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Comparison of Optimum Dosages of Biocoagulant and Commercial Coagulant Alum in the Coagulation-Flocculation Process of Tofu Wastewater

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ABSTRACT

The tofu industry produces wastewater containing organic matter, suspended solids, and high nitrogen compounds that have the potential to pollute the environment. This research compares the effectiveness of natural biocoagulants derived from maggot shells and moringa seeds with commercial alum coagulants in the coagulation-flocculation process of tofu wastewater. The novelty of this research lies in the use of maggot shells, which are biomass waste, as a natural coagulant. Until now, maggot shells have rarely been used in wastewater treatment, unlike moringa seeds, which have been extensively researched and proven to be effective due to their 44.8% cationic protein content. The research methods included the production of biocoagulants, the determination of the optimum dose through jar tests, and the analysis of pH, TSS, turbidity, and color parameters. The results indicated that all coagulants effectively reduced TSS, turbidity, and color levels. The alum coagulant demonstrated the highest efficiency, achieving 98.66% TSS removal, 86.67% turbidity removal, and 96.17% color removal at an optimal dose of 250 $mg.L^{-1}$. The moringa seed biocoagulant achieved a comparable performance with 98.66% TSS, 86.67% turbidity, and 96.17% color removal at 150 $mg.L^{-1}$. In contrast, the maggot shell biocoagulant showed moderate efficiency, removing 83.89% TSS, 74.96% turbidity, and 77.48% color removal at 150 $mg.L^{-1}$.

1. INTRODUCTION

The rapidly growing tofu industry in Indonesia has resulted in high demand for soybean-based products, producing wastewater with high levels of organic matter, suspended solids, and nitrogen compounds that have the potential to pollute the environment if not treated (Anifah et al. 2024). This wastewater contains organic matter that causes high levels of suspended particles, mainly from the release of skin residues and fine organic particles during the soybean boiling process (Pramaningsih et al. 2022). In addition, the turbidity level of tofu wastewater, which reaches 238–294 NTU, is also caused by the release of colloidal particles and organic matter during processing (Anifah et al. 2024).

In response to this pollution challenge, the use of synthetic coagulants such as alum has become common in water treatment due to its high efficiency and relatively low cost. However, excessive use of alum can leave residues and pose risks to human health and the environment (Ramakrishnan & Sathiyamoorthy 2025). As a more environmentally friendly alternative, plant- and animal-based biocoagulants are now being developed because they contain functional groups such as hydroxyl, carboxylic acid, and amine, which play an important role in the coagulation-flocculation process, thereby increasing the efficiency of various types of wastewater treatment (Kurniawan et al. 2020). Previous research on the use of biocoagulants in wastewater treatment has shown a 97% reduction in turbidity (Bouchareb et al. 2021).

The performance of coagulants in reducing suspended particles is known to be greatly influenced by dosage, type of coagulant, pH, and stirring intensity (Aragaw & Bogale 2023). Various types of coagulants have been developed, including animal-based, plant-based, and metal salt-based coagulants, each with its own advantages and limitations in terms of effectiveness and environmental impact (Diver et al. 2023). Therefore, this research aims to analyze and compare the performance of three types of coagulants, namely maggot shells as animal-based coagulants, moringa seeds as plant-based coagulants, and alum as metal salt-based coagulants, in reducing color, turbidity, and total suspended solids (TSS) in tofu wastewater.

2. MATERIALS AND METHODS

The samples used in this research were wastewater from the tofu production process in Waru, Sidoarjo. All samples were taken at the same time and from the same source to maintain the consistency of the wastewater characteristics. The treatment process was carried out using the coagulation-flocculation method with two types of natural biocoagulants, namely moringa seeds and maggot shells, with alum used as a commercial coagulant comparator.

This research used three replications for each dose variation to ensure consistency in the test results. The coagulant solution was prepared in three concentration variations, namely 50 $mg.L^{-1}$, 100 $mg.L^{-1}$, and 150 $mg.L^{-1}$ for moringa seeds and maggot shells, and 150 $mg.L^{-1}$, 200 $mg.L^{-1}$, and 250 $mg.L^{-1}$ for alum. The coagulation-flocculation test was conducted using the jar test method in accordance with SNI 19-6449-2000, using a sample volume of 1000 mL. The process included rapid stirring at 120 rpm for 1 minute, slow stirring at 40 rpm for 20 minutes, and sedimentation for 20 minutes. In this research, no pH adjustment was performed before or after the coagulation-flocculation process.

