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Effects of Combined Tamarind Seeds (*Tamarindus indica*) and Jackfruit Seeds (*Artocarpus heterophyllus*) as Biocoagulants for Tofu Wastewater Treatment

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Abstract

Tofu wastewater contains high concentrations of organic matter and suspended solids that require treatment before discharge. This study evaluated tamarind (Tamarindus indica) and jackfruit (Artocarpus heterophyllus) seed powders as individual and combined biocoagulants, focusing on dosage, mixture ratio, pollutant removal, and pH changes. Laboratory jar tests used 1 L of wastewater per treatment, with individual dosages of 2, 4, 6, and 8 g/L and combined dosages of 2 and 4 g/L at tamarind-to-jackfruit ratios of 70:30, 50:50, and 30:70. Rapid mixing at 100 rpm for 5 minutes was followed by slow mixing at 20 rpm for 30 minutes and sedimentation for 60 minutes. Initial TSS, BOD, and COD concentrations were 3,216, 4,074, and 9,329 mg/L, respectively, with pH 5.3. Tamarind seeds at 2 g/L achieved 50.1% BOD and 54.9% COD removal, while jackfruit seeds at 4 g/L achieved 94.9% TSS removal. The best mixture, 2 g/L at 70:30, removed 84.0% TSS, 53.7% BOD, and 54.0% COD, yielding residual concentrations of 516, 1,888, and 4,290 mg/L, respectively, and pH 5.6. A higher combined dosage of 4 g/L consistently reduced removal performance across the three tested mixing ratios. The treated effluent remained noncompliant with discharge standards, indicating that additional treatment is necessary.

Keywords: *Biocoagulant, Coagulation–Flocculation, Jackfruit Seeds, Tamarind Seeds, Tofu Wastewater.*

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INTRODUCTION

Tofu production represents an important component of Indonesia's food-processing industry, although the generation of wastewater containing substantial organic pollutants presents persistent challenges for environmental management. Wastewater generated during soybean washing, coagulation, pressing, and tofu formation contains varying concentrations of organic substances, reflecting differences in raw materials and production stages (Hardyanti et al., 2023). These processing activities generate liquid residues containing proteins, carbohydrates, fats, and suspended particles that may contribute to environmental deterioration when discharged without adequate treatment. Investigations into tofu whey wastewater have demonstrated the relevance of protein-rich residues and their potential recovery through coagulation-based treatment, emphasizing the need to consider both pollution reduction and resource utilization (Widyarani et al., 2025). The heterogeneous composition of tofu wastewater creates treatment challenges because suspended particles and dissolved organic substances may respond differently to physical and chemical separation processes. Previous investigations using tamarind seed coagulants have specifically examined biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) as indicators of treatment effectiveness in tofu wastewater (Yusuf et al., 2022). Recent comparisons between natural biocoagulants and commercial alum have further emphasized the importance of identifying suitable coagulation conditions for tofu wastewater treatment, particularly where accessible and operationally practical alternatives are required (Cahyonugroho et al., 2026).

Coagulation–flocculation has attracted considerable scientific attention as a wastewater treatment approach because it facilitates the destabilization of suspended and colloidal particles and their subsequent aggregation into settleable flocs. The effectiveness of coagulation depends on interactions among coagulant characteristics, wastewater composition, particle surface properties, and operational conditions, including dosage and solution pH (El-Taweel et al., 2023). Plant-derived

coagulants contain naturally occurring compounds capable of participating in adsorption, charge neutralization, and polymer bridging, although the relative contribution of these mechanisms varies according to the characteristics of the biological material (Benalia et al., 2024). Tamarind seeds have received particular attention because their extractable constituents exhibit coagulation potential, with solvent selection, extraction concentration, and applied dosage influencing their performance in aquaculture wastewater treatment (Kurniawan et al., 2025). Jackfruit seeds represent another potential biocoagulant source, with recent investigations examining the synthesis, characterization, and operational optimization of seed-derived coagulants for turbidity removal (Ho et al., 2026). These developments establish a scientific basis for evaluating agricultural seed materials as wastewater treatment agents while indicating that their effectiveness must be assessed under the specific characteristics of the target effluent.

Current research on tamarind and jackfruit seeds demonstrates the potential of both materials as natural coagulants, although their applications have generally been examined under different wastewater conditions and treatment objectives. Tamarind seed coagulation has been investigated specifically for tofu wastewater, with reported reductions in BOD, COD, and TSS indicating its potential to improve effluent quality through particle aggregation and subsequent separation (Yusuf et al., 2022). Research involving extracted tamarind seeds has expanded this understanding by evaluating the effects of solvent characteristics, extract concentration, coagulant dosage, and toxicity considerations in aquaculture wastewater treatment (Kurniawan et al., 2025). Investigations of jackfruit seed coagulation have examined treatment performance and coagulation–flocculation kinetics in paint industrial wastewater, demonstrating the relevance of this material for treating industrial effluents with different contamination characteristics (Iloamaeke et al., 2024). Recent research has also investigated jackfruit and durian seed-derived coagulants through synthesis, characterization, and process optimization, providing additional evidence regarding seed-based turbidity removal (Ho et al., 2026). The available findings suggest that both seed materials have coagulation potential, but differences in wastewater composition, treatment conditions, and material preparation constrain direct comparisons of their performance. Evidence regarding the combined application of tamarind and jackfruit seeds to tofu wastewater remains insufficient within the selected literature, particularly concerning their mixture proportions and responses across multiple organic pollution indicators.

