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Optimization of Alum Coagulant Dosage Using a Modified Jar Test Method for TDS and Turbidty Reduction in Shrimp Aquaculture Wastewater

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A R T I C L E I N F O

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A B S T R A C T

This study aims to optimize the dosage of alum coagulant ($Al_2(SO_4)_3$) to reduce Total Dissolved Solids (TDS) levels and improve the visual quality of shrimp aquaculture wastewater. The evaluation was conducted using a modified Jar Test with dosage variations of 0 g, 5 g, 10 g, and 15 g per 500 mL sample, applying a Completely Randomized Design (CRD). The ANOVA results indicated that the coagulant dosage had a highly significant effect ($p<0,05$) on reducing pH and TDS. The 15 g dosage was determined as the optimal point that triggers the sweep coagulation mechanism, proven to drastically reduce TDS from ~2000 mg/L to 1320 mg/L and improve water clarity. Conversely, the application of sub-optimal dosages actually increased TDS due to the accumulation of free ions. This approach is effective for controlling the pollution load of aquaculture effluents.

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INTRODUCTION

The aquaculture industry, particularly intensive shrimp farming, has expanded rapidly and contributed significantly to meeting global protein demands and driving economic growth. However, this intensification of cultivation is directly proportional to an increase in environmental pollution loads due to the high volume of wastewater generated (Goto et al., 2023). Effluent from shrimp ponds is generally dominated by undigested feed residues, feces, and both dissolved and suspended organic matter. The primary characteristics of this wastewater are high Total Dissolved Solids (TDS) and turbidity. Direct discharge of effluents into receiving water bodies without adequate treatment can trigger environmental degradation, such as eutrophication, depletion of dissolved oxygen levels, and imbalances in coastal ecosystems. Therefore, the implementation of efficient and applicable wastewater treatment technologies has become an urgent necessity.

Physicochemical treatment via coagulation and flocculation is recognized as one of the most effective conventional approaches for removing suspended solids and colloidal matter from wastewater. This mechanism works by destabilizing the negative charges on colloidal particles through the addition of chemicals (coagulants), followed by slow mixing to induce particle agglomeration into large flocs that easily settle by gravity. Aluminum sulfate, or alum ($Al_2(SO_4)_3$), is the most commonly used inorganic coagulant due to its abundant availability (Nurjanah et al., 2026), economical operational costs, and high effectiveness in adsorbing pollutants.

Although alum exhibits good binding performance, the efficiency of the coagulation-flocculation process is highly sensitive to the applied coagulant dosage (Tahraoui et al., 2024). Applying a dosage below the required threshold (underdosing) will fail to bridge colloidal particles to form flocs completely, leaving turbidity high. Conversely, excessive dosing (overdosing) not only leads to economic inefficiency but also risks causing colloid restabilization and an increase in residual solids. More crucially, the hydrolysis of alum in water releases acidic hydrogen ions, meaning an excessive dose will trigger an extreme drop in pH. This fluctuating condition underscores the need for precise dosage optimization before application in field-scale treatment plants.

The Jar Test approach is a representative operational standard for simulating the coagulation-flocculation process and determining the optimal coagulant dosage at a laboratory scale (Karunarathna et al., 2025). Therefore, this study aims to optimize the alum coagulant dosage to minimize TDS values and turbidity in shrimp aquaculture wastewater using a modified Jar Test method. Performance evaluation focuses on the analysis of quantitative parameters (TDS reduction efficiency and final pH dynamics) as well as qualitative visual parameters (floc formation and settling time). This study is expected to provide a comprehensive technical foundation for aquaculture practitioners in designing waste treatment systems that are accurately dosed, effective, and compliant with environmental quality standards.

