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Effects of Cassava Peel Waste as a Biocoagulant Under Different pH and Dosage Conditions for Tofu Wastewater Treatment

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Abstract

Tofu industry wastewater contains substantial organic matter and suspended solids that require treatment before discharge. This study evaluated cassava peel powder as a biocoagulant for reducing total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) under different initial pH and dosage conditions. Laboratory jar tests combined five dosages (3, 3.5, 4, 4.5, and 5 g/L) with three initial pH levels (5, 7, and 9), producing 15 treatments. Rapid mixing at 200 rpm for 2 minutes was followed by slow mixing at 20 rpm for 30 minutes and sedimentation for 60 minutes. Untreated wastewater had a pH of 4.41, with TSS, COD, and BOD concentrations of 872, 14,189, and 8,346 mg/L, respectively. Pollutant removal generally increased with dosage and was greatest at pH 9. TSS removal at pH 5 and 7, however, peaked at 4.5 g/L. Treatment 9E (pH 9; 5 g/L) yielded the highest measured removal efficiencies: 69.5% for TSS, 71.0% for COD, and 67.9% for BOD. Residual concentrations were 266, 4,116, and 2,678 mg/L, respectively, exceeding applicable discharge limits. Cassava peel powder showed potential as a preliminary treatment, but additional processes are needed to achieve compliance with discharge standards and protect receiving water bodies. Post-treatment pH was not measured, limiting interpretation of pH-dependent effects.

Keywords: *Biocoagulant, Cassava Peels, Coagulation–Flocculation, Pollutant Removal, Tofu Wastewater.*

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INTRODUCTION

Tofu production constitutes an important component of Indonesia's food-processing sector, yet its wastewater generation presents persistent environmental management challenges, particularly among small-scale enterprises with limited treatment infrastructure. The physicochemical characteristics of tofu wastewater indicate substantial organic pollution, as field investigations have identified biochemical oxygen demand (BOD), chemical oxygen demand (COD), and pH values that fail to satisfy applicable wastewater quality standards (Pambudi et al., 2021). These characteristics reflect the complex composition of soybean-processing effluents, in which biodegradable organic matter and suspended particles may contribute differently to the deterioration of receiving water quality. The application of natural coagulants has consequently attracted attention as an alternative treatment approach, with papaya seed-based coagulation demonstrating its potential for addressing TSS, BOD, and COD contamination in tofu wastewater (Afrianisa & Yasmine, 2025). Experimental investigations using chempedak seed extracts have further demonstrated that natural coagulation can reduce suspended solids while producing less favorable responses in certain dissolved organic pollution indicators (Anifah et al., 2024). Such differences indicate that the effectiveness of wastewater treatment cannot be determined exclusively through visual clarification or suspended solids removal, because organic pollutants may remain after particle aggregation and sedimentation. Investigations involving natural waste-derived coagulants have reinforced the potential of biological materials for wastewater treatment while emphasizing the importance of selecting suitable materials and operational conditions for particular wastewater characteristics (Ahmed et al., 2024).

Recent developments in coagulation–flocculation technology have increasingly emphasized plant-derived materials containing functional groups capable of facilitating particle destabilization, adsorption, and interparticle bridging, thereby expanding alternatives to conventional chemical

treatment. The effectiveness of these mechanisms depends on several physicochemical conditions, including solution pH, coagulant concentration, particle characteristics, and interactions between organic polymers and wastewater constituents (Benalia et al., 2024). Experimental applications involving agricultural residues have demonstrated that discarded biological materials can serve as functional coagulants, although their treatment performance varies with material composition and wastewater characteristics (Ahmed et al., 2024). Cassava peel waste represents a particularly relevant agricultural residue because its starch-based constituents offer potential coagulation functionality while providing an opportunity to utilize a by-product of cassava processing. Earlier investigations demonstrated the applicability of cassava peel starch combined with aluminum sulfate for turbidity reduction, establishing the functional potential of cassava-derived materials in coagulation systems (Mohd Asharuddin et al., 2018). Subsequent research extended this approach to institutional wastewater treatment through the characterization, optimization, and techno-economic evaluation of cassava peels as sustainable coagulant aids, indicating opportunities for developing waste-derived treatment technologies (Kumar et al., 2021).

Despite these developments, existing investigations reveal substantial differences in experimental approaches, wastewater matrices, and operational conditions that constrain the direct transferability of reported treatment efficiencies. Research comparing conventional and modified cassava peel starch demonstrated that pH, coagulant dosage, and settling time significantly influence COD removal, with chemical modification producing different flocculation behavior and treatment efficiencies (Rahmat et al., 2025). Comparable optimization research involving cassava starch and other environmentally preferable coagulants has shown that treatment conditions must be adjusted according to wastewater characteristics and the specific pollutant indicators being evaluated (Appiah-Brempong et al., 2023). The dependence of treatment performance on these variables suggests that optimum operating conditions established for one wastewater matrix cannot automatically be generalized to effluents containing different proportions of organic and suspended pollutants. Investigations using cassava peel-derived coagulants for domestic wastewater have demonstrated promising suspended solids removal, although the reported treatment performance was also evaluated alongside conventional chemical coagulation and combined treatment approaches (Ormaza et al., 2025). Studies involving tofu wastewater have established the applicability of plant-based coagulants but have also identified differences between suspended solids removal and organic pollutant reduction, indicating that treatment responses are not necessarily consistent across water quality indicators (Anifah et al., 2024). The specific research gap addressed by the present study therefore concerns the limited directly comparable evidence within the selected literature regarding how variations in pH and cassava peel biocoagulant dosage influence TSS, COD, and BOD removal simultaneously in tofu wastewater.

The unresolved relationship between operating conditions and pollutant-specific removal responses has scientific and practical implications for developing treatment systems based on locally available agricultural residues. Previous assessments of tofu-processing wastewater have demonstrated that organic contamination and unfavorable pH conditions require treatment approaches capable of addressing multiple water quality parameters rather than targeting a single pollutant indicator (Pambudi et al., 2021). The underlying coagulation mechanisms further indicate that changes in solution acidity can alter the electrochemical behavior of suspended particles and natural coagulants, while inappropriate coagulant concentrations may reduce treatment efficiency through unfavorable particle interactions (Benalia et al., 2024). Experimental optimization of cassava peel starch has confirmed that pH and dosage influence coagulation performance, supporting the need to evaluate these parameters systematically rather than assuming that a single operating condition is suitable for different wastewater compositions (Rahmat et al., 2025). Evidence from papaya seed biocoagulation in tofu wastewater also demonstrates the practical importance of dosage optimization, although the optimum conditions associated with one biological material cannot be directly extrapolated to another coagulant with different physicochemical properties (Afrianisa & Yasmine, 2025). Without experimental clarification of these relationships, cassava peel-based treatment may involve inefficient material consumption, inconsistent pollutant removal, and uncertainty regarding its suitability for improving tofu wastewater quality, thereby limiting the development of technically justified operating recommendations.