The supernatant from the sedimentation was analyzed to evaluate the effectiveness of the coagulant in reducing turbidity and total suspended solids (TSS). The water quality parameters measured included pH (SNI 06-6989.11-2004), TSS (SNI 06-6989.3-2004), color (SNI 6989.80-2011), and turbidity (SNI 06-6989.25-2005). The data from the coagulation-flocculation effectiveness test were statistically analyzed using one-way ANOVA to determine significant differences between variations in dosage and type of coagulant on water quality parameters (TSS, color, and turbidity). The effectiveness of the photocatalysis process was evaluated through the calculation of the removal percentage using the formula:

$$\%\text{removal} = \frac{C0 - Ct}{C0} \times 100\% \qquad \ldots(1)$$

Description:

C_0 represents the initial concentration

C_t represents the concentration at time t

3. RESULTS AND DISCUSSION

3.1. Characteristics of Tofu Wastewater

Previous research has reported that tofu wastewater typically has a low pH due to the use of acetic acid during production (Pangestika & Saksono 2018). Another study showed that the pH value of tofu wastewater was 5.08 (Djari & Asyfiradayati 2024). The TSS value in tofu wastewater is 1,166.67 $mg.L^{-1}$ (Nora et al. 2023). Most of the suspended solids content is produced during the soybean boiling process, where skin residues and fine organic particles are released during tofu and tempeh production (Pramaningsih et al. 2022). In addition, the high turbidity, ranging from 238 to 294 NTU, is also caused by the release of colloidal particles and organic matter during tofu processing (Anifah et al. 2024). Based on Table 1 and the results of previous studies, these levels are still above the quality standards. The quality standards for tofu industry wastewater are regulated under East Java Governor Regulation No. 72 of 2013 concerning Wastewater Quality Standards for Industries or Other Business Activities.

3.2. Comparison of Coagulant Effectiveness on Wastewater Quality Parameters

To provide a comprehensive understanding of the performance of coagulants in industrial tofu wastewater treatment, this section presents a comparative analysis of their effectiveness based on various quality parameters, including pH variation, turbidity reduction, total suspended solids (TSS) removal, and color reduction. The evaluation was conducted using different doses of biological coagulants from maggot shells and moringa seeds at concentrations of 50 $mg.L^{-1}$, 100 $mg.L^{-1}$, and 150 $mg.L^{-1}$ as well as alum coagulants at concentrations of 150 $mg.L^{-1}$, 200 $mg.L^{-1}$, and 250 $mg.L^{-1}$. These dosage variations were determined based on the optimum dosage for each coagulant. Through

Table 1: Results of preliminary tests on Tofu wastewater before treatment.

Parameters	Units	Test Results	Quality Standards
pH	-	4,8	6,0 – 9,0
TSS	$mg.L^{-1}$	2,980	100
Turbidity	NTU	1,208	-
Color	Pt-Co	2,225	-

