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Effect of the Rapid Mixing Speed on the Coagulation-Flocculation Process Using Natural-Based Coagulant in Domestic Wastewater Treatment

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ABSTRACT

Natural coagulants are an imperative alternative method as they offer a sustainable and eco-friendly approach to replace chemical coagulants in domestic wastewater treatment. The objectives of this research are to investigate the effect of rapid mixing speed on the removal performance of turbidity, total suspended solids (TSS) and total dissolved solid (TDS) using banana peel waste as natural coagulant in domestic wastewater using coagulation-flocculation process. The banana peels were converted into fine powder and used at fixed dosage of 0.02 g/L. The parameter of rapid mixing speed was varied at three different speeds of 100, 150 and 200 rpm for duration of 3 minutes, followed by slow mixing speed at 10 rpm for 20 minutes and settling time period of 30 minutes. The findings indicated that the turbidity removal increased slightly with an increase of rapid mixing speed, with the highest removal of 88.21%. For TSS, the removal performance showed 87.53% at 100 rpm and decreased with the increase of speed, indicating floc breakage due to the high-speed mixing, thus reducing the settling efficiency. While TDS removal was observed, the best result was rapid mixing speed at 150 rpm (23.37%), suggesting limited impact of the speed on the dissolved solids. The result demonstrates the factor of rapid mixing speed enables initial dispersion and particle destabilization, excessive agitation can compromise floc stability, mainly for suspended solids. Hence, it is crucial to optimize the rapid mixing intensity to enhance the coagulation-flocculation performance of the banana peels as natural coagulants, to ensure the treatment of domestic wastewater becomes more effective and sustainable.

1. Introduction

Water pollution caused by domestic wastewater discharge remains a major environmental concern, particularly in developing countries where centralized treatment facilities are limited. Domestic wastewater discharges continue to be a major source of water contamination, especially in developing nations with few treatment facilities. Turbidity, suspended particles, and colloidal

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debris are frequently removed using traditional treatment techniques like coagulation-flocculation. Because of their demonstrated efficacy and affordability, these procedures usually rely on chemical coagulants such as ferric chloride and aluminum sulfate (alum). But their ongoing usage has a number of disadvantages, including as producing non-biodegradable sludge, changing the pH of treated water, and feasibly endangering human health and the environment due to residue iron and aluminum salts [1], [2]. Researchers are now investigating natural-based or bio-coagulants as potential substitutes that are locally accessible, biodegradable, and environmentally acceptable because to the growing emphasis on sustainability and green technology.

Many coagulants derived from plants have shown great promise in the treatment of water and wastewater in recent years. For instance, cationic proteins found in *Moringa oleifera* seeds, which are among the most researched, neutralize negatively charged colloids and efficiently lower turbidity and suspended particles [3]. Also, *Cactus Opuntia ficus-indica* mucilage comprises long-chain polysaccharides that turn as bridging agents, helping the aggregation of fine particles [4]. Extracts from the seeds of *Tamarindus indica* and *Cassia fistula* have also demonstrated exceptional coagulation qualities through hydroxyl and carboxyl functional groups that facilitate charge neutralization and adsorption [5]. When turned into powders or extracts, other agricultural wastes like orange peels, rice husks, papaya seeds, and corn cobs have been shown to have comparable properties [6]. These results imply that a variety of biomass resources can be turned into bio-coagulants, providing affordable options that also lessen the issues associated with disposing of agricultural waste.

Because of its abundance, affordability, and rich composition of lignocellulosic materials including cellulose, hemicellulose, lignin, and pectin from banana peel stands out among other natural coagulant sources. These biopolymers contain active hydroxyl (–OH) and carboxyl (–COOH) functional groups that facilitate charge neutralization, adsorption, and bridging mechanisms during coagulation. Compared with other natural coagulants such as *M. oleifera* seeds, *O. ficus-indica* mucilage, or tamarind seeds, banana peels are readily available year-round, require no extraction or chemical modification, and represent a low-cost agricultural by-product that contributes to waste minimization and circular economy practices [7].