The present investigation is positioned at the intersection of agricultural waste utilization, plant-derived coagulation technology, and the treatment of organic-rich wastewater generated by tofu processing. Previous investigations have established the feasibility of applying cassava peel-derived

coagulants to domestic wastewater, but differences in wastewater composition and the use of comparative or combined chemical treatment approaches limit their direct relevance to tofu-processing effluents (Ormaza et al., 2025). Research on institutional wastewater has provided further evidence concerning cassava peel characterization and treatment optimization, although its experimental context does not directly establish the pollutant-specific behavior of the material under tofu wastewater conditions (Kumar et al., 2021). Studies using cassava starch for tannery wastewater have clarified the relevance of pH and dosage optimization, but their findings were obtained from a different industrial effluent with distinct contamination characteristics (Appiah-Brempong et al., 2023). Recent investigations involving modified cassava peel starch have also improved understanding of COD removal mechanisms, although chemical modification and municipal wastewater characteristics introduce conditions that differ from those of cassava peel waste applied to tofu wastewater (Rahmat et al., 2025). These distinctions establish a contextual and empirical research gap concerning the combined evaluation of cassava peel biocoagulant dosage, wastewater pH, and multiple pollution indicators within a single tofu wastewater treatment framework. The proposed novelty lies in examining the pH-dependent and dosage-dependent performance of cassava peel waste specifically for tofu wastewater, enabling a comparative assessment of TSS, COD, and BOD responses and identification of treatment conditions appropriate to the experimentally investigated wastewater characteristics.

This study aims to evaluate the effects of cassava peel waste as a natural biocoagulant under different pH and dosage conditions for the treatment of tofu wastewater. The investigation specifically examines changes in total suspended solids, chemical oxygen demand, and biochemical oxygen demand to determine the effectiveness of the coagulation process across the selected experimental conditions. The analysis focuses on identifying variations in pollutant removal efficiency associated with changes in initial wastewater pH and biocoagulant dosage, including differences in the responses of individual water quality indicators. The study also seeks to determine the most effective treatment conditions within the investigated experimental range by considering the measured removal performance of the selected pollution parameters. Its scientific contribution is expected to provide experimentally grounded evidence regarding the application of cassava peel-derived coagulation materials to organic-rich tofu wastewater and the relevance of operational conditions to pollutant-specific treatment responses. Its practical contribution is directed toward supporting the development of accessible, agricultural waste-based treatment approaches and providing an empirical basis for selecting suitable coagulation conditions in small-scale tofu wastewater management.

RESEARCH METHODS

The study was conducted from March to October 2026 using an experimental jar-test design, with tofu wastewater collected through grab sampling from a small-scale tofu-processing business in Sidodadi Subdistrict, Samarinda Ulu District, Samarinda City, Indonesia, using a dipper and transferred into four 5-L containers with a total volume of 20 L. Biocoagulant preparation and coagulation–flocculation experiments were performed at the Environmental Technology Laboratory, Faculty of Engineering, Mulawarman University, while TSS, COD, and BOD analyses were conducted at Laboratory X in Samarinda, East Kalimantan. The experimental equipment included a jar-test apparatus, Imhoff cones, an oven, an analytical balance, an electric blender, a mortar and pestle, a 100-mesh sieve, a water quality meter, and laboratory glassware, while the materials consisted of tofu wastewater, cassava peels, distilled water, Whatman No. 42 filter paper, aluminum foil, and sodium hydroxide (NaOH). Following the preparation procedure described by Yasrah (2022), cassava peels obtained from local markets and household cassava-chip producers were separated from their outer skins, washed under running water, rinsed with distilled water, sun-dried for 6 h, and oven-dried at 105 °C for 1 h. The dried peels were subsequently crushed using a mortar and pestle, ground with an electric blender, and passed through a 100-mesh sieve to obtain powdered biocoagulant, consistent with the particle-size preparation approach employed by Riyandini et al. (2025). The experimental design comprised five biocoagulant dosages of 3, 3.5, 4, 4.5, and 5 g/L combined with three pH conditions of 5, 7, and 9, with the pH variation informed by the tofu wastewater coagulation research of Yusuf et al. (2022), resulting in 15 treatment combinations presented in Table 1.

Table 1. Treatment Combinations and Sample Codes (1 L of Wastewater)

pH	3 g/L	3.5 g/L	4 g/L	4.5 g/L	5 g/L
5	5A	5B	5C	5D	5E
7	7A	7B	7C	7D	7E
9	9A	9B	9C	9D	9E

A 5 N NaOH solution was prepared by dissolving 50 g of NaOH in distilled water to a final volume of 250 mL, and this solution was added dropwise to fifteen 1-L wastewater samples with an initial pH of 4.41 to establish the designated experimental pH conditions. Initial and treated wastewater samples were characterized using SNI 6989.11:2019 for pH, SNI 6989.3:2019 for TSS through gravimetric analysis, SNI 6989.2:2019 for COD through closed-reflux spectrophotometry, and SNI 6989.72-2009 for BOD through the Winkler method. Coagulation–flocculation experiments were conducted using a jar-test apparatus following SNI 19-6449-2000, with each treatment receiving its assigned biocoagulant dosage before rapid mixing at 200 rpm for 2 min and slow mixing at 20 rpm for 30 min, using mixing conditions adapted from the experimental approach of Mendrofa et al. (2025). Following coagulation–flocculation, the samples were carefully transferred into Imhoff cones and allowed to settle for 60 min before determining the remaining TSS, COD, and BOD concentrations, consistent with the settling procedure employed by Yasrah (2022). Pollutant removal efficiency was calculated using Equation (1), where E represents removal efficiency (%), C_0 represents the initial pollutant concentration (mg/L), and C_1 represents the pollutant concentration after treatment (mg/L). The experimental data were analyzed using quantitative descriptive methods to compare pollutant removal across the 15 pH–dosage combinations and evaluate the treated effluent against the wastewater quality standards for soybean-processing activities established under the Indonesian Minister of Environment Regulation No. 5 of 2014 (Kementerian Lingkungan Hidup Republik Indonesia, 2014).