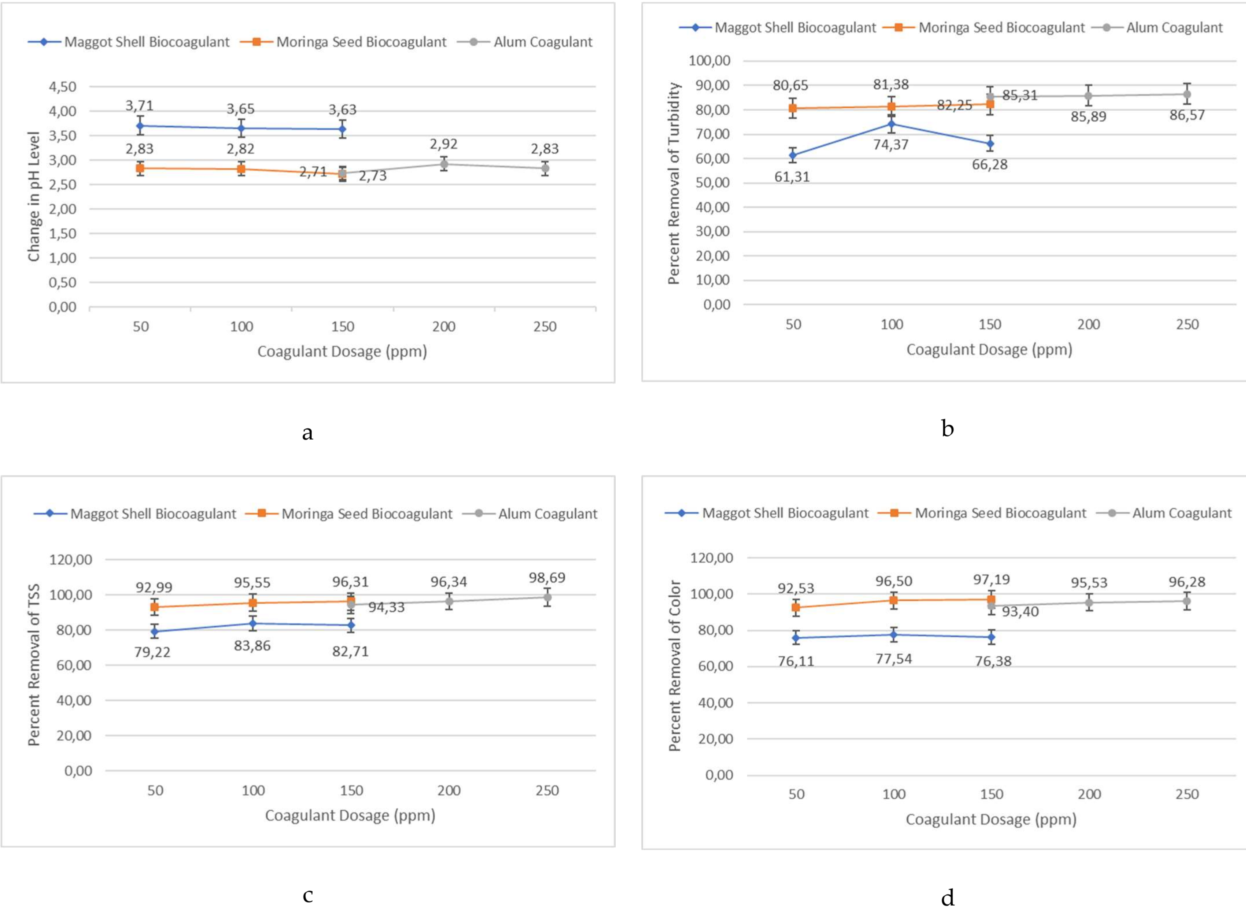


Fig. 1: Comparison of decreases in (a) pH, (b) turbidity, (c) TSS, and (d) color.

this approach, the research aimed to reveal the relationship between coagulant dosage and improvements in wastewater quality parameters, thereby identifying the most effective and environmentally friendly coagulant formulation. The following sections present changes in pH, along with decreases in turbidity, TSS, and color values.

3.2.1. The Effect of Coagulant Type Variations on pH

The initial pH value of tofu wastewater before coagulation-flocculation was 4.8, which is considered acidic. After treatment with various types and doses of coagulants, there was a decrease in pH that varied depending on the type and concentration of the coagulant.

Fig. 1 point (a) shows a graph depicting the pH results after the coagulation-flocculation process using maggot shell and moringa seed biocoagulants, as well as the commercial coagulant alum. For the maggot shell biocoagulant, the final pH decreased to 3.72, 3.69, and 3.68 for doses of 50 $mg.L^{-1}$, 100 $mg.L^{-1}$, and 150 $mg.L^{-1}$, respectively. This decrease indicates that this coagulant is sufficiently acidic. A similar trend was observed for the moringa seed biocoagulant, with final pH values of 2.86, 2.86, and 2.78 at the same doses of 50 $mg.L^{-1}$, 100 $mg.L^{-1}$, and 150 $mg.L^{-1}$. These values indicate a more drastic pH decrease compared to other coagulants. Meanwhile, the pH of the alum coagulant ($Al_2(SO_4)_3$) had final pH values of 2.78, 2.91, and 2.83 at doses of 150, 200, and 250 $mg.L^{-1}$. Although it still decreased, the pH with the alum coagulant also increased at doses of 200 $mg.L^{-1}$ and 250 $mg.L^{-1}$.

The more pronounced pH decrease observed in the moringa seed treatment can be explained by its chemical composition, particularly the presence of proteins containing amino and carboxyl functional groups. The amino acids present in moringa seed proteins can accept protons from water and release hydroxyl group ions, leading to basic buffering behavior. However, the decrease in pH of the treated wastewater in this research might be attributed to the presence of low-molecular-weight proteins that carry positive charges. These positively charged proteins interact with negatively charged particles such as silt, clay, and other colloidal impurities, resulting in proton exchange and a subsequent reduction in pH. The active cationic proteins and carboxyl groups in the seed structure contribute to charge neutralization and effective destabilization of colloids, which enhances coagulation efficiency but simultaneously promotes a stronger pH drop compared to other coagulants (Basra et al. 2014).

Fig. 1 point (a) shows that all types of coagulants cause a decrease in the pH of tofu wastewater. Maggot shell biocoagulant produced the lowest pH of 3.68 at a dose of 150 mg.L^{-1}, while moringa seed biocoagulant and alum coagulant both produced the lowest pH of 2.78 at the same dose of 150 mg.L^{-1}. If the environmental pH aligns with the optimal pH of the coagulant used, the floc formation process will occur more efficiently, thereby significantly impacting the reduction of pollutant parameters such as total suspended solids (TSS) and turbidity levels (Hutabarat et al. 2022). However, using coagulants in excess of the optimum dose can increase impurities in the water and cause saturation of the colloid surface. This condition will result in particle instability and the formation of repulsive forces between the contaminants and the coagulants, thereby inhibiting the floc formation process (Patchaiyappan & Devipriya 2021).

3.2.2. The Effect of Coagulant Type Variations on Turbidity

Turbidity indicates the presence of various organic and inorganic materials in water, such as sludge or pollutants from industrial wastewater (Kastali et al. 2021). The initial turbidity value of the tofu wastewater was 1,208 NTU, indicating that the wastewater had a very high turbidity level. After the coagulation-flocculation process, there was a decrease in turbidity with all types of coagulants.