THEORETICAL REVIEW

Coagulation and Flocculation Theory

The coagulation and flocculation theory explains the separation mechanisms of colloidal particles and suspended solids in water (Farasat et al., 2017). Shrimp aquaculture wastewater contains colloidal particles that are generally negatively charged, generating repulsive forces between particles that prevent them from settling naturally. Coagulation is the process of destabilizing these negative charges through the addition of positively charged chemicals (coagulants) such as alum ($Al_2(SO_4)_3$), followed by rapid mixing. Once the charges are neutralized, the flocculation process occurs via slow mixing, where small particles collide and agglomerate to form larger and heavier masses (flocs), allowing them to settle by gravitational force (sedimentation).In the context of wastewater treatment, various prior quantitative studies consistently concur with the theory that adding inorganic coagulant dosages significantly increases turbidity and Total Dissolved Solids (TDS) removal efficiency. Studies by Nurjanah et al. (2026) and Malik et al. (2017) demonstrated that adding alum up to the optimal point can bind organic matter and dissolved solids in aquaculture wastewater. However, other studies [Insert Researcher's Name, Year] reject the infinite linear hypothesis, finding that coagulant addition exceeding the saturation point (overdosing) will actually increase TDS values again due to the accumulation of unbound sulfate ions from the alum itself. Based on this theoretical foundation and the debates in prior studies, the first hypothesis is proposed:
H1: There is a significant effect of varying alum coagulant dosages on the reduction rate of Total Dissolved Solids (TDS) and turbidity in shrimp aquaculture wastewater.

Theory of Aluminum Salt Hydrolysis and pH Dynamics

This theory explains the chemical properties of aluminum-based coagulants when dissolved in an aqueous medium. When aluminum sulfate (alum) is added to wastewater, the compound undergoes a hydrolysis reaction (Lala et al., 2025). Alum reacts with the natural alkalinity of the water (such as bicarbonate ions) to form aluminum hydroxide precipitates ($Al_2(OH_3)$) that function to entrap impurities through sweep flocculation. However, as a byproduct of this hydrolysis reaction, free hydrogen ions (H^+) are released into the water body. This release of H^+ ions directly consumes the buffer capacity of the wastewater.

Previous quantitative studies conducted by Wahyudin (2022) and Lala et al. (2025) fully concur with this theory, finding a very strong negative correlation between the added concentration of aluminum sulfate coagulant and the final pH value of the treated water. The results from various literatures indicate that the higher the applied alum dosage, the more the pH value will drop exponentially toward strongly acidic conditions, particularly if the raw water has low alkalinity. Based on this chemical phenomenon, the second hypothesis is proposed:

H2: An increase in alum coagulant dosage concentration has a significant effect on the reduction of the final pH value of treated shrimp aquaculture wastewater.

Conceptual Framework

This study is a quantitative experimental research that examines the cause-and-effect relationship between independent and dependent variables. The conceptual framework is constructed based on a modified Jar Test method. The independent variable in this study is the alum coagulant dosage concentration, which consists of four treatment levels (0 g, 5 g, 10 g, and 15 g). These dosages are applied to shrimp aquaculture wastewater samples through rapid mixing (coagulation) and slow mixing (flocculation) processes. The outputs of these processes are measured through dependent variables, which include the physical and chemical quality of the treated water. The statistically tested quantitative parameters comprise TDS removal efficiency and the final pH value, while the supporting parameters (visual evaluation) encompass observations of floc size formation, estimation of settling time, and the turbidity level of the supernatant water. The relationship between these variables aims to identify the optimal dosage point.