The limited evidence concerning combined tamarind and jackfruit seed biocoagulants constitutes a contextual and empirical research gap that requires evaluation beyond the performance of individual materials. Previous research combining tamarind and avocado seeds has demonstrated the applicability of mixed plant-derived coagulants for tofu wastewater treatment, establishing a relevant precedent for investigating combinations of natural materials (Assha et al., 2025). Investigations involving tamarind seeds alone provide evidence of pollutant removal in tofu wastewater, but they do not establish whether incorporating jackfruit seed material would improve, reduce, or otherwise modify treatment performance (Yusuf et al., 2022). Jackfruit seed coagulation studies involving paint industrial wastewater provide insights into coagulation behavior and treatment kinetics, although their findings cannot be transferred directly to tofu wastewater because of differences in pollutant composition (Iloamaeke et al., 2024). The recovery of protein from tofu whey through coagulation further illustrates the importance of wastewater-specific interactions between coagulant materials and organic constituents, which may influence the effectiveness of different seed combinations (Widyarani et al., 2025). The unresolved issue concerns how the proportions and total dosage of tamarind and jackfruit seed biocoagulants affect COD, BOD, TSS, and pH when applied together to tofu wastewater under comparable experimental conditions.

The scientific justification for investigating mixed biocoagulants arises from the possibility that different plant-derived constituents may influence particle destabilization, aggregation, and organic pollutant removal through distinct physicochemical interactions. Plant-based coagulants possess heterogeneous chemical compositions, and their treatment behavior depends on the availability and interaction of functional groups associated with proteins, polysaccharides, and other organic compounds (Benalia et al., 2024). Coagulation research has emphasized that coagulant selection and dosage optimization influence treatment effectiveness, making it necessary to assess combinations experimentally rather than assuming that their individual performances can be directly combined (El-Taweel et al., 2023). Research comparing biocoagulants and alum in tofu wastewater has demonstrated the relevance of optimizing coagulant application, although comparisons between individual materials

do not directly explain interactions within a mixed biological treatment system (Cahyonugroho et al., 2026). Studies combining tamarind and avocado seeds provide evidence that mixed natural coagulants can be investigated for tofu wastewater, but their findings do not establish the behavior of combinations incorporating jackfruit seeds (Assha et al., 2025). The proposed novelty lies in evaluating tamarind and jackfruit seed materials together and examining whether variations in their individual dosages and mixture proportions produce different pollutant removal responses within the same wastewater matrix. Such an approach distinguishes the unresolved research gap, concerning the absence of directly comparable evidence for this particular combination, from the intended contribution of systematically assessing its treatment performance and identifying suitable experimental conditions.

This study aims to evaluate the effectiveness of combined tamarind seeds (*Tamarindus indica*) and jackfruit seeds (*Artocarpus heterophyllus*) as natural biocoagulants for treating wastewater generated by a tofu-processing enterprise in Sidodadi, Samarinda Ulu District, Samarinda City, Indonesia. The investigation specifically examines the treatment performance associated with the individual dosages of both seed materials and their application in combined formulations. Variations in total biocoagulant dosage and mixture proportion are evaluated to determine how the selected treatment combinations influence wastewater characteristics. Treatment effectiveness is assessed through changes in chemical oxygen demand, biochemical oxygen demand, total suspended solids, and wastewater pH, providing a basis for comparing the responses of the measured parameters. The study seeks to identify the best-performing combination within the investigated experimental conditions without assuming that the selected formulation represents an optimum beyond the tested range. Its scientific contribution is directed toward providing empirical evidence on mixed plant-seed coagulation in organic-rich tofu wastewater, while its practical contribution concerns the potential application of locally available agricultural materials as alternative wastewater treatment agents.

RESEARCH METHODS

This laboratory-scale experimental study was conducted from April to September 2026 using tofu wastewater collected through grab sampling from a small-scale tofu producer in Sidodadi, Samarinda Ulu District, Samarinda City, Indonesia. A total of 15 L of wastewater was collected in three 5-L jerrycans, while biocoagulant preparation and jar testing were conducted at the Environmental Technology Laboratory, Faculty of Engineering, Mulawarman University, and water-quality analyses were performed at PT Global Environment Laboratory, Samarinda. Tamarind seeds were washed, air-dried for one day, peeled, blended, sieved through a 100-mesh screen, and oven-dried at 105 °C for 60 minutes, following the preparation procedure described by Nurhidayanti et al. (2022). Jackfruit seeds were washed, oven-dried at 105 °C for 24 hours, peeled, blended, and passed through a 100-mesh sieve according to the procedure described by Savira (2023). The experimental design consisted of two stages, with tamarind and jackfruit seed biocoagulants initially tested individually at dosages of 2, 4, 6, and 8 g/L, followed by combined treatments at total dosages of 2 and 4 g/L selected based on the first-stage observations. The combined treatments employed tamarind-to-jackfruit seed ratios of 70:30, 50:50, and 30:70, following the mixture-ratio approach reported by Assha et al. (2025), resulting in six experimental combinations presented in Table 1.