Fig. 1 point (b) shows a graph depicting the percentage of turbidity removal after the coagulation-flocculation process using maggot shell and moringa seed biocoagulants, as well as the commercial coagulant alum. The maggot shell bioflocculant produced final turbidity values of 463.5 NTU, 302.5 NTU, and 400.5 NTU at doses of 50 mg.L^{-1}, 100 mg.L^{-1}, and 150 mg.L^{-1}, respectively. The highest turbidity removal percentage occurred at a dose of 100 mg.L^{-1}, amounting to 74.96%. This indicates that the optimal dose for the maggot shell bioflocculant is 100 mg.L^{-1}. The moringa seed bioflocculant showed better results, with final turbidity values of 241.5 NTU, 228 NTU, and 217 NTU for doses of 50 mg.L^{-1}, 100 mg.L^{-1}, and 150 mg.L^{-1}, respectively. The highest turbidity removal percentage occurred at a dose of 100 mg.L^{-1}, which was 82.04%. This indicates that the optimal dose for the moringa seed bioflocculant is 150 mg.L^{-1}. Meanwhile, the alum coagulant showed the highest removal, with final turbidity values of 180.5 NTU, 169.5 NTU, and 161 NTU for doses of 150 mg.L^{-1}, 200 mg.L^{-1}, and 250 mg.L^{-1}, respectively. The highest turbidity removal percentage occurred at a dose of 250 mg.L^{-1}, which was 86.67%. This indicates that the optimal dose for the alum coagulant is 250 mg.L^{-1}.

Based on the research results, all types of coagulants were able to reduce turbidity, with the alum coagulant showing the highest effectiveness, followed by moringa seeds and maggot shells. The effectiveness of alum is due to its high aluminum sulfate ($Al_2(SO_4)_3$) content, which has a high positive charge, enabling it to quickly neutralize the negative charge of colloidal particles and form dense flocs through the sweep flocculation mechanism. Research conducted by Akutteh et al. (2022) showed that the use of alum at a dose of 80 mg.L^{-1} with a pH value of 7.5 was able to remove turbidity by up to 82.3% (Akutteh et al. 2022). This advantage makes alum still widely used as a commercial coagulant to effectively reduce TSS and turbidity, despite its disadvantage of potentially leaving metal residues in treated water (Purnomo 2023).

3.2.3. The Effect of Coagulant Type Variation on Total Suspended Solids (TSS)

Tofu wastewater contains 2,980 mg.L^{-1} of TSS, which exceeds the TSS quality standard of 100 mg.L^{-1} as stipulated in East Java Governor Regulation No. 72 of 2013. After undergoing coagulation-flocculation, all types of coagulants used were able to reduce the TSS level.

Fig. 1 point (c) shows a graph depicting the percentage of TSS removal after the coagulation-flocculation process using maggot shell biocoagulants and moringa seeds, as well as commercial coagulants such as alum. The maggot shell biocoagulant produced final TSS values of 610 mg.L^{-1}, 480 mg.L^{-1}, and 510 mg.L^{-1}, with the highest removal percentage at a dose of 100 mg.L^{-1}, which was 83.89%. The moringa seed bio-flocculant showed lower removal results, with final TSS values of 210 mg.L^{-1}, 130 mg.L^{-1}, and 117 mg.L^{-1}, with the highest removal percentage at a dose of 150 mg.L^{-1}, which was 96.31%. Meanwhile, alum showed the lowest removal results, with final TSS values of 170 mg.L^{-1}, 110 mg.L^{-1}, and 40 mg.L^{-1}, with the highest removal percentage at a dose of 250 mg.L^{-1}, which was 98.66%.

Aluminum sulfate demonstrated the highest efficiency in reducing TSS in tofu wastewater compared to natural coagulants. The positively charged aluminum ions released by aluminum sulfate neutralize the negative charge of colloidal particles and trigger the formation of compact flocs that settle easily. This process improves the efficiency of separating suspended solids from the liquid phase through the sweep flocculation mechanism (Tahraoui et al. 2024).

3.2.4. The Effect of Coagulant Type Variations on Color

The initial color of the tofu wastewater, which has a value of 2,225 Pt-Co, indicates a high content of dissolved organic compounds. This color originates from proteins, phenolic compounds, and other organic components produced during the tofu production process (Putro et al. 2021).

The effectiveness of color removal by coagulants was tested based on the decrease in Pt-Co values. The maggot shell biocoagulant produced final color values of 534, 501, and 522 Pt-Co, with the best removal efficiency of 77.48% at a dose of 100 mg.L^{-1}. The biocoagulant from moringa seeds showed significantly better results, with final color values of 177 Pt-Co, 79.5 Pt-Co, and 60.7 Pt-Co, achieving the highest removal efficiency of 97.27% at a dose of 150 mg.L^{-1}. Meanwhile, the alum coagulant produced final color values of 151.7 Pt-Co, 100 Pt-Co, and 85.3 Pt-Co, with the best removal efficiency of 96.17% at a dose of 250 mg.L^{-1}.

