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Eco-friendly flocculation of tapioca wastewater: Efficiency evaluation of *Alcaligenes latus* bioflocculant in combination with alum

Achyani Achyani [1*], Agus Sutanto [2], Handoko Santoso [2]

[1] Department of Science Education, Muhammadiyah Metro University, Lampung, INDONESIA
[2] Department of Biology Education, Muhammadiyah Metro University, Lampung, INDONESIA
***Corresponding Author:** acysbd@gmail.com

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ABSTRACT

Tapioca industrial wastewater contains high concentrations of organic matter, suspended solids, and toxic compounds, necessitating the need for effective and sustainable treatment prior to discharge. This study evaluated the performance of bioflocculants produced by *Alcaligenes latus* in treating tapioca processing effluent, applied both independently and in combination with the chemical coagulant alum. Experiments were conducted at the bioindustry laboratory, faculty of agricultural technology, Bogor Agricultural University, using wastewater from *PT Inti Sumber Agung Lancar*, East Lampung. Bioflocculants were produced through fermentation and tested using the jar test method. Key parameters analyzed included total suspended solids (TSS), biological oxygen demand over 5 days (BOD_5), chemical oxygen demand (COD), color, cyanide content, and pH. The optimal combination of 2 mL bioflocculant and 6 mg alum achieved the highest removal efficiencies for COD (83.80%), TSS (70.15%), and BOD_5 (67.38%), with notable reductions in cyanide (31.29%) and color (15.98%), while maintaining neutral pH (6.85-6.94). The results demonstrate a synergistic effect between biological and inorganic coagulants, highlighting their potential as an eco-friendly alternative to synthetic agents. This approach contributes to achieving the goals of SDG 6, SDG 9, SDG 12, and SDG 14 by promoting cleaner industrial processes. Moreover, the study's outcomes provide enrichment material for environmental biology education, fostering awareness of biotechnological innovations that support sustainable development.

Keywords: *Alcaligenes latus*, bioflocculant, environmentally sustainable treatment, flocculation efficiency, tapioca industrial wastewater

INTRODUCTION

The tapioca industry is one of the agro-industrial sectors experiencing rapid development in developing countries such as Indonesia. The industry has significant economic value in developing countries, with its applications in the food, textile, pharmaceutical, and other sectors (Li et al., 2020). Tapioca starch derived from cassava has significant economic value, with processed starch being 2.7 times higher than the market price of the original starch (Adewale et al., 2022). Its starch and flour are used in various sectors, including textiles, pharmaceuticals, paper, and adhesives (Awoyale et al., 2017; Chisenga et al., 2019). In addition, cassava products can be flexibly modified according to the needs of specific industries (Adewale et al., 2022). However, tapioca produces large amounts of liquid waste that can pollute the environment if not handled properly.

Liquid waste from tapioca factories contains high concentrations of organic matter and suspended matter, as well as nutrients, which can cause serious environmental problems if discharged directly into the aquatic environment without proper treatment (Adnan et al., 2020; Costa et al., 2022). Organic matter refers to degradable carbon-based compounds, whereas suspended matter consists of fine solid particles that do not dissolve in water (Lau et al., 2021; Safar et al., 2022). The discharge of such waste poses significant environmental risks, including dissolved oxygen depletion, foul odors, and harm to aquatic organisms (Zainuddin et al., 2021). Furthermore, tapioca liquid waste generally exhibits high levels of organic matter, with biological oxygen demand (BOD) and chemical oxygen demand (COD) values that exceed regulatory standards (Costa et al., 2022; Supriyadi et al., 2021). Therefore, effective and environmentally sustainable treatment methods are essential to mitigate the adverse impacts of tapioca liquid waste on aquatic ecosystems.