Table 1. Experimental Design for Combined Biocoagulants Per 1 L of Wastewater

Total dosage (g/L)	Tamarind : jackfruit ratio	Tamarind seeds (g)	Jackfruit seeds (g)
2	70:30	1.4	0.6
2	50:50	1.0	1.0
2	30:70	0.6	1.4
4	70:30	2.8	1.2
4	50:50	2.0	2.0
4	30:70	1.2	2.8

$$\text{Removal efficiency (\%)} = \frac{C_0 - C_1}{C_0} \times 100$$

Each treatment used 1 L of tofu wastewater in a beaker, with an additional beaker containing no biocoagulant serving as the control, while the dosage selection was informed partly by the 2 g/L dosage reported by Rafi and Mirwan (2025). Jar testing followed SNI 19-6449-2000 and involved rapid mixing at 100 rpm for 5 minutes, slow mixing at 20 rpm for 30 minutes, and sedimentation in an Imhoff cone for 60 minutes, using operational conditions informed by Agusta et al. (2024). The supernatant was filtered before analysis, and wastewater pH, COD, BOD, and TSS were measured before and after treatment using potentiometry (SNI 6989.11:2019), closed-reflux spectrophotometry (SNI 6989.2:2019), the Winkler method (SNI 6989.72:2009), and gravimetry (SNI 6989.3:2019), respectively. Pollutant removal efficiency was calculated using Equation (1), where C_0 represents the initial pollutant concentration and C_1 represents the concentration after treatment, both expressed in mg/L. The measured parameters were used to evaluate biocoagulant treatment performance, consistent with the assessment of BOD, COD, and TSS in tofu wastewater conducted by Yusuf et al. (2022). The experimental results were analyzed descriptively and quantitatively and compared with the wastewater discharge limits established under Indonesian Minister of Environment Regulation No. 5 of 2014, namely pH 6–9, TSS 200 mg/L, BOD 150 mg/L, and COD 300 mg/L, while statistical significance testing was not performed because each treatment was measured only once.

RESULTS AND DISCUSSION

Initial Characteristics and Pollution Levels of Tofu Wastewater

The initial characterization of tofu wastewater collected from a small-scale tofu producer in Sidodadi, Samarinda, revealed substantial organic contamination and physicochemical conditions that did not comply with the applicable wastewater discharge standards. Laboratory measurements recorded an initial pH of 5.3, total suspended solids (TSS) of 3,216 mg/L, biochemical oxygen demand (BOD) of 4,074 mg/L, and chemical oxygen demand (COD) of 9,329 mg/L. These concentrations indicate considerable quantities of suspended particles and oxygen-demanding substances that may adversely affect receiving water quality if the wastewater is discharged without adequate treatment. The elevated pollutant concentrations reflect the characteristics of soybean-processing wastewater, which contains organic materials released during washing, coagulation, pressing, and other production activities. Hardyanti et al. (2023) demonstrated that the physicochemical characteristics of tofu wastewater vary according to soybean types and processing stages, indicating that wastewater composition is closely associated with production conditions. The simultaneous occurrence of acidic conditions and high pollutant concentrations presents considerable challenges for treatment processes that rely exclusively on physical separation or conventional sedimentation. Initial characterization therefore provides an essential empirical basis for evaluating the effectiveness of tamarind seed and jackfruit seed biocoagulants under the experimental conditions investigated.

The initial wastewater pH of 5.3 indicated acidic conditions before the application of tamarind and jackfruit seed biocoagulants. This acidity may have originated from the addition of acidic coagulating agents during tofu production and the formation of organic acids associated with the decomposition of residual soybean constituents. Previous investigations of tofu-processing wastewater have similarly identified unfavorable physicochemical characteristics that require appropriate treatment before discharge into receiving aquatic environments (Ariyetti et al., 2022). The acidic environment is particularly relevant to coagulation because pH can influence particle surface charges, the ionization of functional groups, and interactions between natural coagulants and wastewater constituents. Plant-derived coagulants exhibit physicochemical behavior that depends partly on solution conditions, including acidity and the characteristics of suspended or colloidal particles (Benalia et al., 2024). The measured pH consequently represents an important baseline condition for interpreting subsequent treatment responses, although its initial value alone cannot establish how the biocoagulant materials modify wastewater acidity during coagulation.

The initial TSS, BOD, COD, and pH values were compared with the wastewater discharge 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 5.3 was below the permitted range of 6–9, indicating that the untreated wastewater did not satisfy the prescribed acidity requirement. The TSS concentration reached 3,216 mg/L, exceeding the regulatory limit of 200 mg/L by approximately 16.08 times. More substantial exceedances were observed for BOD and COD, which

reached 4,074 mg/L and 9,329 mg/L against their respective limits of 150 mg/L and 300 mg/L. These concentrations corresponded to approximately 27.16 and 31.10 times the applicable discharge limits, indicating a particularly severe burden of oxygen-demanding pollutants. Previous research using tamarind seed coagulants for tofu wastewater has similarly emphasized the relevance of BOD, COD, and TSS as principal indicators for assessing treatment effectiveness (Yusuf et al., 2022). The comparison establishes the initial pollution burden and provides a reference for evaluating whether subsequent biocoagulant treatments achieve pollutant reductions sufficient to approach the prescribed discharge requirements.