The color reduction shows the difference in tofu wastewater before and after the coagulation-flocculation process. This process demonstrates the successful removal of suspended and dissolved solid fractions, including sludge, organic compounds, and microorganisms that contribute to the high initial Pt-Co value. This process occurs through the destabilization of negatively charged colloidal particles by the positive charge of the coagulant, followed by the formation of flocs that trap the components causing color. Research conducted by Anifah et al. (2024) shows that the use of cempedak seed extract as a natural coagulant can significantly reduce turbidity, TSS, and color values in tofu wastewater, supporting the interpretation that color parameters can be used as an indicator of the effectiveness of the coagulation-flocculation process (Anifah et al. 2024).

Color removal efficiency increases with the addition of coagulant doses up to 25 g.L^{-1}, at which point the moringa seed biocoagulant is able to reach optimum conditions by causing suspended particles and dye molecules in wastewater to coagulate into larger flocs (Rendana et al. 2025). The flocs then settle, while the dye molecules attach to their surface and are eliminated from the wastewater (Ibrahim et al. 2021). Moringa seed biocoagulant works by neutralizing the negative charge on dye molecules and suspended particles, resulting in aggregation and particle removal. An adequate coagulant dose is very important to achieve optimal color removal efficiency, while an excessive dose can actually reduce its performance (Desta & Bote 2021). In this research, the highest color removal efficiency achieved was around 89% (Rendana et al. 2025).

3.3. The Effect of Coagulant Type Variations on Floc Density

Floc density is an important parameter that determines the sedimentation rate and overall efficiency of the coagulation-flocculation process. The denser the structure of the floc formed, the faster it settles, thereby improving the removal of turbidity, total suspended solids (TSS), and color in wastewater (Teh et al. 2016). Floc density can be observed from the zeta potential value, which is close to zero (Fitri et al. 2019). The variation in floc density observed in this research was greatly influenced by the type of coagulant used.

3.3.1. Characteristics of Floc Using Maggot Shell Biocoagulant

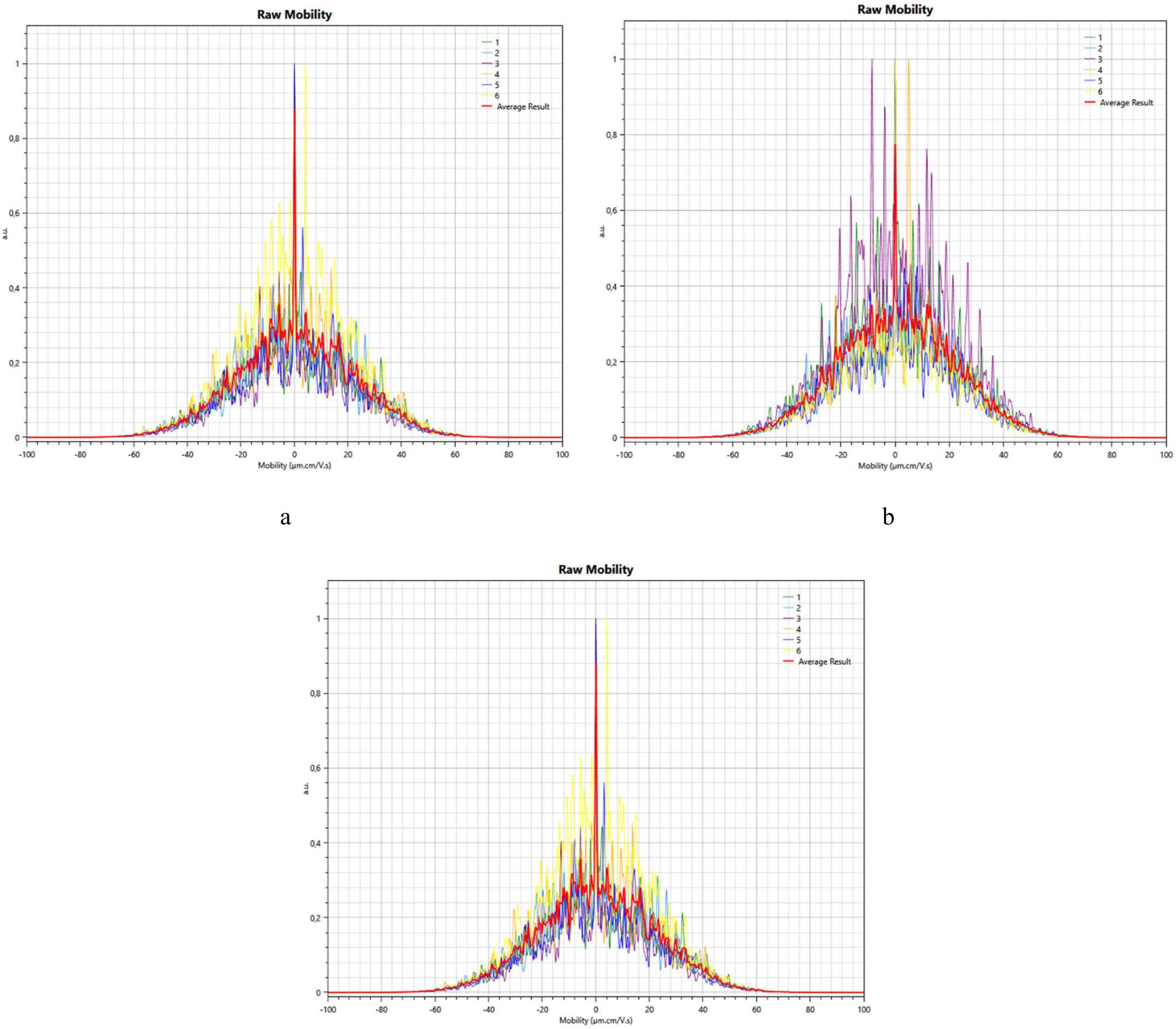
The zeta potential test was conducted to analyze colloid stability, where values close to the isoelectric point indicate a decrease in particle stability and a tendency for aggregation or floc formation. The results of this test provide a comprehensive empirical basis for evaluating the effectiveness of maggot shell biocoagulants in reducing the stability of dissolved particles, as well as a reference for determining optimal performance in the treatment of Jagir River water.