Untreated tapioca wastewater poses significant environmental and public health challenges that directly undermine several of the sustainable development goals (SDGs). It particularly affects SDG 6 (ensure availability and sustainable management of water and sanitation for all) and SDG 14 (conserve and sustainably use the oceans, seas, and marine resources) because improper waste management leads to water quality deterioration and ecosystem damage (Al-Hazmi et al., 2023; Obaideen at al., 2022). Addressing these issues through sustainable wastewater treatment can reduce pollutant loads and promote safer industrial practices, contributing to sustainable development (Obaideen et al., 2022). Such actions also contribute to SDG 12 (ensure sustainable consumption and production patterns) and SDG 3 (ensure healthy lives and promote well-being for all), highlighting the broader role of environmentally friendly technologies in achieving global sustainability targets (Saravanan et al., 2021).

Various wastewater treatment methods have been employed to address these challenges, including physical, chemical, and biological processes. Among them, biological treatment methods are favored due to their relatively low operational costs and high efficiency in degrading organic pollutants, although they typically require longer retention times (Singh et al., 2024). For example, Clostridium species have successfully treated tapioca wastewater through anaerobic digestion, demonstrating considerable pollutant removal (Luo et al., 2018). Additionally, Wang et al. (2017) demonstrated the effectiveness of acid hydrolysis in decomposing complex organic compounds, facilitating subsequent biological or chemical treatment. Other approaches, such as fermentation-based optimization, have also shown promise in enhancing the degradation of tapioca waste (Shanmugam et al., 2018). Despite these advances, treatment methods that are rapid, cost-effective, and scalable remain limited.

One promising alternative for wastewater treatment is the coagulation-flocculation process. This process is a critical technique in water and wastewater treatment that consists of two main stages: coagulation, which involves the neutralization of particle charges to destabilize colloidal particles, and flocculation, which facilitates the aggregation of these destabilized particles into larger, removable flocs (Zaki et al., 2023). The coagulation-flocculation process is widely recognized for its effectiveness in reducing total suspended solids (TSS), BOD, COD, and color in various industrial effluents (Zaki et al., 2023). The efficiency of this process is influenced by several factors, including coagulant dosage, solution pH, mixing intensity, and flocculation time (Sheng et al., 2023; Zaki et al., 2023). Although it is an efficient and relatively simple method, the use of synthetic polymers or metal salts as coagulants can introduce secondary environmental and health concerns. Thus, developing safer and more environmentally friendly alternatives remains an important focus in wastewater treatment research.

Synthetic coagulants such as polyacrylamide, polyethylene oxide, and poly aluminum chloride are widely used in industrial applications due to their convenience and rapid action (Zaman et al., 2020). However, these substances pose considerable environmental hazards, as they are often non-biodegradable, potentially carcinogenic, and persistent in aquatic environments (Badawi et al., 2023; Lapointe & Barbeau, 2017). The long-term accumulation of such compounds threatens ecological integrity and complicates downstream water treatment processes. Consequently, there is a growing demand for sustainable flocculants that are both efficient and environmentally benign.

In response to these environmental concerns, natural and bio-based flocculants have emerged as promising alternatives to synthetic coagulants. Natural flocculants, particularly those derived from plant-based polysaccharides or microbial metabolites, are gaining attention due to their biodegradability, non-toxicity, and comparable performance to conventional agents (Arulraj et al., 2022; Diver et al., 2023; Gautam & Saini, 2020). These bio-based materials have demonstrated efficacy in treating effluents from diverse industries, including food processing, metal plating, and textile dyeing (Arulraj et al., 2022). Among microbial sources, bioflocculants produced by *Alcaligenes latus* (*A. latus*) have received particular attention for their high flocculating activity and environmental safety (Rebah et al., 2018; Sumarno et al., 2022). These bioflocculants bind with colloidal particles through charge neutralization and bridging mechanisms, resulting in effective aggregation and sedimentation.