Table 2. Initial Characteristics of Tofu Wastewater

Parameter	Unit	Discharge Limit	Measured Value	Test Method	Compliance
pH	-	6–9	5.3	SNI 6989.11:2019	Non-compliant
TSS	mg/L	200	3,216	SNI 6989.3:2019	Non-compliant
BOD	mg/L	150	4,074	SNI 6989.72:2009	Non-compliant
COD	mg/L	300	9,329	SNI 6989.2:2019	Non-compliant

Source: Primary data, 2026

The results presented in Table 2 demonstrate that the untreated wastewater exceeded the permissible pollutant concentrations for all three measured pollution indicators. COD exhibited the highest numerical concentration, followed by BOD and TSS, although these parameters represent different aspects of wastewater contamination and cannot be interpreted as equivalent chemical fractions. The substantial exceedances indicate that the wastewater contained considerable amounts of suspended material and oxidizable organic constituents requiring removal before discharge. Similar investigations have shown that tofu-processing wastewater composition varies across production stages, making initial characterization essential for determining appropriate treatment requirements (Hardyanti et al., 2023). The simultaneous exceedance of suspended solids and oxygen-demanding pollutant limits suggests that treatment effectiveness should be evaluated using several water-quality indicators rather than relying exclusively on visual clarification. The non-compliant conditions also establish that a reduction in pollutant concentrations does not necessarily indicate satisfactory treatment unless the remaining concentrations satisfy the applicable discharge standards.

The initial TSS concentration of 3,216 mg/L indicates substantial suspended solid contamination associated with the production of tofu from processed soybeans. These suspended materials may include residual soybean particles and other particulate substances released during washing, grinding, filtration, and coagulation processes, although their specific composition was not directly characterized. The presence of suspended and colloidal particles is relevant because smaller particles may remain dispersed in wastewater when surface interactions inhibit their aggregation and gravitational settling. Coagulation–flocculation is intended to destabilize such particles and promote their aggregation into larger flocs that can be removed through sedimentation (El-Taweel et al., 2023). Plant-derived coagulants may facilitate this process through adsorption, charge neutralization, and polymer bridging, depending on the chemical properties of the materials and surrounding aqueous conditions (Benalia et al., 2024). The considerable initial TSS burden provides an appropriate basis for investigating the particle-removal capabilities of tamarind and jackfruit seed powders when applied individually and in combination. Differences in residual TSS concentrations after treatment can consequently be used to assess the effectiveness of the tested biocoagulant formulations, although the precise mechanisms of particle destabilization require additional physicochemical characterization.

The initial BOD and COD concentrations of 4,074 mg/L and 9,329 mg/L indicate a substantial organic pollution burden that extends beyond the suspended solids fraction. BOD represents the oxygen consumed during the biochemical oxidation of biodegradable substances under specified testing conditions, whereas COD measures the oxygen equivalent required for chemical oxidation of susceptible compounds. The difference between these parameters indicates that the measured chemical oxygen demand was considerably greater than the oxygen demand recorded through biochemical analysis, although the specific organic fractions were not identified. Research investigating protein recovery from tofu whey wastewater has highlighted the presence of recoverable organic constituents

in soybean-processing effluents and their relevance to coagulation-based treatment processes (Widyarani et al., 2025). The removal of particulate and colloidal organic substances through coagulation may contribute to reductions in both BOD and COD, but dissolved constituents may remain in the treated effluent after sedimentation. Separate measurements of these parameters are therefore necessary to determine whether the tested biocoagulants effectively reduce oxygen-demanding pollution rather than merely improving wastewater clarity.

The initial BOD-to-COD ratio was approximately 0.44, calculated from the measured concentrations of 4,074 mg/L BOD and 9,329 mg/L COD. This ratio provides an indication of the relationship between biochemically measured oxygen demand and the total oxidizable load represented by COD. The observed value suggests that a substantial portion of the measured chemical oxygen demand was associated with substances contributing to biochemical oxygen consumption, although the ratio does not independently establish biodegradation kinetics or the distribution of dissolved and particulate organic matter. The characteristics of wastewater constituents are relevant to coagulation performance because different organic fractions may exhibit distinct interactions with natural coagulant materials. El-Taweel et al. (2023) emphasized that coagulation efficiency depends on wastewater characteristics, coagulant properties, and operational conditions influencing particle destabilization and aggregation. The high initial COD concentration also indicates that substantial percentage reductions may still leave considerable residual organic pollution requiring additional treatment. Interpretation of subsequent treatment performance must consequently consider both removal efficiency and the absolute concentrations remaining after coagulation–flocculation.

The initial characterization establishes a quantitative reference for examining the performance of tamarind seed and jackfruit seed biocoagulants in treating organic-rich tofu wastewater. The pronounced differences between measured pollutant concentrations and applicable discharge limits demonstrate that the wastewater requires treatment capable of addressing suspended solids, biodegradable organic substances, and chemically oxidizable constituents. Previous investigations using tamarind seed coagulants have demonstrated their potential to reduce BOD, COD, and TSS in tofu wastewater, providing a relevant comparison for evaluating the present experimental treatments (Yusuf et al., 2022). The distinct physicochemical characteristics of the wastewater also justify comparing the individual seed materials before assessing their combined performance under different dosage and mixture-ratio conditions. Since each experimental treatment was measured once, the resulting removal efficiencies can be interpreted descriptively, but statistical significance and treatment variability cannot be established from the available observations. The subsequent evaluation of individual and combined biocoagulants therefore focuses on measured pollutant reductions, parameter-specific treatment responses, and the extent to which the treated wastewater approaches the applicable discharge requirements.