$$E = [(C_0 - C_1) / C_0] \times 100\%$$

RESULTS AND DISCUSSION

Initial Characteristics of Tofu Wastewater and Experimental pH Adjustment

The initial characterization of tofu wastewater revealed substantial organic contamination and acidic conditions that require treatment before discharge into receiving water bodies. Laboratory measurements recorded an initial pH of 4.41, total suspended solids (TSS) of 872 mg/L, chemical oxygen demand (COD) of 14,189 mg/L, and biochemical oxygen demand (BOD) of 8,346 mg/L. These concentrations indicate that the wastewater contains considerable quantities of suspended and oxygen-demanding substances that may adversely affect receiving water quality if discharged without adequate treatment. Similar characteristics have been documented in tofu-processing wastewater, where organic contamination and unfavorable physicochemical conditions constitute major challenges for wastewater management (Pambudi et al., 2021). The presence of organic residues associated with soybean processing contributes to the accumulation of biodegradable substances and increases the pollution potential of untreated effluent (Rasmito et al., 2019). These characteristics establish a demanding initial condition for evaluating the capacity of cassava peel waste to function as a natural biocoagulant. The simultaneous measurement of pH, TSS, COD, and BOD provides a basis for assessing the initial pollution burden and determining subsequent changes in wastewater quality following coagulation–flocculation treatment.

The initial pH of 4.41 indicates that the wastewater was acidic before any experimental adjustment or addition of cassava peel biocoagulant. This condition is relevant because solution acidity may influence the stability of suspended particles, the ionization of functional groups, and interactions between natural coagulants and wastewater constituents. Benalia et al. (2024) explained that the performance of plant-based coagulants depends partly on the physicochemical conditions governing particle destabilization and floc formation. The acidic characteristics of the untreated sample therefore represent an important experimental factor rather than merely an initial wastewater property. Variations in pH may influence the behavior of cassava peel constituents during coagulation, although the magnitude and mechanisms of these effects require experimental evaluation. The selection of acidic,

neutral, and alkaline treatment conditions provides a basis for comparing biocoagulant performance under different initial chemical environments.

The initial wastewater parameters were compared with the quality standards applicable to soybean-processing activities under the Indonesian Minister of Environment Regulation No. 5 of 2014, as presented in Table 2. The measured pH of 4.41 was below the permitted range of 6–9, indicating that the untreated wastewater did not satisfy the prescribed acidity requirement. The TSS concentration reached 872 mg/L, substantially exceeding the regulatory limit of 200 mg/L. More pronounced differences were observed for COD and BOD, which reached 14,189 mg/L and 8,346 mg/L against their respective limits of 300 mg/L and 150 mg/L. These results demonstrate that none of the four measured parameters complied with the applicable discharge requirements before treatment. Previous investigations of tofu wastewater have similarly identified excessive organic pollutant concentrations as a major consideration in selecting appropriate treatment technologies (Pambudi et al., 2021). The comparison provides an empirical reference for evaluating both the effectiveness of coagulation–flocculation and the remaining treatment requirements after the application of cassava peel biocoagulant.

Table 2. Initial Tofu Wastewater Characteristics Compared with Quality Standards

Parameter	Unit	Quality Limit	Measured Value	Compliance
pH	-	6–9	4.41	Non-compliant
TSS	mg/L	200	872	Non-compliant
COD	mg/L	300	14189	Non-compliant
BOD	mg/L	150	8346	Non-compliant

The results presented in Table 2 indicate substantial differences between the initial pollutant concentrations and their respective permissible limits. The measured TSS concentration was 4.36 times the regulatory limit, demonstrating a considerable suspended solids burden in the untreated wastewater. The COD and BOD concentrations were approximately 47.30 and 55.64 times their respective limits, indicating that oxygen-demanding pollution was particularly severe relative to the applicable standards. The ratio between COD and BOD was approximately 1.70, suggesting the presence of a substantial biodegradable organic fraction, although this ratio alone cannot establish the wastewater's biological treatability. Research involving natural coagulants for tofu wastewater has demonstrated that suspended solids removal and organic pollutant reduction may exhibit different treatment responses, requiring separate evaluation of these parameters (Anifah et al., 2024). The pronounced exceedances observed in the initial samples indicate that effective treatment must address both particulate contamination and oxygen-demanding organic substances rather than relying exclusively on visible wastewater clarification.

The elevated concentrations of TSS, COD, and BOD reflect the complex pollutant characteristics of wastewater generated during soybean processing. Organic residues originating from tofu production can contribute proteins, carbohydrates, and fats to the liquid waste stream, increasing the quantities of substances requiring removal or stabilization (Rasmito et al., 2019). Suspended particles contribute directly to TSS measurements, whereas COD and BOD also represent oxygen demand associated with organic substances that may occur in particulate, colloidal, or dissolved forms. Coagulation–flocculation is principally intended to destabilize suspended and colloidal particles and facilitate their aggregation into larger flocs that can subsequently be separated through sedimentation. Plant-derived coagulants may support this process through adsorption, polymer bridging, and electrochemical interactions, depending on their functional groups and the characteristics of the surrounding aqueous medium (Benalia et al., 2024). The substantial initial organic burden suggests that removal of suspended matter alone may be insufficient to achieve the required reductions in COD and BOD. The experimental evaluation of cassava peel biocoagulant must consequently distinguish between changes in suspended solids concentrations and reductions in the oxygen-demanding components of the wastewater.

The adjustment of wastewater pH was performed to establish three experimental conditions representing acidic, neutral, and alkaline environments before the coagulation–flocculation process. Starting from an initial pH of 4.41, the addition of 2 mL of 5 N sodium hydroxide solution was required

to increase the pH of 1 L of wastewater to 5. Increasing the pH to 7 required 3.7 mL of the same solution, while adjustment to pH 9 required 4.8 mL. The increasing volumes of sodium hydroxide reflected the greater adjustment necessary to establish progressively higher pH conditions from the acidic initial sample. Previous investigations have identified pH as a relevant operational variable in the optimization of cassava peel-based coagulation systems, particularly when evaluating pollutant removal under different treatment conditions (Kumar et al., 2021). These adjustments established consistent initial pH categories for assessing the effects of five cassava peel dosages across the 15 experimental treatment combinations.