Although several studies have verified the ability of banana peel powder to remove turbidity, total suspended solids (TSS), and even trace metals from water, most previous research has focused primarily on dosage optimization, pH, or contact time, with little emphasis on hydrodynamic parameters that strongly influence the efficiency of the coagulation–flocculation process. To date, the effect of rapid-mixing intensity on the coagulation performance of banana-peel-based coagulants has not been systematically investigated [8].

Therefore, this study specifically aims to evaluate the impact of rapid mixing speed on turbidity, TSS, and total dissolved solids (TDS) removal in domestic wastewater treatment using banana peel powder as a natural coagulant. The findings are expected to provide new insights into operational optimization and scale-up feasibility of plant-based coagulants as sustainable alternatives to conventional chemical coagulants.

2. Methodology

2.1 Preparation of Natural Coagulant

The banana waste (peels) were selected as the main material for producing natural coagulant in this research due to its nature of abundance, biodegradability and availability as agricultural waste. The peels were collected from Pagoh Jaya, Johor (Malaysia), specifically taken from local vendor. The waste was washed meticulously using tap water to remove any impurities and then rinsed to minimize to reduce or remove any residue of impurities.

The washed and cleaned banana peels were cut into small pieces with the size of approximately 1-2 cm to help uniform drying process. The peels then were dried using oven at set temperature at 90°C for estimated 2 hours to remove moisture content in the sample. Drying at moderate temperature ensured the preservation of the natural organic composition of the material. After the drying process completed, the sample was grounded using blender (Panasonic, Malaysia) to obtain a fine powder. To attain a consistent size of powder, the dried sample was sieved through 250 µm mesh filter to ensure uniform particle size distribution, due to the fine particle could improve solubility and dispersion throughout coagulation-flocculation process. The produced powder was collected and stored in an airtight polyethylene container at room temperature to avoid any moisture absorption and microbial growth prior its usage for the experimental purposes. No additional chemical treatment or activation was useful, to assess the essential coagulation potential of the untreated banana peel biomass.

2.2 Coagulation Test Conditions

Coagulation–flocculation experiments were conducted at room temperature using a standard jar-test apparatus to simulate conventional wastewater treatment. Each test used 500 mL of domestic wastewater with a fixed banana-peel powder dosage of 0.02 g/L, determined from preliminary trials as the most effective dose. The effect of rapid-mixing intensity was examined at 100, 150, and 200 rpm, while other parameters slow mixing (10 rpm for 20 min) and settling time (30 min) were kept constant. The rapid-mixing stage lasted 3 minutes to disperse the coagulant and initiate particle destabilization. After settling, the clarified supernatant was carefully withdrawn and analyzed for turbidity, TSS, and TDS. All tests were performed in triplicate to ensure reproducibility.

2.3 Parameters Measured

2.3.1 Turbidity

Turbidity of the treated and untreated wastewater samples was measured using a portable digital turbidity meter, and expressed in Nephelometric Turbidity Units (NTU). Each sample was gently mixed before analysis to achieve homogeneity without resuspending settled flocs. Approximately 25 mL of the supernatant was carefully transferred into a clean, dry glass cuvette, avoiding air bubbles and turbidity disturbance. The exterior of the cuvette was wiped with a lint-free tissue to remove fingerprints or moisture that could scatter light. The cuvette was then inserted into the instrument, aligning the index mark on the vial with the reference mark inside the sample compartment to maintain consistent optical orientation.

The turbidity reading was allowed to stabilize for several seconds before recording. Three replicate measurements were taken for each sample, and the average value was reported. Between measurements, the cuvette was rinsed thoroughly with distilled water to prevent cross-contamination. All turbidity measurements were conducted under ambient laboratory conditions and expressed as mean ± standard deviation to account for minor instrumental variations.