Effects of Individual Tamarind and Jackfruit Seed Biocoagulants on Tofu Wastewater Quality

Individual jar tests revealed distinct dose-dependent responses between tamarind seed (*Tamarindus indica*) and jackfruit seed (*Artocarpus heterophyllus*) biocoagulants in reducing pollutant concentrations in tofu wastewater. Both seed powders were evaluated separately at dosages of 2, 4, 6, and 8 g/L using wastewater with initial TSS, BOD, and COD concentrations of 3,216, 4,074, and 9,329 mg/L, respectively. These treatments were intended to identify effective individual dosages before evaluating the combined application of both materials under different mixing proportions. The measured concentrations indicated that the greatest removal of suspended solids did not necessarily coincide with the most effective reduction of oxygen-demanding organic pollutants. This variation is consistent with the dependence of plant-based coagulation on coagulant composition, particle characteristics, and the physicochemical properties of wastewater constituents (Benalia et al., 2024). Differences in treatment performance therefore require separate evaluation of TSS, BOD, COD, and pH rather than assuming that a single dosage produces equivalent improvements across all measured parameters.

The experimental results demonstrated contrasting treatment patterns between the two biocoagulants, particularly in their responses to increasing dosage. Tamarind seed powder achieved TSS removal efficiencies ranging from 85.8% to 88.8%, whereas its highest BOD and COD removal efficiencies occurred at the lowest tested dosage of 2 g/L. Jackfruit seed powder produced TSS removal efficiencies between 88.6% and 94.9%, with the greatest removal achieved at 4 g/L. Unlike tamarind

seeds, jackfruit seeds exhibited progressively increasing BOD and COD removal efficiencies as dosage increased from 2 to 8 g/L. These differences suggest that the physicochemical interactions responsible for suspended particle removal may not produce equivalent reductions in oxygen-demanding constituents. Previous investigations of jackfruit seed coagulation in industrial wastewater have similarly examined the relationship between coagulant application, treatment kinetics, and pollutant removal performance (Iloamaeke et al., 2024). The complete experimental results, including residual pollutant concentrations, removal efficiencies, and final pH values, are presented in Table 3 to facilitate direct comparison between the individual treatments.

Table 3. Treatment Results Using Individual Biocoagulants; Removal Efficiencies Calculated from Concentrations

Biocoagulant	Dose (g/L)	TSS (mg/L)	TSS removal (%)	BOD (mg/L)	BOD removal (%)	COD (mg/L)	COD removal (%)	pH
Initial	-	3,216	-	4,074	-	9,329	-	5.3
Tamarind seeds	2	458	85.8	2,032	50.1	4,204	54.9	5.3
Tamarind seeds	4	431	86.6	2,297	43.6	4,833	48.2	5.4
Tamarind seeds	6	360	88.8	2,364	42.0	4,983	46.6	5.4
Tamarind seeds	8	397	87.7	2,526	38.0	5,258	43.6	5.5
Jackfruit seeds	2	339	89.5	2,705	33.6	5,973	36.0	5.4
Jackfruit seeds	4	164	94.9	2,384	41.5	4,858	47.9	5.5
Jackfruit seeds	6	250	92.2	2,297	43.6	4,707	49.5	5.5
Jackfruit seeds	8	368	88.6	2,195	46.1	4,495	51.8	5.6

The results presented in Table 3 demonstrate substantial reductions in suspended solids following treatment with both natural biocoagulants, although their effectiveness varied across the investigated dosages. The lowest residual TSS concentration was 164 mg/L after treatment with jackfruit seed powder at 4 g/L, corresponding to a removal efficiency of 94.9%. In contrast, the lowest residual BOD and COD concentrations among individual treatments were 2,032 mg/L and 4,204 mg/L, respectively, both achieved using tamarind seed powder at 2 g/L. These findings indicate that the most effective biocoagulant and dosage depended on the specific pollutant parameter evaluated. The observed differences correspond to established coagulation principles, in which pollutant removal efficiency depends on the dosage and interactions between coagulant constituents and wastewater particles (El-Taweel et al., 2023). The remaining BOD and COD concentrations also demonstrate that substantial percentage reductions do not necessarily indicate sufficient treatment to satisfy wastewater discharge standards.

Tamarind seed powder exhibited its strongest BOD and COD removal performance at the lowest investigated dosage of 2 g/L, indicating that increasing coagulant quantity did not consistently improve organic pollutant reduction. At this dosage, BOD decreased from 4,074 to 2,032 mg/L, representing a removal efficiency of 50.1%. COD simultaneously decreased from 9,329 to 4,204 mg/L, corresponding to a removal efficiency of 54.9%. Increasing the dosage to 4, 6, and 8 g/L resulted in progressively higher residual BOD concentrations of 2,297, 2,364, and 2,526 mg/L, respectively. A comparable pattern occurred for COD, which increased to 4,833, 4,983, and 5,258 mg/L across the same dosage sequence. One possible explanation is that additional seed-derived organic constituents remained dispersed or dissolved in the treated wastewater rather than being incorporated into settleable flocs, although the experiment did not directly measure organic matter released from the powder. Research on extracted tamarind seed biocoagulants has identified dosage and preparation conditions as important determinants of wastewater treatment performance, supporting the need for careful evaluation of applied coagulant quantities (Kurniawan et al., 2025).

TSS removal by tamarind seed powder followed a different response pattern from the reductions observed for BOD and COD, demonstrating the parameter-specific effects of increasing dosage. The residual TSS concentration decreased from 458 mg/L at 2 g/L to 431 mg/L at 4 g/L and reached its minimum of 360 mg/L at 6 g/L, representing a maximum removal efficiency of 88.8%. Increasing the dosage to 8 g/L produced a higher residual TSS concentration of 397 mg/L, with removal

efficiency declining to 87.7%. The reduction in efficiency at the highest dosage may reflect changes in particle aggregation behavior, including possible restabilization or the presence of excess biocoagulant particles that remained suspended after sedimentation. Previous research on tamarind seed coagulation for tofu wastewater has demonstrated that the removal of suspended solids and oxygen-demanding pollutants can be assessed through different treatment responses, reinforcing the need for parameter-specific interpretation (Yusuf et al., 2022). The measured pH changed only slightly across the dosage range, recording 5.3, 5.4, 5.4, and 5.5 at 2, 4, 6, and 8 g/L, respectively, indicating that tamarind seed addition did not sufficiently neutralize wastewater acidity.