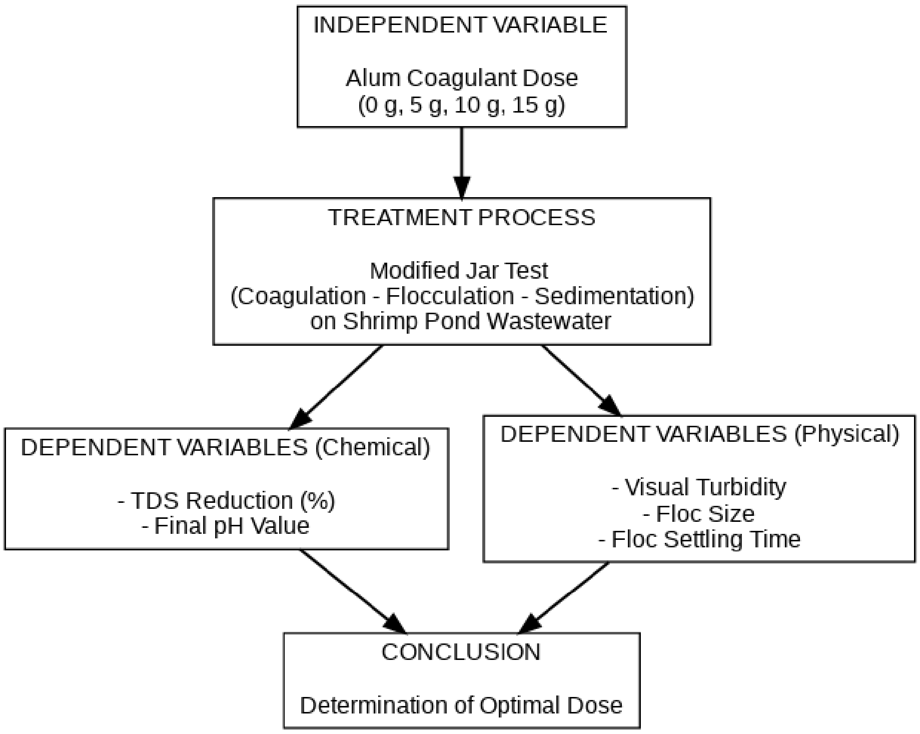

Figure 1. Conceptual Framework

METHODOLOGY

Research Design

This study employs a quantitative experimental approach utilizing a non-factorial Completely Randomized Design (CRD). The independent variable in this research is the variation in alum (aluminum sulfate) coagulant dosages, consisting of four treatment levels: 0 g (control), 5 g, 10 g, and 15 g. Each treatment is repeated three times (replications), resulting in a total of 4x3=12 experimental units.

Apparatus and Materials

The primary equipment used in this study includes 1000 mL capacity glass beakers as reactors, a set of mechanical stirring apparatuses (mixers) as a modified Jar Test setup with adjustable rotational speeds for rapid and slow mixing, a stopwatch for time control, and water quality measurement instruments consisting of a digital pH meter and a digital TDS meter. The primary materials used are brackish wastewater samples collected from shrimp pond effluents and commercial alum coagulant powder.

Experimental Procedure (Modified Jar Test)

The coagulation-flocculation process is performed using a modified Jar Test method with the following operational stages:

1. Preparation Stage: The wastewater sample is initially homogenized, followed by the measurement of its initial parameters (pH, TDS, and visual turbidity). A volume of 500 mL of the wastewater sample is then poured into each of the four glass beakers.
2. Coagulation Stage (Rapid Mixing): Alum coagulant is added to each reactor at the predetermined dosages (0 g, 5 g, 10 g, and 15 g). The rapid mixing process is immediately executed at a rotational speed of 100 rpm for 15 minutes. This stage aims to ensure the coagulant is evenly dispersed and destabilizes the charges of the colloidal particles within the waste.
3. Flocculation Stage (Slow Mixing): Upon completion of the coagulation phase, the mixing intensity is drastically reduced to 30 rpm and stirred for 60 minutes (slow mixing). This slow mixing facilitates the probability of interparticle collisions (agglomeration), allowing micro-flocs to combine and form larger, heavier macro-flocs.
4. Sedimentation Stage: The stirring process is completely halted. The samples in the beakers are left undisturbed for 60 minutes to provide retention time for the formed flocs to settle to the bottom of the reactor by gravity. The treated liquid effluent and residual sludge are subsequently discharged into a dedicated waste containment tank.

Evaluation Parameters and Optimization Criteria

A comprehensive performance evaluation of the coagulant is conducted on the supernatant water after the sedimentation phase using two approaches:

a. Visual and Physical Evaluation: This includes observations of floc size and compactness, estimation of settling velocity/time, as well as color degradation and turbidity of the treated water. Visual observation of rapid floc formation and ease of settling serves as the primary empirical indicator in determining process effectiveness.

b. Quantitative Water Quality Evaluation: Instrumental measurements are performed to determine the final TDS and pH values.