The selected pH conditions were intended to examine the relationship between initial wastewater acidity and the performance of cassava peel biocoagulant during coagulation–flocculation. Differences in solution pH can modify the chemical environment surrounding suspended particles and influence interactions involving natural polymeric substances. Research on plant-based coagulants has identified solution chemistry as an important consideration in understanding particle destabilization, aggregation, and the formation of settleable flocs (Benalia et al., 2024). Experimental investigations involving conventional and modified cassava peel starch have also demonstrated the relevance of pH and coagulant dosage in determining treatment performance for organic wastewater (Rahmat et al., 2025). The use of pH 5, 7, and 9 allowed comparisons across three distinct initial conditions while maintaining the same rapid mixing, slow mixing, and sedimentation procedures. The alkaline treatment condition coincided with the upper boundary of the regulatory pH range before biocoagulant addition, although this did not establish the final pH of the treated effluent. The experimental design consequently provides a basis for evaluating pollutant removal under different starting pH conditions without presuming that a particular coagulation mechanism has been directly demonstrated.

The interpretation of pH-dependent treatment performance must account for the absence of pH measurements after cassava peel biocoagulant addition. The designated pH values represent conditions established before coagulation rather than verified pH values maintained throughout mixing and sedimentation. Ashari et al. (2023) reported changes in wastewater pH following the application of cassava peel extract, indicating that natural coagulant addition may influence the chemical conditions of the treated medium. The use of sodium hydroxide to establish the experimental conditions also means that any independent contribution of pH adjustment cannot be isolated from the combined treatment response without an appropriate control. The observed differences among treatments can therefore be interpreted as responses to the designated pH–dosage combinations, but they cannot independently establish the contributions of alkalization, particle destabilization, or specific chemical interactions. These methodological considerations provide a necessary basis for interpreting the subsequent changes in TSS, COD, and BOD concentrations and identifying the best-performing treatment among the experimentally tested conditions.

Effects of Cassava Peel Biocoagulant Dosage and pH on TSS, COD, and BOD Concentrations

The residual concentrations of total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) were examined across 15 cassava peel biocoagulant treatments combining five dosages with three initial pH levels. The untreated wastewater contained 872 mg/L TSS, 14,189 mg/L COD, and 8,346 mg/L BOD, providing common reference concentrations for evaluating the experimental responses. Every treatment produced lower concentrations of all three parameters than those measured in the untreated sample, although the magnitude of the decrease varied considerably among the treatment combinations. Differences across the pH series were more consistent than those associated with increasing dosage, particularly when comparing acidic and alkaline conditions. Studies of cassava-derived coagulation materials similarly recognize treatment conditions and wastewater composition as factors affecting pollutant removal, although the observed responses depend on the material and wastewater characteristics (Kumar et al., 2021). These observations require parameter-specific interpretation because the behavior of suspended solids cannot be assumed to represent the removal of dissolved or colloidal organic substances.

Table 3 presents the measured residual TSS, COD, and BOD concentrations for the untreated sample and each coded treatment. At pH 5, TSS ranged from 596 to 809 mg/L, COD from 8,991 to 12,873 mg/L, and BOD from 5,501 to 8,021 mg/L across the five dosages. At pH 7, corresponding concentration ranges were 416–784 mg/L for TSS, 5,007–11,445 mg/L for COD, and 3,091–6,945 mg/L for BOD. The alkaline series yielded concentrations of 266–715 mg/L TSS, 4,116–8,239 mg/L

COD, and 2,678–5,300 mg/L BOD. These ranges indicate that pH 9 consistently achieved the lowest residual concentration of each measured parameter at every corresponding dosage. The results nevertheless describe combined treatment conditions rather than an independently isolated pH effect, since sodium hydroxide was used for adjustment and no pH-only control was reported. The importance of evaluating pH and biocoagulant loading together is consistent with optimization research on natural and conventional coagulants applied to industrial wastewater (Appiah-Brempong et al., 2023).

Table 3. Residual TSS, COD, and BOD Concentrations Under All Treatments

pH	Dose (g/L)	Sample code	TSS (mg/L)	COD (mg/L)	BOD (mg/L)
4.41	-	Initial	872	14189	8346
5	3	5A	809	12873	8021
5	3.5	5B	733	11566	7998
5	4	5C	701	10954	7412
5	4.5	5D	596	10247	6705
5	5	5E	629	8991	5501
7	3	7A	784	11445	6945
7	3.5	7B	666	9341	6022
7	4	7C	537	7377	4958
7	4.5	7D	416	6552	4143
7	5	7E	429	5007	3091
9	3	9A	715	8239	5300
9	3.5	9B	425	6731	4111
9	4	9C	328	5212	3508
9	4.5	9D	275	4900	3201
9	5	9E	266	4116	2678

Source: Primary data, 2026

The concentration patterns in Table 3 show that increasing cassava peel dosage generally improved pollutant reduction, but the response differed among TSS, COD, and BOD. COD and BOD decreased continuously from 3 to 5 g/L at all three pH levels, whereas TSS increased slightly at the highest dosage under pH 5 and pH 7. At 3 g/L, raising the initial pH from 5 to 9 reduced residual COD from 12,873 to 8,239 mg/L and BOD from 8,021 to 5,300 mg/L. At 5 g/L, the corresponding values decreased from 8,991 to 4,116 mg/L for COD and from 5,501 to 2,678 mg/L for BOD. Research on conventional and modified cassava peel starch has also identified pH and dosage as operational variables relevant to COD removal, although its wastewater characteristics differed from those investigated here (Rahmat et al., 2025). The present observations indicate more favorable treatment performance under higher initial pH and greater dosage within the tested ranges, without establishing an optimum beyond those experimental conditions.