2.3.2 Total Suspended Solids (TSS)

The concentration of TSS in the samples was determined using the gravimetric method. This procedure quantifies the mass of particulate matter retained on a filter after sample filtration and drying. Clean filter papers were pre-dried in a hot-air oven at 105 ± 5 °C for 1 hour to remove any residual moisture. After drying, the filters were cooled in a desiccator for 30 minutes and their initial dry weight (W_1) was recorded using an analytical balance.

An aliquot of 100 mL of the supernatant sample was filtered through the pre-weighed filter under gentle vacuum. The filtrate was discarded while the filter containing the retained solids was again dried at 105 ± 5 °C for 2 hours, then cooled in a desiccator and weighed to obtain the final dry weight (W_2). TSS concentration (mg/L) was calculated using the following equation. Eq.(1):

$$TSS\ \left(\frac{mg}{L}\right) = \frac{W_2 - W_1}{V} \tag{1}$$

where W_1 = initial dry weight (mg), W_2= final dry weight (g) and V= sample volume (L)

Each analysis was performed in triplicate, and the mean values were reported. All glassware and filtration apparatus were rinsed with distilled water between runs to prevent contamination or residue carry-over.

2.3.3 Total Dissolved Solids (TDS)

TDS concentration of the treated and untreated wastewater samples was measured using a digital TDS meter. Measurements were conducted by immersing the probe of the TDS meter directly into a clean beaker containing approximately 50 mL of the supernatant sample. Care was taken to avoid air bubbles or contact between the probe and the vessel wall, which could interfere with sensor accuracy. The reading was allowed to stabilize for several seconds, and the displayed value was recorded.

Between successive measurements, the probe was rinsed thoroughly with distilled water and gently dried with a lint-free tissue to prevent cross-contamination. All readings were taken at ambient temperature (25 °C). For each condition, three replicate measurements were obtained, and the mean values were reported. This method provides a rapid and reliable estimate of the dissolved ionic and molecular species present in the water sample and complements turbidity and TSS analyses to evaluate the overall treatment efficiency of the coagulation–flocculation process.

3. Results

3.1 Effect of on Turbidity Removal

The influence of rapid mixing speed on turbidity removal using banana-peel-based natural coagulant was evaluated at three agitation speeds of 100, 150, and 200 rpm. The untreated domestic wastewater used in this study had an initial turbidity of 180 ± 3.5 NTU, total suspended solids (TSS) of 310 ± 4.1 mg/L, and total dissolved solids (TDS) of 291 ± 2.1 mg/L, which served as baseline reference values. The reported removal efficiencies were calculated relative to these initial readings. All analyses were performed in triplicate, and the data are expressed as mean ± standard deviation to indicate reproducibility and minimize random experimental error. The results, illustrated in Figure 1, indicate a positive correlation between mixing speed and turbidity removal efficiency.