The determination of the most optimal coagulant dosage is based on the accumulation of the following criteria:

- Floc morphology that is large, dense, heavy, and resistant to breakage.
- A short precipitation/settling time.
- The treated water (supernatant) exhibits the highest visual clarity and meets the criteria for chemical parameter reduction (TDS).

Data Analysis

The success rate of the coagulation-flocculation process in treating brackish shrimp pond wastewater is quantified through the percentage reduction (removal efficiency) of the Total Dissolved Solids (TDS) parameter. This efficiency calculation is computed using the following mathematical equation (Reynolds & Richards, 1996):

$$Efisiensi\ (\%) = \frac{C_0 - C_t}{C_0} \times 100\% \quad \text{...} \quad (1)$$

Where:

- C_0 = Initial concentration of the TDS parameter before treatment (mg/L)
- C_t = Final concentration of the TDS parameter after the sedimentation process (mg/L)

The obtained quantitative data are validated using a non-factorial Completely Randomized Design (CRD) with the following mathematical linear model (Gaspersz, 1991):

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad \text{...} \quad (2)$$

Where:

- Yij = Observed value at the i-th alum dosage treatment and j-th replication
- μ = Grand mean
- Ti = Effect of the i-th alum coagulant dosage treatment
- €ij = Experimental error effect at the i-th treatment and j-th replication

The TDS reduction efficiency and pH fluctuation data are subsequently analyzed using the parametric statistical method, One-Way Analysis of Variance (ANOVA). Prior to executing the ANOVA, the data are assumed to have met the classical prerequisite tests, namely the normality test (Shapiro-Wilk) and the homogeneity of variance test (Levene's Test). If the ANOVA results indicate a significant effect (p-value < 0,05), the analysis is proceeded with the Tukey Honestly Significant Difference (HSD) Post-Hoc test.

All computational stages and statistical data processing in this study are processed using the Python programming language via the Google Colab cloud-computing platform. The primary libraries involved include pandas for database structuring, scipy.stats and statsmodels for the calculation of ANOVA algorithms and post-hoc tests, as well as matplotlib and seaborn for data visualization into scientific graphs.

RESULTS

Effect of Coagulant Dosage Variations on Visual Quality and TDS Values

The wastewater treatment process in this study was conducted using the coagulation-flocculation method via a modified Jar Test simulation. The initial post-treatment evaluation focused on visual observations of water quality and measurements of TDS concentrations. This first-stage measurement is crucial to identify which dosage begins to exhibit visible floc formation and a reduction in turbidity, as well as to observe the initial fluctuations of dissolved solids prior to statistical analysis. The comprehensive measurement results of physical and visual parameters post-sedimentation are presented in Table 1.

Table 1. Measurement of TDS Values and Visual Water Quality After Treatment

Alum Dose (g)	Replication	TDS (ppm)	Average (ppm)	Water Quality
0 (Control)	1	1308	1312	Turbid
	2	1308		
	3	1320		
5	1	1380	1372	Turbid
	2	1360		
	3	1377		
10	1	1420	1421	Turbid
	2	1420		
	3	1422		
15	1	1320	1320	Moderate
	2	1320		
	3	1321		

Based on Table 1, the addition of alum coagulant provided highly interesting dynamics regarding the average TDS values and the visual quality of the supernatant. In the control treatment (0 g) without coagulant addition, the wastewater had an average TDS value of 1312 ppm with a highly turbid physical appearance. Interestingly, when alum dosages were increased to 5 g and 10 g, sequential increases in TDS values were observed, reaching 1372 ppm and 1421 ppm, respectively, while the visual quality of the water showed no improvement (remaining turbid).

Significant improvement in wastewater quality was only observed at the 15 g dosage treatment. At this highest dose, the visual water quality improved to the moderate category. In line with this increasingly clear visual improvement, the average accumulation of TDS at the 15 g dosage also experienced a sharp decline to 1320 ppm when compared to its peak increase at the 10 g dosage (1421 ppm).