Based on the zeta testing results in Fig. 2 point (a), the average zeta potential value was 8.8 mV, with a standard deviation of 19.67. The standard deviation value was much greater than the mean, indicating large fluctuations between repetitions. The positive zeta potential value is caused by the surface charge, which is dominated by chitosan, so the potential difference between the electrical double-layer system and the medium is positive (Fitri et al. 2019). Overall, the average zeta potential value of 8.8 mV is classified as low, indicating that the colloid is in an unstable condition. This value range (0 to ±30 mV) indicates that the repulsive force between particles has weakened, facilitating the process of destabilization and floc formation (Fitri et al. 2019).

The maggot shell biocoagulant, derived from chitosan, primarily functions through weak charge neutralization. Under acidic conditions, the amino groups ($-NH_2$) on chitosan become protonated to form $-NH_3^+$, enabling limited interaction with negatively charged colloids. However, due to its lower cationic charge density and partial degree of deacetylation, chitosan from maggot shells exhibits a reduced capacity for bridging and particle entrapment. This results in the formation of lighter and more porous flocs with lower settling velocity compared to those produced by moringa seed and alum coagulants.

3.3.2. Characteristics of Floc Using Moringa Seed Biocoagulant

The zeta potential test was conducted to analyze colloid stability, where values close to the isoelectric point indicate a decrease in particle stability and a tendency for aggregation or floc formation. The results of this test provide a comprehensive empirical basis for evaluating the effectiveness of moringa seed biocoagulants in reducing



a b

C

Fig. 2: Zeta potential test of Jagir river water treatment flocs using (a) maggot shell biocoagulant, (b) moringa seed bio-coagulant, and (c) alum coagulant

the stability of dissolved particles, as well as a reference for determining optimal performance in the treatment of Jagir River water.

Based on the results obtained in Fig. 2 point (b), the average zeta potential value was –7.7 mV, with a standard deviation of 51.32. The standard deviation value was much greater than the mean, indicating large fluctuations between repetitions. A negative zeta potential value indicates that the colloidal particles in the suspension still have a dominant negative surface charge. This indicates that the moringa seed biocoagulant works by reducing colloidal stability through a mechanism of partial charge neutralization and polymeric bridging, causing the colloidal particles to undergo destabilization and form flocs. However, the zeta potential value of –7.7 mV is in the low range because, in general, colloid stability is considered to decrease significantly within the range of ±30 mV (Fitri et al. 2019).

The moringa seed biocoagulant operates through a dual mechanism involving both charge neutralization and polymer bridging. The cationic proteins in moringa seeds contain amino (–NH_2) and carboxyl (–COOH) functional groups that interact with negatively charged colloids.

Partial neutralization of charges occurs as these functional groups form electrostatic attractions, while long protein chains act as natural polymers, bridging multiple particles together. This combination produces moderately compact flocs that are stable and settle efficiently even at lower dosages. The moderate zeta potential (–7.7 mV) supports controlled aggregation, preventing excessive repulsion while maintaining bridging capacity, which explains why moringa seed coagulant exhibits near-alum performance in turbidity and TSS removal despite being used at lower concentrations.

3.3.3. Characteristics of Floc Using Alum Coagulant

The zeta potential test was conducted to analyze colloid stability, where values close to the isoelectric point indicate a decrease in particle stability and a tendency for aggregation or floc formation. The results of this test provide a comprehensive empirical basis for evaluating the effectiveness of maggot shell biocoagulants in reducing the stability of dissolved particles, as well as a reference for determining optimal performance in the treatment of Jagir River water (Table 2).

Based on the zeta testing results in Fig. 2 point (c), the zeta potential test results of the alum coagulant in the treatment of Jagir River water were obtained. The average zeta potential value recorded was 0 mV, with a relatively small standard deviation of 2.54 mV. This value indicates that the colloidal system in the Jagir River water is at the isoelectric point, which is a state where the surface charge of the particles is completely neutralized by coagulant ions (Al^{3+} from alum) (Fitri et al. 2019). Under these conditions, the repulsive forces between colloidal particles disappear, facilitating the flocculation process and accelerating the sedimentation of suspended particles. The low standard deviation obtained indicates that the measurement results are quite consistent in each repetition, so the effectiveness of alum as a coagulant can be said to be stable in reducing the zeta potential to reach the optimum point. This shows that the alum dosage used in this test is truly at the optimum dosage, where the system conditions are most conducive to the formation of large flocs that can be easily separated through sedimentation or filtration processes.