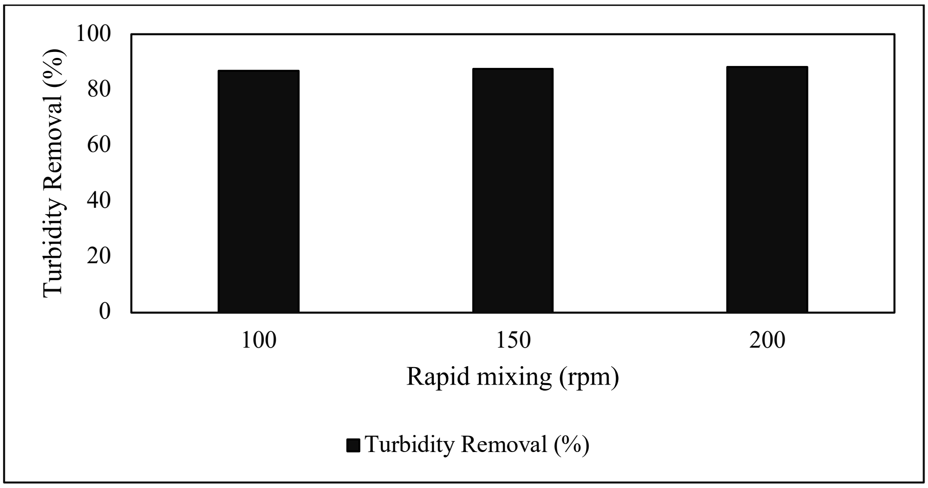

Fig. 1. Removal performance of turbidity

At 100 rpm, the turbidity removal reached 86.77%, increasing to 87.65% at 150 rpm, and achieving the highest removal of 88.21% at 200 rpm. This gradual increase demonstrates that greater agitation during the rapid-mixing phase enhances coagulant dispersion and particle destabilization.

The graph trend shows a consistent upward pattern, suggesting that higher mixing intensity promoted more effective contact between the coagulant particles and colloidal impurities. The improvement at higher rpm can be attributed to better hydrodynamic distribution of the coagulant, allowing active sites on the banana peel powder to interact more efficiently with negatively charged suspended particles. This enhances charge neutralization and adsorption-bridging mechanisms, which are crucial for turbidity reduction [8], [9].

Among the tested speeds, 200 rpm produced the highest turbidity removal (88.21%), representing the optimum condition under the current experimental setup. The improvement, although moderate, confirms that sufficient shear energy is necessary during the initial coagulation phase to disperse the coagulant effectively throughout the solution [10]. However, the differences between 150 rpm and 200 rpm were relatively small, implying that moderate agitation could achieve comparable results with lower energy demand, an important consideration for small-scale or rural wastewater-treatment systems. This behaviour can be explained by the combined effects of charge neutralization and adsorption–bridging mechanisms. At higher mixing speeds, the dispersion of banana-peel-derived coagulant particles increases the collision frequency between negatively charged colloids and the functional groups (–OH, –COOH) on the coagulant surface, enhancing destabilization. However, excessive turbulence can disrupt microflocs before they mature, leading to re-suspension of fine particles and limiting further turbidity reduction. Therefore, an optimal balance between energy input and floc stability is essential for effective turbidity removal [8].

A comparison with previous studies supports these observations. Studies indicated that a rapid mixing speed of around 200 rpm for 1 minute is optimal for turbidity removal, achieving up to 96.5% efficiency in highly turbid water (500 NTU) [11]. Similarly, Increased mixing energy initially promotes better dispersion and interaction of coagulants with particles, leading to improved floc formation. For instance, studies indicate that optimal rapid mixing times for natural coagulants like Moringa Oleifera can significantly enhance the removal of contaminants such as Fe and Mn, with specific optimal times identified for maximum efficiency [12] . In another study, Azamzam et al., [7] achieved up to 90% turbidity removal using banana-peel powder in synthetic wastewater, consistent with the results obtained in the present research. Furthermore, effective rapid mixing is crucial in the coagulation-flocculation process, as it enhances initial particle destabilization, leading to improved floc formation. However, excessive turbulence can compromise floc stability, resulting in reduced efficiency of the treatment process [13], [14].

Overall, the findings demonstrate that the rapid mixing speed significantly affects the performance of banana-peel coagulant, with higher speeds promoting better dispersion and contact between coagulant and suspended solids. The optimum performance was achieved at 200 rpm, providing the best turbidity removal efficiency of 88.21%. These results are in good agreement with literature findings and confirm that banana peel powder can serve as an effective, sustainable, and low-cost natural coagulant for domestic wastewater treatment.

3.2 Total Suspended Solids (TSS) Removal

The impact of rapid mixing speed on the removal efficiency of total suspended solids (TSS) was evaluated at 100, 150, and 200 rpm, with all other conditions held constant. The results in Figure 2 showed a decreasing trend in TSS removal as mixing speed increased.