Comparison of Initial and Final Post-Treatment TDS Concentrations

To determine the effectiveness of the alum coagulant in reducing the pollution load of dissolved solids, a comparison was made between the initial TDS values before treatment and the final TDS values post-sedimentation. A side-by-side comparison of the absolute values of both conditions across various dosage variations is visualized in Figure 2.

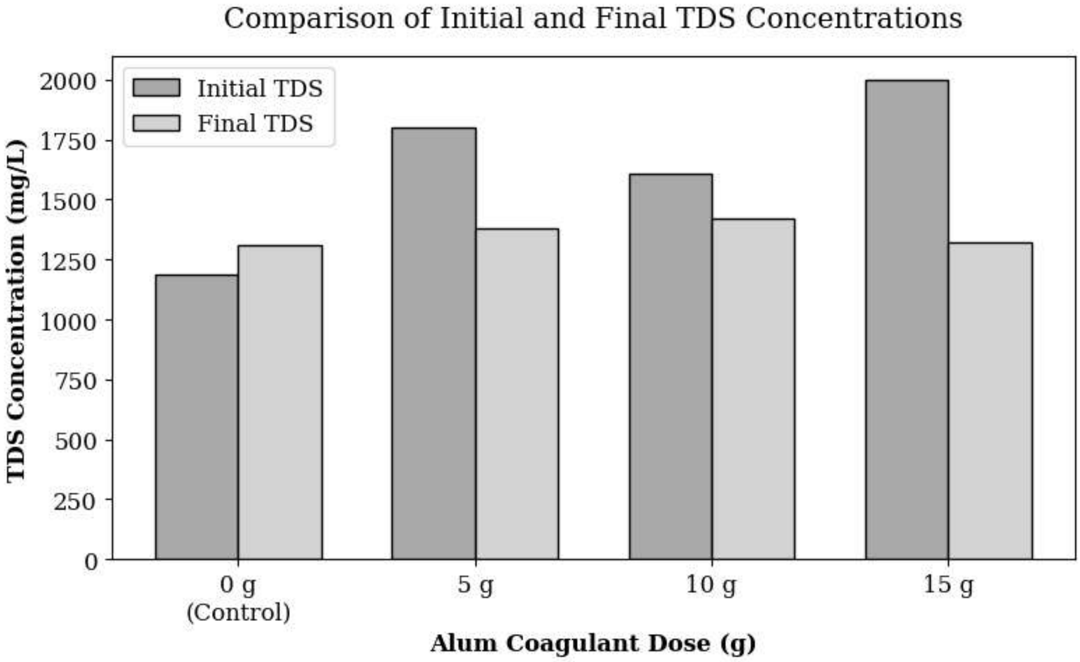

Figure 2. Comparison of Initial and Final TDS Concentrations at Various Coagulant Doses

Based on the graph in Figure 2, it can be observed that the wastewater samples used in each test group exhibited relatively high fluctuations in initial TDS values, ranging from approximately 1180 mg/L to as high as 2000 mg/L. This variance in baseline values is common in real wastewater samples due to their highly dynamic characteristics. The observations revealed a contrasting trend between the control group and the treatment groups. In the control group (0 g) that received no coagulant, the natural sedimentation process during the observation period actually resulted in an increase in the final TDS concentration, rising from an initial value of around 1180 mg/L to the range of 1300 mg/L.

Conversely, the addition of alum coagulant at doses of 5 g, 10 g, and 15 g consistently suppressed the final TDS values, keeping them lower than their initial baselines. The most moderate concentration reduction (difference) occurred in the 10 g dosage treatment, where the initial TDS of around 1600 mg/L dropped to approximately 1420 mg/L. Better performance was observed in the 5 g dosage treatment, which successfully reduced the TDS from around 1800 mg/L to 1380 mg/L. The sharpest and most massive peak reduction in absolute concentration was observed in the 15 g alum dosage treatment. In this test group, even though the wastewater recorded the most extreme initial TDS load (reaching 2000 mg/L), the coagulant drastically reduced this figure to a final level of approximately 1320 mg/L.