In alum-based coagulation, aluminum sulfate ($Al_2(SO_4)_3$) dissociates to produce trivalent aluminum ions (Al^{3+}), which have a high positive charge density. These ions neutralize the negative surface charges of colloidal particles, reducing the zeta potential to near zero (0 mV). Once the charge is neutralized, aluminum hydroxide precipitates [$Al(OH)_3$] are formed, acting as sweep flocs that capture and settle suspended particles. This mechanism, known as charge neutralization and sweep flocculation, results in the formation of compact and dense flocs with high sedimentation rates.

Thus, the overall coagulation-flocculation mechanism shows that the closer the zeta potential is to zero and the higher the floc density, the higher the pollutant removal efficiency. The dual mechanism of Moringa seeds allows them to effectively mimic the performance of alum, while maggot shell coagulants provide an environmentally friendly alternative with optimization potential through chitin modification or mixing approaches.

3.4. Mechanism of Various Coagulation

3.4.1. Mechanism Using Moringa Seed Biocoagulant

Moringa seeds contain cationic proteins and active compounds (4-Alpha-4-Rhamnosyloxy-Benzyl-Isothiocyanate) that are positively charged and have a low molecular weight due to short polymer chains, enabling them to bind particles in water and reduce the repulsive forces between negatively charged colloidal particles. This process causes colloid destabilization and the formation of interconnected flocs. The small particle size of moringa seeds provides a larger surface area, thereby increasing the contact area and effectiveness of interaction between the active substances and colloidal particles (Nenohai et al. 2023). The efficiency of removing turbidity, TSS, and color parameters shown in Fig. 1 occurs because the positively charged cationic proteins in moringa seeds can electrostatically attract and neutralize negatively charged colloidal particles, such as those causing turbidity and TSS, which then form bound flocs. Additionally, these proteins also play a role in precipitating color-causing molecules in water, thereby improving the clarity and quality of the treated water.

3.4.2. Mechanism Using Maggot Shell Biocoagulant

Chitosan in maggot shells can be used in the coagulation-flocculation process because it is a cationic polyelectrolyte and a long-chain polymer with a large molecular weight, made reactive by the presence of amino (NH_2) and hydroxyl (OH) groups that act as electron donors to destabilize particles in water (Sirajudheen et al. 2021). The removal of turbidity and TSS using maggot shell biocoagulants occurs

Table 2: Summary of coagulant performance in Tofu wastewater treatment.

Coagulant Type	Zeta Potential [mV]	Floc Density	Relative Performance
Maggot Shell Biocoagulant	0 (isoelectric point)	Very dense	Highest
Moringa Seed Biocoagulant	–7.7	Moderately dense	Near alum
Alum Coagulant	8,8	Low	Moderate

because chitosan dissolved in an acidic solution activates positively charged groups to neutralize colloidal particles and causes the particles to form large, dense flocs (Ardianto & Amalia 2023). In addition, hydroxyl (OH) and amine (NH_2) groups in chitosan can be protonated under acidic conditions to become (NH_3^+) and (OH^-), thus becoming positively charged and capable of adsorbing or forming hydrogen bonds and complexes with dye molecules (Adilla Safitria & Rahmayanti 2020). This mechanism is also reinforced by chitosan's ability to destabilize particles through electrostatic interactions and hydrogen bond formation (Sirajudheen et al. 2021). The efficiency of turbidity, TSS, and color removal shown in Fig. 1 occurs due to the mechanism of colloid destabilization, floc formation through particle interactions neutralized by the positive charge of chitosan, and the presence of electrostatic interactions between chitosan and particles causing turbidity and color.

3.4.3. Mechanism Using Alum Coagulant

Alum coagulants work by destabilizing colloids through the formation of cationic species that neutralize the negative charge of particles, forming flocs, but excessive doses can cause charge reversal and particle restabilization (Malik 2018). This process is called charge neutralization, in which the positive charge of aluminum ions reduces the repulsive forces between particles, allowing them to come closer and form flocs (Husen et al. 2024). In the field of water treatment, the use of alum can remove suspended particles, organic matter, metals, and other contaminants from wastewater (Tahraoui et al. 2024). This is in accordance with the efficiency of turbidity, TSS, and color removal parameters shown in Fig. 1**.**

3.5. ANOVA One-Way Analysis

Three coagulants were used in this research, namely code 1 (maggot shell biocoagulant), code 2 (moringa seed biocoagulant), and code 3 (alum coagulant). The results of the one-way ANOVA test in Fig. 3 show an F value of 18.01 and a P-value of 0.000 (<0.05), indicating a significant difference among the coagulant types in terms of percentage removal. The Tukey pairwise comparison test shows that moringa seeds and alum are in group A, while maggot shells are in group B, indicating that the first two coagulants are more effective. Based on the mean results, each treatment had nine samples (N=9), with separation efficiencies of 75.31% for maggot shells, 90.59% for moringa seeds, and 92.35% for alum. The standard deviations were 7.32, 7.06, and 5.33, respectively, with 95% confidence intervals of 70.75–79.87%, 86.04–95.15%, and 87.79–96.91%.