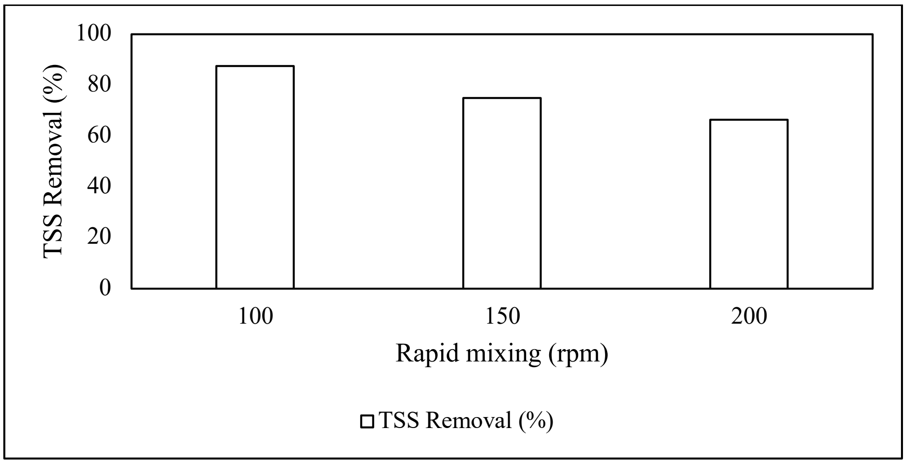

Fig. 2. Removal performance of TSS

At a rapid mixing speed of 100 rpm, the highest removal efficiency of 87.53% was achieved. As the speed increased to 150 rpm, the removal efficiency dropped to 74.95%, and further declined to 66.45% at 200 rpm. This downward trend indicates that excessive mixing intensity has an adverse effect on the coagulation–flocculation process, mainly due to floc disintegration during the high-shear mixing phase [15].

At the lower speed of 100 rpm, gentle agitation allowed the formation and growth of stable flocs, resulting in efficient settling during the sedimentation period. However, when the mixing intensity increased beyond this level, the turbulence likely exceeded the structural strength of the flocs, causing breakage and re-suspension of particles, which reduced the overall TSS removal performance [16]. This observation suggests that the optimum mixing intensity for TSS removal is lower than that required for turbidity removal, since suspended solids are more sensitive to shear stress once larger flocs have formed. The opposite trend observed for TSS removal compared to turbidity is due to the fragility of larger flocs formed during slow mixing. At low rpm, gentle agitation promotes aggregation and growth of dense flocs that settle efficiently. Increasing the shear rate weakens the interparticle bonds and fragments the flocs into smaller particles that remain suspended. This behavior aligns with classical flocculation theory, where excessive hydrodynamic stress exceeds the cohesive strength of the flocs, resulting in reduced sedimentation efficiency [17].

Similar findings have been reported in previous studies. Marques et al., [18] highlighted that high mixing energy can break flocs formed by natural coagulants, reducing sedimentation efficiency and increasing residual turbidity. Likewise, it was observed that for bio-based coagulants, the size and integrity of flocs are strongly influenced by hydrodynamic shear conditions during rapid mixing. When shear forces exceed the cohesive strength of the flocs, smaller and lighter particles remain suspended, leading to poorer solid–liquid separation [19], [20].

The present results align with the multiple studies confirm that moderate agitation speeds during coagulation-flocculation with *M. oleifera* are optimal for TSS and turbidity removal. Excessive agitation can break up flocs, reducing removal efficiency, while too little agitation leads to poor floc formation and lower performance [21], [22]. The efficiency of natural coagulants in water treatment is highly dependent on the velocity gradient during mixing. Exceeding the optimal velocity gradient leads to decreased removal efficiency, primarily because intense agitation causes floc breakage, which is a key limitation for these systems [23], [24].

From the graph, it is evident that 100 rpm provided the optimum condition for TSS removal, balancing adequate mixing for coagulant dispersion with minimal shear stress on flocs. Beyond this point, the negative impact of turbulence outweighs any benefit of increased dispersion. These results highlight the importance of optimizing mixing conditions specifically for each water parameter, as the mechanisms governing turbidity and TSS removal differ in their sensitivity to hydrodynamic forces [25], [26].