Statistical Analysis of Coagulant Dosage Significance

To validate the significance of the effect of alum dosage variations on changes in water quality parameters, a One-Way Analysis of Variance (ANOVA) statistical test was performed. This analysis utilized a 95% confidence level (α= 0.05), where a probability value (p) < 0.05 indicates a significant effect of the applied treatment. A summary of the ANOVA statistical test results and post-hoc tests regarding the effect of coagulant dosage on pH and TDS parameters is presented in Table 2.

Table 2. Post-Hoc and ANOVA Test Results for pH and TDS Parameters.

Parameter	Alum Dose (g)	Replicate 1	Replicate 2	Replicate 3	Mean ± SD	F-Value	p-value
pH (Δ)	0	0.00	0.00	0.03	0.01 ± 0.02^{a}	7.81	0.009
	5	-4.50	-4.40	0.58	-2.77 ± 2.91^{ab}		
	10	-4.54	-4.77	-4.59	-4.63 ± 0.12^{b}		
	15	-4.61	-7.27	-5.93	-5.94 ± 1.33^{b}		
TDS (ppm)	0	118.00	118.00	130.00	122.00 ± 6.93^{c}	184.49	< 0.001
	5	190.00	170.00	187.00	182.33 ± 10.79[illegible]		
	10	230.00	230.00	232.00	230.67 ± 1.15^{d}		
	15	130.00	130.00	131.00	130.33 ± 0.58^{c}		

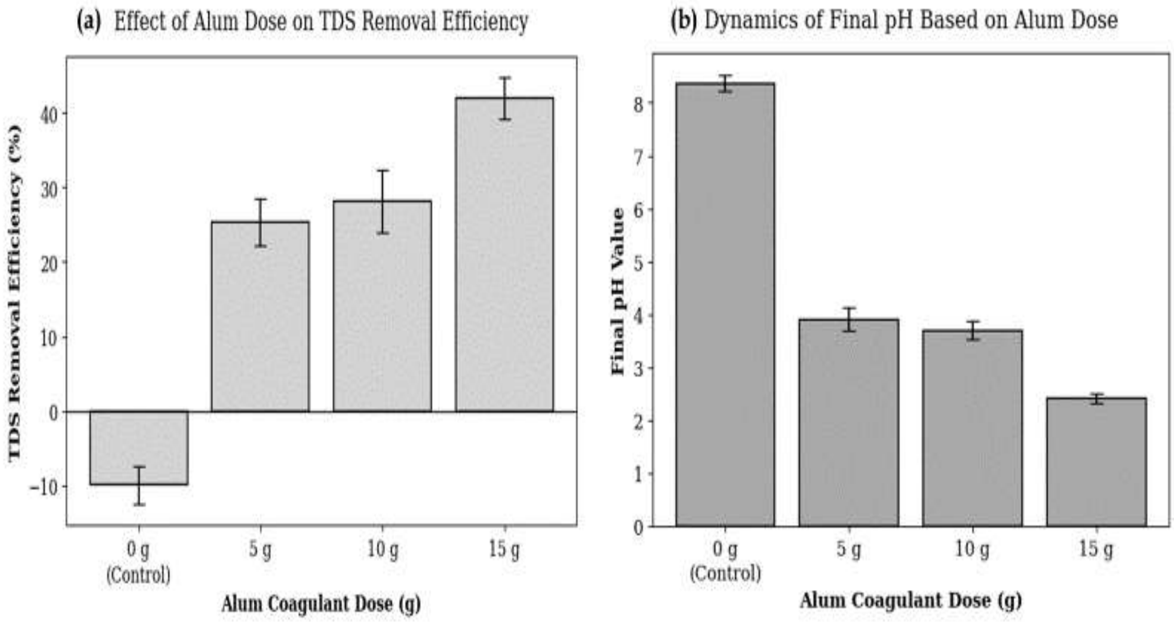

Figure 3. (a) TDS Removal Efficiency and (b) Dynamics of Final pH Value Based on Coagulant Dose