The TSS profiles shown in Figure 1 demonstrate a dose-dependent decline that was interrupted at the highest dosage under two pH conditions. At pH 5, residual TSS decreased from 809 mg/L at 3 g/L to 596 mg/L at 4.5 g/L, before increasing to 629 mg/L at 5 g/L. A similar pattern appeared at pH 7, where TSS declined from 784 to 416 mg/L between 3 and 4.5 g/L before rising to 429 mg/L at 5 g/L. At pH 9, TSS declined continuously from 715 to 266 mg/L across all five dosages, indicating a different response under alkaline conditions. Nonmonotonic suspended-solids responses have been discussed in natural-coagulant studies, where exceeding a suitable dose may diminish flocculation performance under particular treatment conditions (Anifah et al., 2024). Polymeric bridging and particle destabilization provide possible explanations for the initial reductions, but neither charge reversal nor floc structure was directly measured in this study (Benalia et al., 2024). The experimental data support a dosage-related variation in TSS response, while the mechanism responsible for the concentration increases at pH 5 and 7 remains unverified.

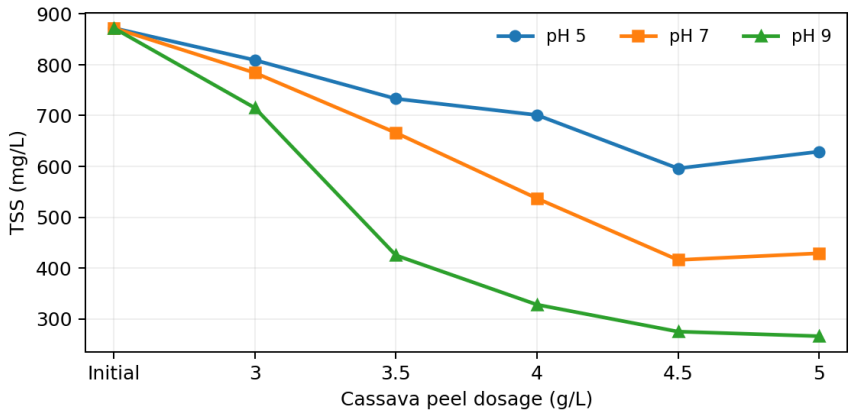

Figure 1. TSS Concentrations at Different Cassava Peel Doses and pH Levels

Residual COD declined with each increment in cassava peel dosage at pH 5, 7, and 9, as indicated in Figure 2. The lowest COD concentrations were obtained at 5 g/L, reaching 8,991 mg/L at pH 5, 5,007 mg/L at pH 7, and 4,116 mg/L at pH 9. At a constant dosage of 4 g/L, COD decreased from 10,954 mg/L under pH 5 to 7,377 mg/L under pH 7 and 5,212 mg/L under pH 9. The data show no reversal in COD reduction at the maximum tested dosage, although the actual optimum cannot be established without evaluating additional concentrations beyond the experimental range. Cassava peel-based coagulation studies have identified operational conditions as important determinants of organic pollutant removal, but differences in material preparation and wastewater composition constrain direct numerical comparisons (Kumar et al., 2021). COD represents oxygen demand associated with oxidizable constituents in wastewater, so the measured reductions do not independently establish which particulate, colloidal, or dissolved organic fractions were removed during coagulation.

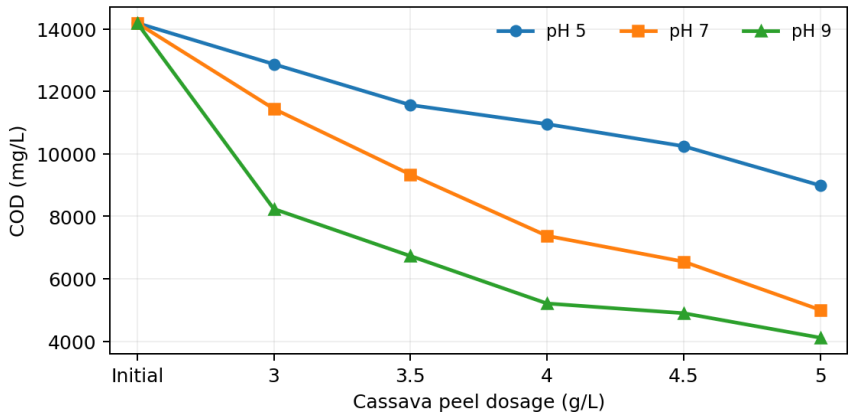

Figure 2. COD Concentrations at Different Cassava Peel Doses and pH Levels

The BOD concentration profiles presented in Figure 3 followed the same decreasing direction as COD across increasing dosages, although their absolute concentrations and changes between treatments differed. At pH 5, BOD decreased from 8,021 mg/L at 3 g/L to 5,501 mg/L at 5 g/L, with a relatively small difference between the 3 and 3.5 g/L treatments. At pH 7, the concentration decreased from 6,945 to 3,091 mg/L over the same dosage interval, indicating a more pronounced reduction than under acidic conditions. The pH 9 series produced the lowest BOD concentrations, declining from 5,300 mg/L at 3 g/L to 2,678 mg/L at 5 g/L. The decrease in BOD following sedimentation does not necessarily indicate biological degradation during treatment, because the experimental procedure involved chemical adjustment, mixing, and physical separation rather than a biological treatment stage. Relationships between suspended matter removal and organic pollutant reduction have also been examined in filtration systems, demonstrating that particulate-associated organic removal may contribute to improvements in wastewater quality (Kim et al., 2018). The continued decline at 5 g/L

indicates that the highest investigated dosage produced the lowest residual BOD at each initial pH, although higher dosages were not evaluated.

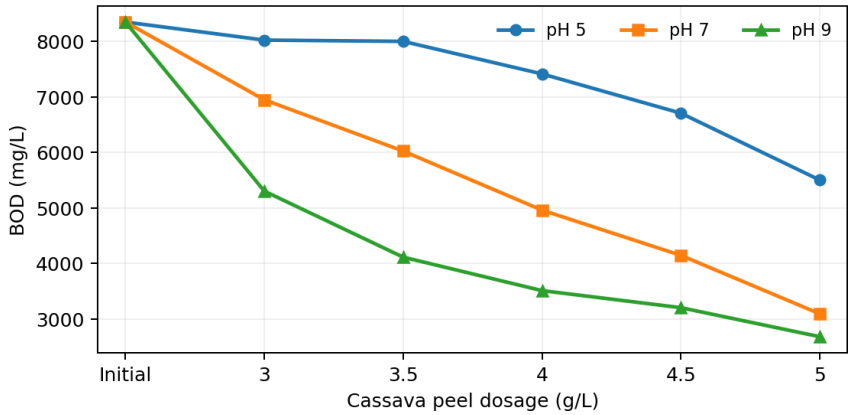

Figure 3. BOD Concentrations at Different Cassava Peel Doses and pH Levels

Comparisons among the three pollution indicators reveal that initial pH and biocoagulant dosage did not influence residual concentrations in identical ways. TSS reached its lowest concentration at 4.5 g/L under pH 5 and 7, whereas COD and BOD reached their respective minimum concentrations at 5 g/L under all three pH conditions. At pH 9, the three indicators simultaneously reached their lowest measured concentrations at 5 g/L, corresponding to treatment code 9E. This divergence suggests that the operating conditions favoring suspended solids removal may differ from those associated with reductions in oxygen-demanding organic constituents. Earlier cassava peel applications to other industrial effluents also reported differences in COD and TSS removal responses, illustrating the need to assess multiple wastewater parameters independently (Ashari et al., 2023). The distinction is particularly relevant to tofu wastewater, where substantial concentrations of organic pollutants may remain even after suspended particles have been removed through coagulation and sedimentation.