Jackfruit seed powder demonstrated greater TSS removal than tamarind seed powder at each corresponding dosage, although the magnitude of improvement varied between treatment conditions. At 2 g/L, the residual TSS concentration decreased to 339 mg/L, representing a removal efficiency of 89.5%. Increasing the dosage to 4 g/L further reduced TSS to 164 mg/L and produced the highest measured removal efficiency of 94.9% among all individual treatments. Higher dosages were associated with lower removal efficiencies, as residual TSS concentrations increased to 250 mg/L at 6 g/L and 368 mg/L at 8 g/L. These findings identify 4 g/L as the most effective tested jackfruit seed dosage for TSS removal, although the absence of intermediate dosage measurements prevents determination of a more precise optimum. Investigations involving jackfruit seed coagulants have examined their pollutant removal performance and coagulation–flocculation kinetics, indicating that operational conditions influence the effectiveness of seed-derived treatment materials (Iloamaeke et al., 2024). The residual TSS concentration of 164 mg/L was the only individual-treatment result below the applicable discharge standard of 200 mg/L, demonstrating a stronger suspended-solids removal response than the other tested conditions.

Unlike the TSS response, BOD and COD removal by jackfruit seed powder improved progressively as dosage increased from 2 to 8 g/L. Residual BOD concentrations decreased from 2,705 mg/L at 2 g/L to 2,384, 2,297, and 2,195 mg/L at 4, 6, and 8 g/L, respectively. COD exhibited a similar declining pattern, with residual concentrations of 5,973, 4,858, 4,707, and 4,495 mg/L across the corresponding treatments. The maximum measured removal efficiencies for BOD and COD were consequently 46.1% and 51.8% at 8 g/L, indicating that their most effective tested dosage differed from that required for maximum TSS removal. Recent investigations of jackfruit seed-derived coagulants have emphasized the importance of material characterization and operational optimization for particle removal, although direct extrapolation to dissolved organic pollutants in tofu wastewater remains uncertain (Ho et al., 2026). The wastewater pH increased slightly from 5.4 at 2 g/L to 5.6 at 8 g/L, but the treated effluent remained below the minimum permitted pH of 6.

The comparison between tamarind and jackfruit seed biocoagulants identifies distinct treatment advantages that provide an empirical basis for examining their combined application. Tamarind seed powder at 2 g/L produced the lowest individual-treatment BOD and COD concentrations, whereas jackfruit seed powder at 4 g/L achieved the greatest reduction in suspended solids. The former treatment removed 50.1% of BOD and 54.9% of COD, while the latter achieved 94.9% TSS removal under the tested experimental conditions. These results indicate potential complementarity between the two seed materials, although separate treatment performance does not establish whether their combined application will produce additive, synergistic, or antagonistic effects. Previous investigations combining tamarind and avocado seeds for tofu wastewater treatment demonstrate the applicability of mixed biocoagulant formulations, but their findings cannot directly establish the performance of tamarind and jackfruit seed mixtures (Assha et al., 2025). The absence of replicated measurements also prevents statistical assessment of differences between individual treatments, restricting interpretation to the observed concentrations and calculated removal efficiencies. The subsequent combined-treatment experiments consequently examine total dosages of 2 and 4 g/L with tamarind-to-jackfruit seed ratios of 70:30, 50:50, and 30:70 to determine whether these formulations improve pollutant removal and wastewater quality relative to the individual treatments.

Performance of Combined Biocoagulants, Optimum Treatment Conditions, and Compliance with Discharge Standards

The combined application of tamarind seed (*Tamarindus indica*) and jackfruit seed (*Artocarpus heterophyllus*) powders produced measurable reductions in TSS, BOD, and COD concentrations, although treatment effectiveness varied according to total dosage and mixture proportion. Six treatment

combinations were evaluated using total biocoagulant dosages of 2 and 4 g/L, with tamarind-to-jackfruit seed ratios of 70:30, 50:50, and 30:70. These combinations were selected following the individual-treatment experiments, which demonstrated different responses of the two seed materials to suspended solids and oxygen-demanding pollutants. At both total dosages, formulations containing a greater proportion of tamarind seed powder consistently produced lower residual TSS, BOD, and COD concentrations than mixtures dominated by jackfruit seed powder. The highest measured treatment performance was obtained using a total dosage of 2 g/L and a 70:30 ratio, which achieved removal efficiencies of 84.0% for TSS, 53.7% for BOD, and 54.0% for COD. These findings indicate that the combined treatment performance was sensitive to the proportions of the two plant-derived materials rather than being determined exclusively by total coagulant dosage. Previous investigations combining tamarind and avocado seeds for tofu wastewater treatment have similarly demonstrated the relevance of evaluating mixed biocoagulant formulations, although differences in constituent materials limit direct performance comparisons (Assha et al., 2025).