Based on the ANOVA results for the pH parameter in Table 2, an F-value of 7.81 was obtained with $p = 0.009$. Since the $p < 0.05$, it can be concluded that the addition of alum coagulant dosages had a highly significant effect on reducing wastewater pH. Post-hoc test results using letter notations showed that the control group (0 g dose) had the highest average pH change (0.01 ± 0.02^a). The decrease in pH began to show a significant difference at the 10 g and 15 g dosages; because both shared the letter notation 'b', this indicates that statistically, increasing the dosage from 10 g to 15 g did not produce a significant difference in pH reduction.Meanwhile, for the TDS parameter, the ANOVA analysis demonstrated a highly significant effect with an F-value reaching 184.49 and a $p < 0.001$. This probability value, which is far smaller than 0.05, confirms that variations in alum coagulant dosages exert a highly significant (strongest) influence on TDS value fluctuations in the sample water. Based on the post-hoc test for the TDS parameter, significant differences were clearly observed among several dosage levels. The TDS value experienced the highest increase in the 10 g dosage treatment with an average of 230.67 ± 1.15^a ppm. Interestingly, when the dosage was increased to 15 g, the TDS value dropped drastically to 130.33 ± 0.58^c ppm. Statistically, the value at the 15 g dose shares a similarity with the control group (0 g dose), meaning that the efficiency of suppression or stabilization of the TDS value at the 15 g dose statistically resembles the control condition, but with a more measurable stability.

DISCUSSION

Based on the observations from Table 1 and Figure 2, the natural sedimentation process in the control treatment (0 g) failed to improve visual water quality (remaining turbid) and instead exhibited a tendency toward increasing TDS values, rising from an initial value of 1180 mg/L to 1312 mg/L. This increase is presumed to result from the ongoing decomposition of suspended organic matter during the retention period, which generates additional dissolved compounds without any removal mechanism. This finding indicates that gravity settling alone is insufficient to control the TDS load, thereby supporting the necessity of coagulant intervention to halt the rate of TDS increase through the removal of colloids and suspended solids that serve as precursors to dissolved compounds.

However, the addition of coagulant at low-to-medium doses (5 g and 10 g) conversely demonstrated a post-treatment upward trend in TDS to 1372 ppm and peaking at 1421 ppm, which was also accompanied by a persistently turbid visual quality. This phenomenon of increasing TDS at low-to-medium dosages can be explained chemically. The added alum ($Al_2(SO_4)_3$) is a highly soluble inorganic salt (El-Bacha et al., 2024). When the applied dosage has not yet reached the optimal point to fully destabilize the colloidal particles in the wastewater, the alum dissociates and instead contributes free aluminum (Al3+) and sulfate (SO42-) ions into the water body (Mortadi et al., 2022). Consequently, instead of forming settling precipitates, the presence of these free ions automatically boosts water conductivity, thereby increasing the total dissolved solids (TDS) value.

Significant improvement in wastewater quality was only observed at the 15 g dosage treatment. At this point, a breakthrough in visual quality occurred, shifting from turbid to moderate, followed by a sharp decline in average TDS accumulation to 1320 ppm (Table 1). This fact is further reinforced by the comparative data in Figure 2, where the 15 g treatment successfully reduced a highly extreme initial TDS load (reaching 2000 mg/L) drastically down to a final level of 1320 mg/L. This indicates that the 15 g dose marks the onset of an effective sweep coagulation mechanism. At this concentration, the added alum exceeds its solubility limit (Mortadi et al., 2022), allowing aluminum ions to react with the water's alkalinity to form amorphous aluminum hydroxide precipitates ($Al(OH)_3$). This precipitate functions like a "net" that sweeps and maximally entraps suspended particles, colloids, and a portion of dissolved minerals to form macro-flocs (Lin et al., 2008). The formed macro-flocs possess a heavier specific gravity, enabling them to settle effectively via gravity. Consequently, the water becomes visibly clearer, and the initially high TDS pollution load is drastically suppressed.