Overall, the findings confirm that rapid mixing speed is detrimental to suspended-solids removal, and that controlled agitation at 100 rpm provides the most effective TSS reduction (87.53%) when using banana-peel-based natural coagulant. This result is consistent with earlier studies and underscores the need for process optimization to maintain floc stability while achieving efficient clarification.

3.3 Total Dissolved Solids (TDS) Removal

The effect of rapid mixing speed on the removal of total dissolved solids (TDS) is presented in Figure 3. In contrast to turbidity and TSS, the removal of TDS did not follow a consistent linear trend with increasing mixing speed. The TDS removal efficiency was 18.21% at 100 rpm, increased slightly to the highest value of 23.37% at 150 rpm, and then declined to 16.38% at 200 rpm. This non-linear pattern suggests that TDS removal is governed primarily by weak adsorption and entrapment mechanisms rather than coagulation alone. At moderate mixing speeds (around 150 rpm), better coagulant dispersion enhances the likelihood of dissolved ions and fine colloidal matter becoming trapped within forming flocs. However, high turbulence (200 rpm) prevents stable attachment and can cause previously adsorbed ions to detach. Since TDS includes dissolved salts and organic molecules not easily precipitated, coagulation using banana peel powder mainly provides partial reduction through physical entrapment rather than chemical removal [26].

The graph pattern suggests that an intermediate level of mixing energy (150 rpm) enhances the interaction between the banana peel coagulant and dissolved substances in the wastewater. At this speed, the coagulant particles were likely dispersed efficiently without excessive turbulence, allowing partial adsorption or entrapment of soluble ions and fine colloidal matter within the forming flocs. However, when the mixing speed was increased to 200 rpm, the intense turbulence likely prevented effective contact between dissolved species and coagulant surfaces, while also disrupting microflocs that could otherwise capture dissolved materials [27], [28]. Conversely, at 100 rpm, insufficient mixing may have limited coagulant dispersion, reducing the number of available active sites for interaction [27].

Among the tested speeds, 150 rpm was identified as the optimum condition for TDS removal, providing a balance between effective coagulant dispersion and stable floc formation. However, it is important to note that the overall TDS removal efficiencies were considerably lower compared to turbidity and TSS. This is expected because TDS primarily consists of dissolved ions and very fine particles that remain in the aqueous phase and are not easily removed through coagulation–flocculation, which mainly targets colloidal and suspended matter [29], [30].