The experimental results revealed a consistent difference between the two tested total dosages, with 2 g/L producing lower residual pollutant concentrations than 4 g/L at every corresponding mixture ratio. At 2 g/L, the residual TSS concentrations ranged from 516 to 530 mg/L, while BOD and COD concentrations ranged from 1,888 to 2,037 mg/L and from 4,290 to 4,478 mg/L, respectively. Increasing the total dosage to 4 g/L resulted in higher residual concentrations, with TSS ranging from 552 to 578 mg/L, BOD from 2,095 to 2,190 mg/L, and COD from 4,556 to 4,739 mg/L. This pattern indicates that the additional biocoagulant material did not improve pollutant removal under the investigated mixing and sedimentation conditions. Coagulation efficiency depends on the balance between the applied coagulant quantity and the characteristics of suspended and dissolved wastewater constituents, making excessive dosage a potential limitation rather than an automatic improvement (El-Taweel et al., 2023). The complete concentrations, calculated removal efficiencies, and final pH values for the six combined treatments are presented in Table 4.

Table 4. Treatment Results Using Combined Tamarind and Jackfruit Seed Biocoagulants

Dose (g/L)	Ratio	TSS (mg/L)	TSS removal (%)	BOD (mg/L)	BOD removal (%)	COD (mg/L)	COD removal (%)	pH
Initial	-	3,216	-	4,074	-	9,329	-	5.3
2	70:30	516	84.0	1,888	53.7	4,290	54.0	5.6
2	50:50	522	83.8	1,956	52.0	4,383	53.0	5.7
2	30:70	530	83.5	2,037	50.0	4,478	52.0	5.8
4	70:30	552	82.8	2,095	48.6	4,556	51.2	5.7
4	50:50	560	82.6	2,165	46.9	4,664	50.0	5.8
4	30:70	578	82.0	2,190	46.2	4,739	49.2	5.9

Table 4 demonstrates that the 2 g/L treatment with a 70:30 tamarind-to-jackfruit seed ratio achieved the lowest residual concentrations among all combined formulations. This treatment reduced TSS from 3,216 to 516 mg/L, corresponding to a removal efficiency of 84.0%, while BOD decreased from 4,074 to 1,888 mg/L, representing 53.7% removal. COD simultaneously declined from 9,329 to 4,290 mg/L, producing a removal efficiency of 54.0%, with the final wastewater pH increasing from 5.3 to 5.6. At the same total dosage, the 50:50 formulation produced slightly lower removal efficiencies of 83.8% for TSS, 52.0% for BOD, and 53.0% for COD. The 30:70 formulation yielded corresponding efficiencies of 83.5%, 50.0%, and 52.0%, indicating progressively lower treatment performance as the proportion of tamarind seed powder decreased. A comparable ranking occurred at 4 g/L, where the 70:30 formulation achieved higher removal efficiencies than the 50:50 and 30:70 formulations for all three measured pollutants. Plant-based coagulants contain organic constituents capable of interacting with suspended and colloidal particles through different physicochemical mechanisms, providing a possible explanation for the observed influence of mixture composition (Benalia et al., 2024).

Increasing the combined biocoagulant dosage from 2 to 4 g/L reduced pollutant removal efficiency across all three mixture ratios, suggesting that additional coagulant material was not beneficial within the tested treatment range. At the 70:30 ratio, residual TSS increased from 516 to 552 mg/L, while BOD increased from 1,888 to 2,095 mg/L and COD from 4,290 to 4,556 mg/L. The

corresponding removal efficiencies decreased from 84.0% to 82.8% for TSS, from 53.7% to 48.6% for BOD, and from 54.0% to 51.2% for COD. The deterioration in treatment performance may be associated with an excess of organic coagulant constituents that remained in the wastewater or with the possible restabilization of particles after the effective coagulation dosage was exceeded. Previous investigations have emphasized that coagulation performance depends on operational optimization, including the appropriate application of coagulant materials under specific wastewater conditions (Cahyonugroho et al., 2026). Since the present experiment did not directly measure residual coagulant constituents, particle charge, or floc characteristics, these mechanisms remain plausible explanations rather than experimentally confirmed causes of the observed dosage response.

The influence of mixing ratio was evident from the progressive reduction in treatment efficiency as the proportion of tamarind seed powder decreased from 70% to 30% at a constant total dosage. At 2 g/L, increasing the tamarind proportion from 30% to 70% reduced residual BOD from 2,037 to 1,888 mg/L and residual COD from 4,478 to 4,290 mg/L. Residual TSS also declined from 530 to 516 mg/L, although the absolute difference of 14 mg/L was considerably smaller than the differences observed for the oxygen-demanding parameters. At 4 g/L, the same directional response occurred, with the 70:30 formulation recording TSS, BOD, and COD concentrations of 552, 2,095, and 4,556 mg/L, respectively. Tamarind seed constituents may contribute to the destabilization of suspended particles and the removal of associated organic substances through interactions involving proteins and polysaccharides, although the specific contribution of each constituent was not determined in this experiment (Kurniawan et al., 2025). Jackfruit seed materials may also participate in particle aggregation through starch-associated interactions, as suggested by previous research examining jackfruit seed coagulation and flocculation performance in industrial wastewater (Iloamaeke et al., 2024). The observed differences among ratios establish a descriptive relationship between mixture composition and pollutant removal, but the absence of replicated measurements prevents conclusions regarding statistical significance or synergistic interactions between the two biocoagulants.