The success of this coagulation mechanism is also confirmed by the post-treatment pH dynamics. The ANOVA results (Table 2) indicate that the variation in coagulant dosage exerts a highly significant effect on pH reduction ($p = 0.009$). The hydrolysis of alum coagulant in water is an endotermic reaction that releases hydrogen ions (H^+), which naturally consumes the alkalinity of the wastewater and lowers the system's pH. The post-hoc test showed that the pH decrease at the 10 g and 15 g dosages shared similarities, implying that at the 10 g dose, the buffer capacity (alkalinity) of the wastewater had already begun to deplete due to the hydrolysis reaction. When the dosage was increased to 15 g, the pH did not undergo further extreme drops; instead, the available chemical energy was optimally redirected toward the precipitation phase of sweep coagulation, ultimately yielding TDS reduction and visual clarification.

The ANOVA analysis for the TDS parameter confirms a powerful effect ($F = 184.49$, $p < 0.001$). Although the final statistical TDS value at the 15 g dose resembles the control condition numerically, its ecological significance and technical performance are vastly different. The control group generated a TDS of 1312 ppm from a low initial value (~1180 mg/L) with highly turbid water conditions. Conversely, the 15 g dose yielded a final TDS of 1320 ppm from a severe initial waste load (~2000 mg/L) with a much clearer visual appearance. This proves that the suppression efficiency and stability of the TDS value at the 15 g dose deliver far superior technical performance, capable of handling shock loading pollution parameters, and facilitating solid-liquid phase separation that natural sedimentation (control) cannot achieve.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research results, it can be concluded that variations in alum coagulant dosages exert a highly significant effect on the fluctuations of TDS values and pH reduction in shrimp aquaculture wastewater. The 15 g dosage is proven to be the most optimal coagulation point as it effectively triggers the sweep coagulation mechanism. This mechanism is capable of drastically reducing the TDS load from ~2000 mg/L to 1320 mg/L while simultaneously improving visual water clarity. Conversely, the use of sub-optimal dosages (5 g and 10 g) is not recommended because they fail to form stable flocs and instead elevate TDS values due to the accumulation of free aluminum and sulfate ions in the water.

As a recommendation, this equivalent 15 g dosage can be utilized as a baseline reference for shrimp aquaculture practitioners in designing field-scale physicochemical Wastewater Treatment Plants (IPAL in Indonesia). Furthermore, given that the alum hydrolysis reaction consistently consumes alkalinity and lowers the pH, it is highly recommended to integrate a subsequent neutralization stage (such as lime addition) into the final effluent. This aims to ensure that the discharged wastewater into the receiving water bodies fully complies with environmental quality standards.

FURTHER STUDY

For future development, subsequent studies are suggested to escalate testing from a laboratory scale (Jar Test) to a field pilot scale to evaluate coagulation performance under actual and dynamic wastewater flow conditions. Additionally, further research needs to explore the combination of alum with polymer flocculants to optimize floc size while enhancing dosage efficiency. Expanding the test parameters to include Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), and Total Ammonia Nitrogen (TAN) is also highly recommended, integrated with a cost-benefit analysis to ensure operational cost-efficiency for mass implementation in the aquaculture industry.

Future research is recommended to evaluate the effectiveness of the modified jar test method under different wastewater characteristics, shrimp farming scales, and environmental conditions to enhance the generalizability of the findings. Further studies may also investigate the performance of alternative coagulants, including natural and environmentally friendly materials, and compare their efficiency with alum in reducing Total Dissolved Solids (TDS) and turbidity. In addition, integrating coagulation processes with other treatment technologies, such as filtration, adsorption, membrane systems, or biological treatments, could be explored to achieve higher wastewater treatment efficiency. Economic feasibility, sludge management, and the long-term environmental impacts of coagulant application should also be examined to support the development of sustainable wastewater management practices in shrimp aquaculture.

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