]	BDL [D.L:0.01]
8	K ₂ O	2.01mg/l	4.46mg/l	3.25mg/l	10.09mg/l	1.04mg/l
9	P ₂ O	36.00mg/l	24.54mg/l	45.83mg/l	249.85mg/l	2.82mg/l
10	MgO	88.04mg/l	16.77mg/l	117.36mg/l	184.47mg/l	238.96mg/l

Table 2. Before and after water comparison.

Parameter	Before treatment value (mg/L)	After treatment value (mg/L)	Reduction efficiency (%)
Turbidity	1.3	0.2	84.62%
TSS	172.0	69.0	59.88%
COD	248.0	136.0	45.16%
BOD	66.0	28.0	57.58%
Oil & Grease	3.0	1.0	66.67%
Sulphates	136.0	96.0	29.41%
Chlorides	275.0	240.0	12.73%
Alkalinity	196.0	132.0	32.65%

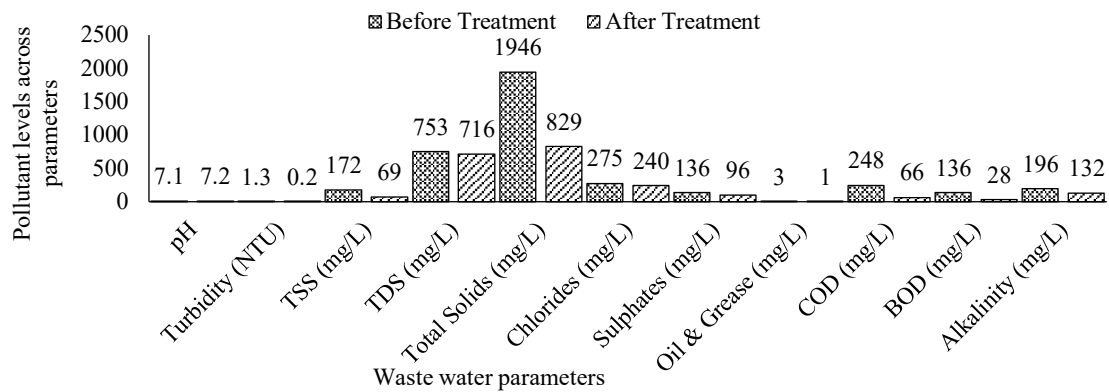


Figure 5. Comparison of wastewater parameters before and after treatment with banana peel powder.

Table 3. Dosage for the use of banana peel powder.

Parameter	Before treatment value	After treatment value	Target standard	Optimum dosage (mg/L)	Remarks
pH	7.14	7.23	Max 9.0	-	pH is within acceptable limits with minimal impact from the coagulant.
Turbidity (NTU)	1.3	0.2	Max 5.0	50–75	Lower dosage is sufficient due to low initial turbidity.
Total Suspended Solids (TSS, mg/L)	172.0	69.0	Max 100.0	75–125	Significant reduction in dosage adjusted for high initial TSS.
Total Dissolved Solids (TDS, mg/L)	753.0	716.0	Max 2100.0	100–150	Minimal impact as banana peel powder primarily targets suspended solids.
Total Solids (mg/L)	1946.0	829.0	No Standard	100–150	Reduction due to TS removal. A high initial value required a moderate dosage.
Chloride as Cl ⁻ (mg/L)	275.0	240.0	Max 1000.0	75–125	Adequate reduction with moderate dosage.
Sulphate as SO ₄ (mg/L)	136.0	96.0	Max 1000.0	75–125	Effective reduction with banana peel powder.
Oil & Grease (mg/L)	3.0	1.0	Max 10.0	50–75	Efficient removal at lower dosages.
Chemical Oxygen Demand (COD, mg/L)	248.0	136.0	Max 250.0	100–150	Organic load is significantly reduced with a moderate dosage.
Biochemical Oxygen Demand (BOD, mg/L)	66.0	28.0	Max 30.0	100–125	High reduction observed dosage adjusted for effectiveness.
Alkalinity (as CaCO ₃ , mg/L)	196.0	132.0	No Standard	75–100	Slight reduction observed, moderate dosage sufficient.