The declining residual concentrations at higher initial pH levels are compatible with the possibility that solution chemistry influenced interactions between wastewater constituents and cassava peel materials during the coagulation process. Plant-derived coagulants may interact with wastewater particles through adsorption and polymer-associated floc formation, although the relative contributions of these processes depend on the chemical composition of the material and the properties of the treated wastewater (Benalia et al., 2024). Previous investigations involving cassava peel starch combined with alum demonstrated the potential of cassava-derived materials in coagulation, but the incorporation of a chemical coagulant prevents direct equivalence with the cassava peel powder treatment applied in the present experiment (Mohd Asharuddin et al., 2018). The absence of final pH measurements prevents the observed concentration patterns from being attributed to stable pH conditions throughout the treatment process. No direct characterization of active cassava peel functional groups, particle surface charge, or floc structure was reported, so the proposed coagulation mechanisms remain explanatory hypotheses rather than experimentally established findings. All treatment combinations nevertheless produced measurable reductions in TSS, COD, and BOD, while substantial residual organic pollution remained after sedimentation. The evaluation of treatment performance must consequently consider both pollutant removal efficiency and the extent to which the remaining concentrations approach the applicable wastewater discharge standards.

Removal Efficiency, Optimum Treatment Conditions, and Compliance with Wastewater Quality Standards

Removal efficiency was calculated relative to the initial TSS, COD, and BOD concentrations to assess the performance of the 15 pH–dosage combinations. The resulting percentages demonstrated that all treatments reduced the measured pollutants, although removal efficiency varied considerably among parameters and experimental conditions. At a given dosage, treatments conducted at an initial pH of 9 consistently achieved higher removal efficiencies than their corresponding treatments at pH 7 and pH 5. Increasing cassava peel dosage generally improved pollutant removal, except for TSS at the

highest dosage under acidic and neutral conditions. These differences indicate that treatment performance cannot be adequately represented by a single removal parameter because suspended solids and oxygen-demanding organic constituents exhibited distinct responses. Previous investigations have similarly identified coagulant dosage, solution pH, and wastewater characteristics as important factors influencing the effectiveness of cassava peel-based coagulation systems (Rahmat et al., 2025). The measured efficiencies provide an empirical basis for examining parameter-specific treatment performance and determining the most effective combination within the investigated experimental range.

Table 4 presents the removal efficiencies of TSS, COD, and BOD for all 15 treatment combinations, calculated using their respective initial and residual concentrations. At pH 5, the maximum removal efficiencies were 31.7% for TSS, 36.6% for COD, and 34.1% for BOD, although these values were obtained at different biocoagulant dosages. At pH 7, the corresponding maximum efficiencies increased to 52.3%, 64.7%, and 63.0%, respectively. The highest removal efficiencies were observed at pH 9, reaching 69.5% for TSS, 71.0% for COD, and 67.9% for BOD under the 5 g/L treatment. The increasing maximum efficiencies across the three pH conditions indicate that alkaline adjustment was associated with more favorable pollutant removal within the experimental conditions. Similar optimization studies involving environmentally preferable coagulants have demonstrated the importance of operating conditions, although the absence of a pH-only control in the present experiment prevents the independent contribution of alkalization from being established (Appiah-Brempong et al., 2023).

Table 4. TSS, COD, and BOD Removal Efficiencies Across Treatments

pH	Dose (g/L)	Sample Code	TSS Removal (%)	COD Removal (%)	BOD Removal (%)
5	3	5A	7.2	9.3	3.9
5	3.5	5B	15.9	18.5	4.2
5	4	5C	19.6	22.8	11.2
5	4.5	5D	31.7	27.8	19.7
5	5	5E	27.9	36.6	34.1
7	3	7A	10.1	19.3	16.8
7	3.5	7B	23.6	34.2	27.8
7	4	7C	38.4	48.0	40.6
7	4.5	7D	52.3	53.8	50.4
7	5	7E	50.8	64.7	63.0
9	3	9A	18.0	41.9	36.5
9	3.5	9B	51.3	52.6	50.7
9	4	9C	62.4	63.3	58.0
9	4.5	9D	68.5	65.5	61.6
9	5	9E	69.5	71.0	67.9

Source: Primary data, 2026.

The TSS removal efficiencies presented in Figure 4 reveal different dosage-response patterns among the acidic, neutral, and alkaline treatment conditions. At pH 5, removal efficiency increased from 7.2% at 3 g/L to 31.7% at 4.5 g/L before declining to 27.9% at 5 g/L. A comparable response occurred at pH 7, where TSS removal increased from 10.1% to 52.3% between 3 and 4.5 g/L before decreasing to 50.8% at the highest dosage. The alkaline treatments exhibited a continuous increase in removal efficiency, reaching 69.5% at 5 g/L without an observable reduction in performance within the tested dosage range. These differences suggest that the dosage producing maximum suspended solids removal depends on the designated initial pH and the associated wastewater conditions. The highest TSS removal exceeded the 50% reported by Yasrah (2022) for cassava peel treatment of slaughterhouse wastewater, although differences in wastewater composition and experimental procedures limit direct comparison. Excessive coagulant addition may interfere with particle aggregation under certain conditions, but charge reversal and polymer saturation remain hypothetical explanations because neither surface charge nor floc structure was directly measured (Benalia et al., 2024).