Combined biocoagulant treatment produced modest increases in wastewater pH, with the initial value of 5.3 rising to between 5.6 and 5.9 across the six formulations. At a total dosage of 2 g/L, final pH values were 5.6, 5.7, and 5.8 for the 70:30, 50:50, and 30:70 mixtures, respectively. At 4 g/L, the corresponding values increased to 5.7, 5.8, and 5.9, indicating that formulations containing greater proportions of jackfruit seed powder were associated with slightly higher final pH values. These changes may reflect interactions between the wastewater and ionizable functional groups present in the natural coagulant materials, although the mechanisms responsible were not directly measured. Research on plant-derived coagulation has established that solution pH influences the behavior of organic functional groups and particle interactions, which may contribute to differences in treatment performance (Benalia et al., 2024). Despite the observed increases, every combined treatment remained below the minimum permitted discharge pH of 6, demonstrating that the seed formulations did not independently achieve compliance with the applicable acidity requirement.

The best-performing combined treatment was identified as the 2 g/L formulation containing 70% tamarind seed powder and 30% jackfruit seed powder, based on its superior pollutant removal among the six evaluated mixtures. This formulation achieved the lowest combined-treatment BOD concentration of 1,888 mg/L, improving upon the lowest individual-treatment BOD concentration of 2,032 mg/L obtained using tamarind seeds alone at 2 g/L. Its COD concentration of 4,290 mg/L, however, remained higher than the 4,204 mg/L achieved using tamarind seeds alone, indicating that the combined formulation did not provide a corresponding improvement in COD removal. A more substantial difference was observed for TSS, because the combined treatment produced a residual concentration of 516 mg/L compared with 164 mg/L obtained using jackfruit seed powder alone at 4 g/L. These results demonstrate that combining the two seed materials did not consistently outperform the best individual treatment for every pollutant parameter, despite producing the lowest BOD concentration among the tested formulations. Previous studies using tamarind seeds for tofu wastewater treatment have demonstrated the importance of evaluating BOD, COD, and TSS separately because treatment performance can differ across pollutant indicators (Yusuf et al., 2022). The designation of the 70:30 formulation as the best combined treatment is consequently restricted to the investigated mixtures and should not be interpreted as evidence of universal optimization or superior performance relative to all individual applications.

Comparison with the applicable wastewater discharge standards demonstrates that substantial pollutant reductions were insufficient to produce compliant effluent under the investigated combined-treatment conditions. Even the best-performing mixture retained TSS, BOD, and COD concentrations of 516, 1,888, and 4,290 mg/L, exceeding their respective limits of 200, 150, and 300 mg/L, while the final pH of 5.6 remained below the permitted range of 6–9. The results indicate that combined tamarind and jackfruit seed coagulation–flocculation may function as a preliminary treatment process but cannot be considered sufficient as a stand-alone method for meeting the applicable discharge requirements. Additional treatment processes are necessary to reduce residual organic pollutants, remove remaining suspended solids, and adjust wastewater acidity before discharge. The effectiveness of coagulation–flocculation depends on operational conditions and the characteristics of the wastewater being treated, supporting the need for further optimization and integration with complementary treatment technologies (El-Taweel et al., 2023). Future investigations should incorporate replicated treatments, additional dosage and mixture-ratio combinations, characterization of residual organic constituents, and evaluation of subsequent treatment stages to determine whether the observed reductions can be improved and consistently reproduced.

CONCLUSION

The experimental results demonstrated that tamarind (*Tamarindus indica*) and jackfruit (*Artocarpus heterophyllus*) seed powders reduced TSS, BOD, and COD concentrations in tofu wastewater, although their effectiveness varied according to coagulant type, dosage, and mixture ratio. For individual applications, tamarind seed powder at 2 g/L achieved the highest BOD (50.1%) and COD (54.9%) removal efficiencies, whereas jackfruit seed powder at 4 g/L produced the greatest TSS removal efficiency (94.9%). Among the combined treatments, the most effective formulation consisted of a total dosage of 2 g/L with a tamarind-to-jackfruit seed ratio of 70:30, reducing TSS from 3,216 to 516 mg/L (84.0%), BOD from 4,074 to 1,888 mg/L (53.7%), and COD from 9,329 to 4,290 mg/L (54.0%). This treatment also increased wastewater pH from 5.3 to 5.6. Across all mixture ratios, the 2 g/L dosage consistently achieved greater pollutant removal than 4 g/L, while increasing the proportion of tamarind seed powder corresponded to lower residual TSS, BOD, and COD concentrations. The combined formulation produced a lower BOD concentration than either individual biocoagulant treatment but did not outperform the best individual treatments for TSS and COD removal. These findings demonstrate the potential of combining both seed materials while indicating that treatment effectiveness remains dependent on the targeted pollutant and selected operating conditions.

Despite the reductions achieved, the best combined treatment did not satisfy the applicable discharge standards for TSS (200 mg/L), BOD (150 mg/L), and COD (300 mg/L), while its final pH remained below the permitted range of 6–9. Combined tamarind and jackfruit seed coagulation–flocculation is therefore more appropriately considered a preliminary treatment process rather than a complete method for producing compliant tofu wastewater effluent. Additional treatment stages are necessary to further reduce residual organic pollutants and suspended solids and correct wastewater acidity before discharge. Future investigations should evaluate additional mixture ratios around the best-performing 70:30 formulation, including 80:20 and 60:40, while examining the effects of controlled initial pH adjustments on pollutant removal efficiency. Experimental replication and appropriate statistical analysis are required to establish the reliability of observed differences between dosage levels and mixture compositions. Further characterization of seed proteins, starch, and functional groups, together with the evaluation of integrated post-coagulation treatment processes, would provide a stronger basis for understanding removal mechanisms and improving the practical applicability of these agricultural waste-derived biocoagulants.

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