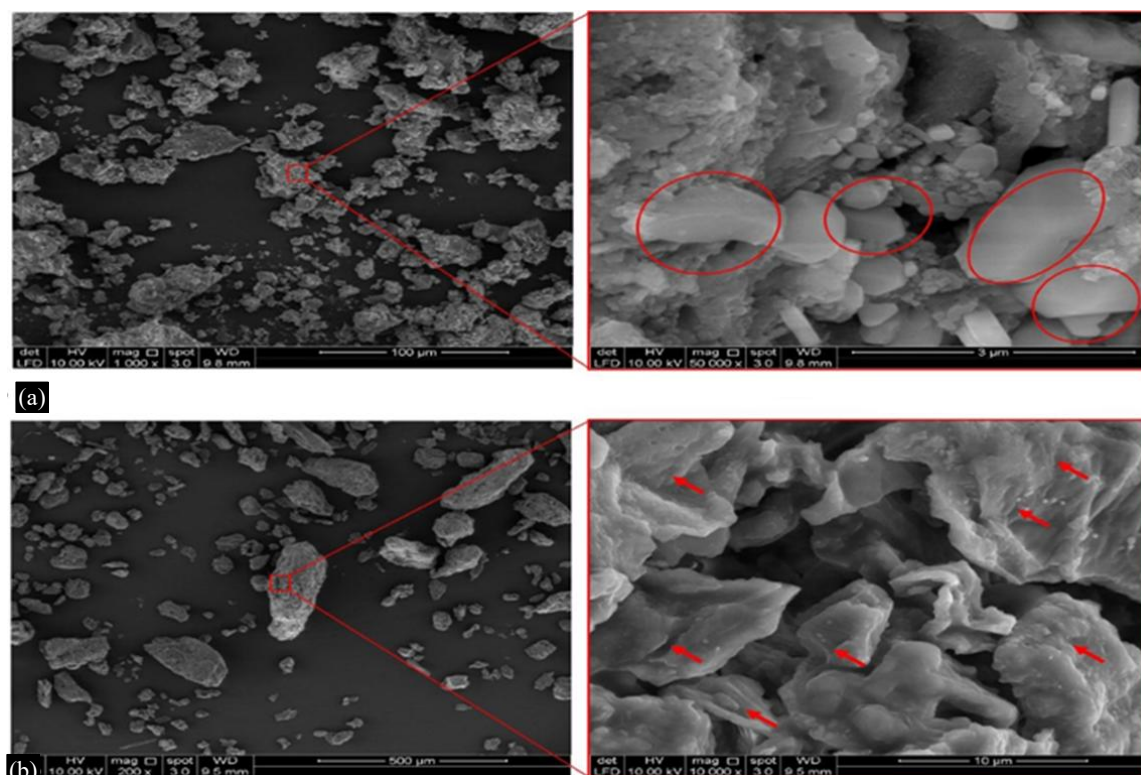


Figure 6. Microstructural analysis of banana peel powder.

The detailed reduction efficiency calculations reveal that banana peel powder is particularly effective in removing turbidity (84.62%), oil and grease (66.67%), TSS (59.88%), and BOD (57.58%), indicating strong coagulation and organic pollutant adsorption capabilities. Moderate reductions were observed in COD (45.16%) and alkalinity (32.65%), while sulphates (29.41%) and chlorides (12.73%) showed lower removal efficiencies, suggesting limited ion-exchange or chemical binding with these inorganic constituents. Overall, the results validate banana peel powder as a promising natural coagulant, especially for reducing particulate and organic contaminants in wastewater.

Figure 6 presents the microstructural analysis of banana peel powder using Scanning Electron Microscopy [30]. Image (a) reveals irregularly shaped, compact particles with smooth surfaces and distinct flake-like structures, as highlighted in the magnified region. These morphologies suggest the presence of cellulose and lignin-rich components conducive to pollutant adsorption. Image (b) shows fragmented and rough-textured surfaces with micro-porosities and layered structures, which increase surface area and potentially enhance coagulation efficiency. The red arrows in the magnified region indicate surface irregularities that support effective interaction with suspended particles in wastewater. These microstructural features affirm the potential of banana peel powder as a natural bio-coagulant with functional topography favorable for pollutant capture.

CONCLUSION

This study highlights the promising potential of banana peel powder as a sustainable, low-cost, and eco-friendly natural coagulant for wastewater treatment. The application of this agro-waste material led to significant improvements in key water quality indicators, including a reduction in COD from 248 mg/L to 136 mg/L, TSS from 172 mg/L to 69 mg/L, turbidity from 1.3 NTU to 0.2 NTU, and BOD from 66 mg/L to 28 mg/L. These reductions affirm banana peel powder's effectiveness in targeting organic and particulate contaminants. The optimal coagulant dosage was identified in the range of 50–150 mg/L, providing a highly efficient pollutant removal rate, particularly in turbidity (84.6%), TSS (59.9%), and BOD (57.6%), while maintaining pH within acceptable limits. This approach utilizes biodegradable agricultural waste and offers a replicable and cost-efficient method suitable for

decentralized wastewater management systems. Future applications could integrate this natural coagulant into hybrid or scaled-up systems, contributing to greener water purification technologies and circular waste management strategies.

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