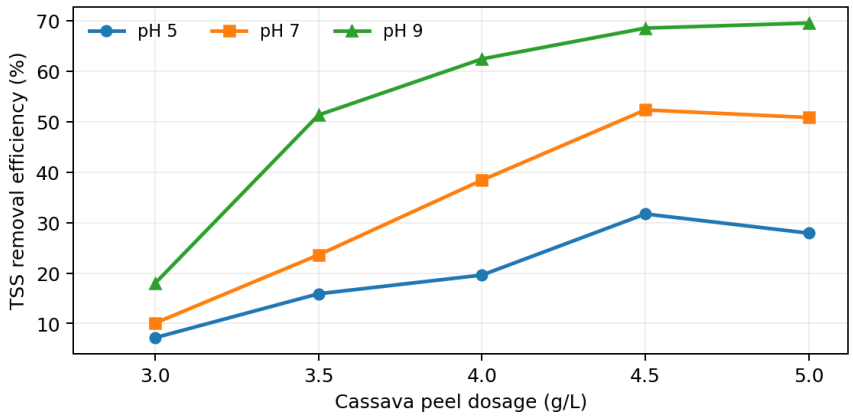

Figure 4. TSS Removal Efficiencies at Different pH Levels

COD removal efficiency increased consistently with cassava peel dosage at all three initial pH levels, without the decline observed for TSS at the highest dosage under acidic and neutral conditions. At pH 5, COD removal increased from 9.3% at 3 g/L to 36.6% at 5 g/L, whereas the corresponding increase at pH 7 was from 19.3% to 64.7%. The alkaline treatment series achieved 41.9% removal at 3 g/L and increased progressively to 71.0% at 5 g/L, as illustrated in Figure 5. Treatment 9A, using only 3 g/L at pH 9, achieved greater COD removal than treatment 5E, which used 5 g/L at pH 5, demonstrating a pronounced difference between the experimental pH conditions. Gali Aba Lulesa et al. (2022) similarly reported increasing COD removal efficiencies of 78.30%, 79.20%, and 81.89% at pH 5, 7, and 9, respectively, using a natural-coagulant treatment system, although differences in wastewater characteristics and treatment materials prevent direct equivalence. The continued increase in COD removal at 5 g/L indicates that this dosage provided the highest measured performance within the experimental range, while the actual optimum beyond the tested conditions remains undetermined.

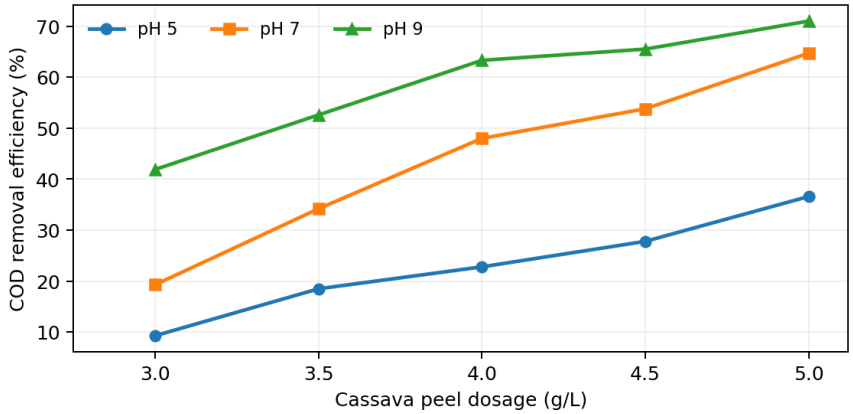

Figure 5. COD Removal Efficiencies At Different pH Levels

BOD removal exhibited a similar directional response to COD, with higher efficiencies generally associated with increasing cassava peel dosage and higher initial pH. The maximum BOD removal efficiencies were 34.1% at pH 5, 63.0% at pH 7, and 67.9% at pH 9, each obtained at a biocoagulant dosage of 5 g/L. Within the alkaline treatment series, BOD removal increased from 36.5% at 3 g/L to 67.9% at 5 g/L, as presented in Figure 6. The lowest removal efficiency was recorded under treatment 5A, where the combination of pH 5 and 3 g/L reduced BOD by only 3.9%. Previous research using natural coagulants reported a similar relationship between increasing pH and BOD removal, with efficiencies of 70.0%, 74.30%, and 76.90% under pH 5, 7, and 9, respectively (Gali Aba Lulesa et al., 2022). The observed reduction in BOD does not establish biological degradation because the treatment involved coagulation, flocculation, and sedimentation without a biological processing stage. Removal

of particulate and colloidal organic matter may contribute to lower oxygen demand, although the precise contributions of different organic fractions require additional characterization (Kim et al., 2018).

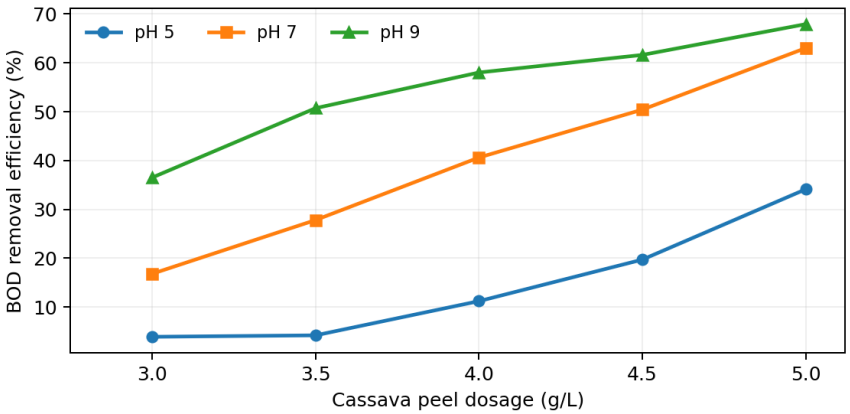

Figure 6. BOD Removal Efficiencies at Different pH Levels

The comparison of maximum pollutant removal efficiencies at each initial pH is presented in Figure 7. Treatment 9E, combining pH 9 with a cassava peel biocoagulant dosage of 5 g/L, achieved the highest measured efficiencies of 69.5% for TSS, 71.0% for COD, and 67.9% for BOD. The corresponding residual concentrations were 266 mg/L TSS, 4,116 mg/L COD, and 2,678 mg/L BOD, indicating substantial reductions from the untreated wastewater concentrations. At pH 5 and 7, maximum TSS removal occurred at 4.5 g/L, whereas COD and BOD removal continued to increase until the highest tested dosage of 5 g/L. Similar differences among pollutant-specific treatment responses have been reported in studies employing plant-derived coagulants for tofu wastewater, indicating that individual parameters may exhibit different removal patterns under comparable treatment conditions (Anifah et al., 2024). Treatment 9E can consequently be identified as the best-performing combination among the investigated conditions, although the experimental results do not establish a universal optimum outside the tested pH and dosage ranges.