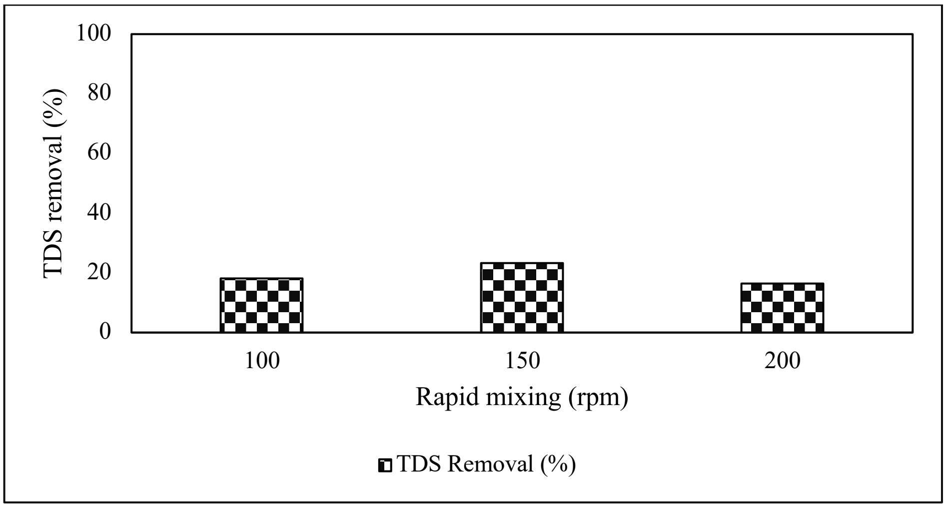

Fig. 3. Removal performance of TDS

Similar behaviour has been reported in previous research. Natural coagulants such as *M. oleifera* and *C. opuntia* primarily reduce turbidity and suspended solids, with minimal effect on TDS due to the limited ability of natural polymers to interact with dissolved ions [31], [32]. Some observation showed only partial TDS reduction when using banana peel powder, attributing it to the weak electrostatic attraction between the biomass and dissolved solids [26], [33]. Additionally, the adsorption capability of banana peel powder is influenced by the presence of lignocellulosic components, which provide some ion-exchange potential but are not sufficient for complete dissolved-solids removal [26], [33].

The findings from the current study therefore align well with literature consensus, confirming that natural coagulants have limited efficiency in TDS removal. The modest improvement observed at 150 rpm highlights that optimized hydrodynamic conditions can enhance the physical entrapment of some dissolved species within floc structures, but further reduction would require additional treatment stages such as adsorption, ion exchange, or membrane filtration [26], [34].

In summary, 150 rpm was identified as the most effective rapid mixing speed for TDS reduction, achieving a removal efficiency of 23.37%. Although this represents only partial improvement, the results reinforce that coagulation using banana peel powder remains primarily effective for turbidity and TSS removal rather than for dissolved constituents. Integrating this natural coagulant with secondary adsorption or filtration processes could further enhance overall water quality.

4. Conclusions

This study demonstrates that rapid mixing speed plays a critical role in optimizing the coagulation–flocculation process using banana peel powder as a natural coagulant for domestic wastewater treatment. While higher agitation enhances initial particle destabilization and coagulant dispersion, excessive turbulence introduces shear forces exceeding the cohesive strength of forming flocs, resulting in their breakage and reduced settling efficiency. The findings reveal that 150 rpm represents the optimal rapid mixing condition, balancing sufficient shear for dispersion with minimal floc disruption, thereby achieving the best overall removal performance for turbidity, TSS, and TDS.

In contrast to previous studies that primarily focused on dosage or pH optimization, this work provides new mechanistic insight into how hydrodynamic energy affects the physicochemical behavior of natural coagulants. The results demonstrate that mixing intensity governs the collision frequency and attachment efficiency between colloidal particles and the functional groups (–OH, –COOH) present in the banana peels lignocellulosic matrix. These active sites promote charge neutralization, adsorption, and hydrogen bonding, while the optimal mixing energy ensures sufficient particle contact without exceeding the shear threshold that destabilizes floc structures.

Beyond numerical efficiency, this study highlights the importance of hydrodynamic control and surface chemistry in achieving consistent and effective floc formation when using plant-based coagulants. These insights provide a valuable theoretical foundation for designing energy-efficient, sustainable water treatment systems, particularly in decentralized or rural applications where natural coagulants offer economic and environmental benefits.

Future work may explore combined treatment strategies, such as coupling banana-peel-based coagulants with alum or ferric chloride, or applying pH adjustment to enhance charge neutralization and coagulation efficiency. In addition, integration with biochar or membrane filtration systems could be investigated to further improve dissolved-solids removal and overall treatment performance. Despite its promising findings, this study has several limitations that should be acknowledged. The investigation was conducted on a laboratory scale with a narrow range of rapid mixing speeds (100–200 rpm) and a fixed banana peel coagulant dosage (0.02 g/L), which may not fully represent the range of conditions encountered in real wastewater treatment systems. In addition, no direct comparison with conventional chemical coagulants (such as alum or ferric chloride) was performed, as the primary objective was to isolate and evaluate the influence of mixing speed on the performance of a natural coagulant. Future work should therefore explore broader operational parameters, dosage optimization, comparative analyses with standard coagulants, and pilot-scale validation to assess scalability, cost-effectiveness, and long-term performance under realistic field conditions.

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