Fig. 4 presents several residual plots used to validate the assumptions of the regression model in the % Removal analysis of the coagulation-flocculation process. The Normal Probability Plot indicates that most residuals align closely with the diagonal line, with minor deviations at the tails, suggesting near-normality. The Residuals versus Fitted Values plot shows that residuals are randomly dispersed around the zero line (dashed horizontal line) across the observed Fitted Value range (approximately 75 to 95). The histogram illustrates a residual distribution that is approximately normal, with the highest frequency near zero. Additionally, the Residuals versus Observation Order plot displays a random pattern, indicating no autocorrelation. Overall, the regression model satisfies the assumptions of normality, homoscedasticity, and residual independence, validating its suitability for analyzing the relationship between coagulant dose and removal efficiency.

4. CONCLUSIONS

Alum achieved the highest performance, removing 86.67% of turbidity, 98.66% of TSS, and 96.17% of color at an optimal dose of 250 mg.L⁻¹. Moringa seeds performed nearly

Factor Information

Factor	Levels	Values
Variation Coagulant	3	1; 2; 3

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Variation Coagulant	2	1581	790,65	18,01	0,000
Error	24	1054	43,91		
Total	26	2635			

Means

Variation Coagulant	N	Mean	StDev	95% CI
1	9	75,31	7,32	(70,75; 79,87)
2	9	90,59	7,06	(86,04; 95,15)
3	9	92,35	5,33	(87,79; 96,91)

Pooled StDev = 6,62615

Grouping Information Using the Tukey Method and 95% Confidence

Variation Coagulant	N	Mean	Grouping	
3	9	92,35	A	
2	9	90,59	A	
1	9	75,31		B

Means that do not share a letter are significantly different.

Fig. 3: ANOVA one-way analysis.

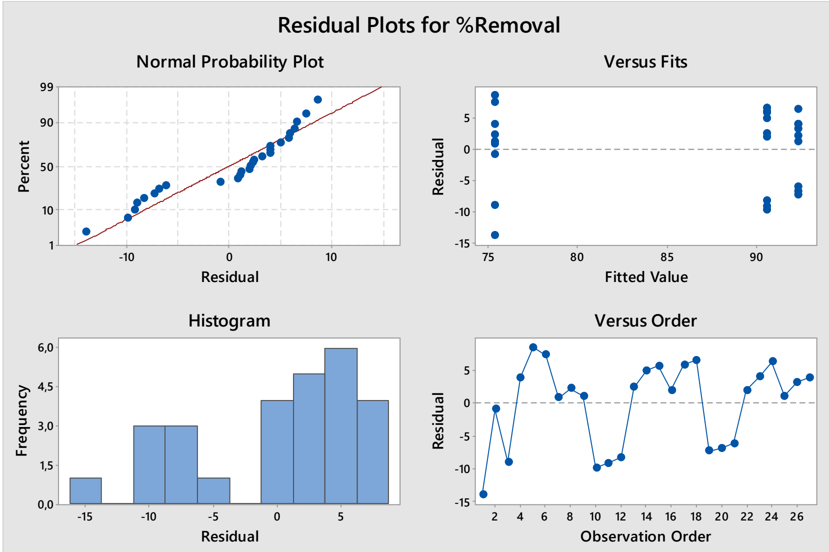


Fig. 4: Residual plots for %removal.

as well, with turbidity removal of 82.04%, TSS removal of 96.31%, and color removal of 97.27% at a dose of 150 mg.L^{-1}, indicating their potential as an environmentally friendly alternative to alum. Maggot shells showed moderate effectiveness, with turbidity removal of 74.96%, TSS removal of 83.89%, and color removal of 77.48% at 100 mg.L^{-1}, which could be improved further through process and dose optimization.

Sustainability of biocoagulant products is crucial for their long-term use without detrimental effects on the environment, economy, or society. In wastewater treatment, sustainability is evaluated from environmental, social, economic, and technical perspectives. Key challenges include process efficiency, raw material availability, and operational costs. Environmental impacts can be assessed using Life Cycle Assessment (LCA) according to ISO 14040 standards, evaluating the environmental footprint of producing moringa seed and maggot shell biocoagulants. Economically, costs are compared between bioflocculants and alum using an economic engineering approach to determine their efficiency and viability.

Currently, this research is limited to laboratory-scale experiments. Scaling up to industrial applications requires further development to evaluate performance and cost-effectiveness under more complex and varied operational conditions. The dosing intervals for moringa seed and maggot shell biocoagulants should also be expanded to more accurately determine optimal doses and removal efficiencies for each parameter. Additionally, a comprehensive LCA covering the entire process chain, from cradle to grave, is necessary to assess the overall environmental impact.

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