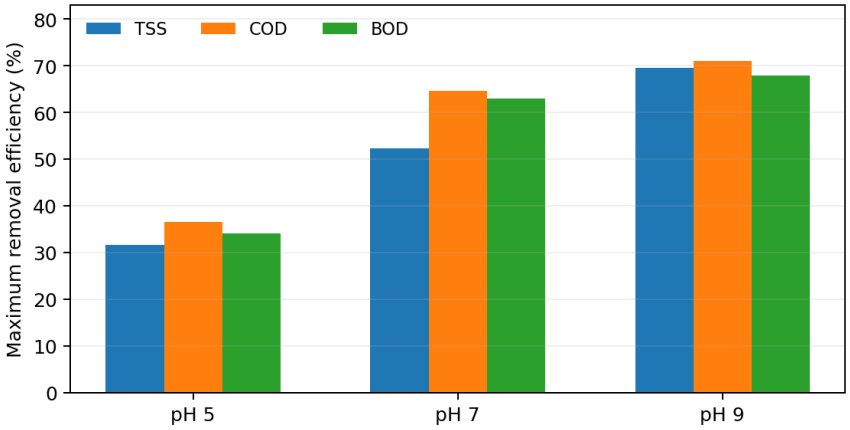

Figure 7. Maximum TSS, COD, and BOD Removal Efficiencies at Each Tested pH

Comparisons with previous investigations provide additional context for evaluating the removal efficiencies achieved using cassava peel waste. The COD removal efficiency of 71.0% under treatment 9E was comparable to the 71% reported by Yasrah (2022) for slaughterhouse wastewater treated with cassava peels at a dosage of 6 g/L. Research using tamarind seed coagulant for tofu wastewater reported higher removal efficiencies of 78% for TSS, 82% for COD, and 82% for BOD at pH 8 and a dosage of 4 g/L (Yusuf et al., 2022). Differences in wastewater composition, coagulant characteristics, experimental procedures, and treatment conditions prevent these comparisons from establishing the relative superiority of the materials. The higher removal efficiencies observed at pH 9 are consistent with the possibility that alkaline conditions promoted more favorable interactions

between natural coagulant constituents and wastewater particles, as discussed in research on tannin-based coagulation systems (Banch et al., 2019). Earlier investigations combining cassava peel starch with aluminum sulfate also demonstrated the relevance of operating conditions for suspended-particle removal, although the presence of a chemical coagulant limits direct comparison with the present treatment (Mohd Asharuddin et al., 2018). The potential mechanisms involving particle destabilization, adsorption, and polymer bridging remain inferential because the experiment did not directly characterize active biocoagulant constituents, surface charge, or floc formation.

Despite the substantial pollutant reductions achieved under treatment 9E, the residual TSS, COD, and BOD concentrations remained above the applicable discharge standards for soybean-processing wastewater established under the Indonesian Minister of Environment Regulation No. 5 of 2014 (Kementerian Lingkungan Hidup Republik Indonesia, 2014). The final TSS concentration of 266 mg/L was approximately 1.33 times the regulatory limit of 200 mg/L, while the COD concentration of 4,116 mg/L remained 13.72 times the permitted limit of 300 mg/L. The residual BOD concentration of 2,678 mg/L was approximately 17.85 times the allowable concentration of 150 mg/L, demonstrating that substantial biodegradable organic pollution remained after treatment. Compliance with the regulatory pH range of 6–9 could not be confirmed because wastewater pH was not measured following biocoagulant addition and sedimentation. The lack of reported treatment replicates, pH-only controls, post-treatment pH measurements, and direct characterization of biocoagulant constituents limits causal interpretation and the statistical generalizability of the observed responses. Cassava peel-based coagulation may therefore serve as a preliminary treatment option under the investigated conditions, but additional treatment stages and further experiments involving wider dosage ranges, appropriate controls, and post-treatment characterization are required before its application as an independent wastewater treatment process can be recommended.

CONCLUSION

Cassava peel powder biocoagulant reduced TSS, COD, and BOD concentrations in tofu wastewater with an initial pH of 4.41 and initial TSS, COD, and BOD concentrations of 872, 14,189, and 8,346 mg/L, respectively. Increasing the biocoagulant dosage from 3 to 5 g/L generally improved pollutant removal, except for TSS at pH 5 and 7, where the highest efficiencies were achieved at 4.5 g/L. Among the investigated conditions, an initial pH of 9 consistently produced the greatest removal of all three pollution parameters. The most effective treatment was identified as treatment 9E, combining pH 9 with 5 g/L cassava peel powder, which achieved removal efficiencies of 69.5% for TSS, 71.0% for COD, and 67.9% for BOD. The corresponding residual concentrations were 266, 4,116, and 2,678 mg/L, demonstrating substantial reductions in suspended solids and organic pollutants. These findings indicate that cassava peel waste has potential as a natural biocoagulant for tofu wastewater treatment, with treatment performance influenced by the selected pH and dosage conditions.

Despite these reductions, the final TSS, COD, and BOD concentrations remained above the applicable wastewater quality standards of 200, 300, and 150 mg/L, respectively, indicating that cassava peel coagulation–flocculation was insufficient as a stand-alone treatment under the investigated conditions. The maximum COD removal efficiency of 71.0% was comparable to the findings of Yasrah (2022), who reported 71% COD removal using cassava peels for slaughterhouse wastewater, although differences in wastewater characteristics limit direct comparison. The results suggest that cassava peel powder may serve as a preliminary treatment material before additional processes are applied to achieve regulatory compliance. The absence of post-treatment pH measurements and pH-only controls limits the interpretation of the independent contributions of alkalization and biocoagulant addition to pollutant removal. Future research should investigate dosages exceeding 5 g/L, monitor pH changes after biocoagulant addition, and evaluate the moisture content and storage stability of cassava peel powder. Further experimental studies incorporating appropriate controls, treatment replication, and integration with downstream treatment technologies are necessary to establish more reliable operating conditions and improve the practical applicability of this agricultural waste-derived biocoagulant.

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