While previous findings highlight the potential of bioflocculants, there remains a need to position their application within the broader sustainability framework. Implementing biodegradable and low-toxicity treatment agents can accelerate progress toward the SDGs by lowering industrial pollution loads, reducing hazardous chemical use, and promoting circular economy practices through the valorization of agro-industrial residues (Cuadrado-Osorio et al., 2022; Padhye et al., 2022). However, studies exploring the synergistic application of *A. latus* flocculants with conventional inorganic coagulants–such as aluminum sulfate (commonly known as alum)–remain limited, particularly in the treatment of tapioca wastewater. Exploring the combined use of bioflocculants and alum may enhance treatment efficiency while reducing dependence on synthetic compounds. According to Mnif and Rebah (2023), integrating microbial bioflocculants with aluminum-based coagulants–such as aluminum sulfate, commonly known as alum–can improve particle removal efficiency, optimize coagulant dosage, and minimize associated environmental risks. Furthermore, such an approach could improve process scalability and affordability, making it more feasible for large-scale industrial implementation.

Building upon this rationale, the present study investigates the flocculation performance of bioflocculants derived from *A. latus*, applied independently and in combination with alum. The aim is to develop a treatment strategy that is not only technically effective but also aligned with the SDGs on water quality, reduced chemical pollution, and sustainable industrial practices (Das et al., 2021; Garcia et al., 2024; Kurniawan et al., 2020). Key performance indicators include reductions in TSS, biological oxygen demand over 5 days (BOD_5), COD, color, cyanide content, and pH variation. By demonstrating the effectiveness of microbial bioflocculants in tandem with conventional coagulants, this research seeks to contribute to the advancement of sustainable and environmentally responsible wastewater management technologies.

This study aims to evaluate the flocculation performance of bioflocculants derived from *A. latus*, applied independently or in combination with alum, in the treatment of tapioca industrial wastewater. Key performance indicators include reductions in TSS, BOD_5, COD, color, cyanide content, and changes in pH. By demonstrating the effectiveness of microbial bioflocculants in tandem with conventional coagulants, this research seeks to contribute to the advancement of sustainable and environmentally responsible wastewater management technologies.

Characteristics of Tapioca Plant Liquid Waste

Liquid waste from tapioca processing typically originates from key production stages, including washing, grating, starch separation, and sedimentation. This wastewater is characterized by elevated concentrations of suspended solids, organic matter, and harmful pollutants such as BOD, COD, and cyanide (Costa et al., 2022; Kadwe et al., 2019; Thepubon et al., 2020). For example, BOD_5 levels in tapioca wastewater can exceed 3,000 mg/L, surpassing permissible discharge thresholds established by environmental regulations (Costa et al., 2022). This wastewater can severely disrupt aquatic ecosystems if discharged without adequate treatment, leading to oxygen depletion, biodiversity loss, and eutrophication (Araujo et al., 2021). These impacts highlight the need for robust and efficient treatment technologies capable of reducing key pollutant parameters to environmentally acceptable levels before discharge into natural water bodies.

Coagulation and Flocculation in Waste Treatment

Coagulation and flocculation are widely applied physicochemical processes that remove colloidal particles and reduce pollutant loads in wastewater treatment systems (Lichtfouse et al., 2019; Zaki et al., 2023). These processes destabilize particle surface charges and promote aggregation, allowing for the formation of flocs that can be efficiently separated via sedimentation or filtration (Wei et al., 2018). The effectiveness of coagulation-flocculation depends on several factors, including pH, coagulant dosage, mixing intensity, and the nature of suspended particles (Benalia et al., 2024). Among various mechanisms, charge neutralization often yields superior floc compactness and clarity of treated effluent compared to sweep flocculation (Jiao et al., 2017). Consequently, optimizing operational parameters is critical to achieving maximum pollutant removal efficiency.

In practice, a range of inorganic coagulants–such as aluminum sulfate (combination with the chemical coagulant alum [$Al_2(SO_4)_3$]), ferrous chloride ($FeCl_3$), and lime–are employed to enhance floc formation and sedimentation (Mohamed et al., 2020; Zhao et al., 2021). While these agents are effective, their long-term use has raised environmental and health-related concerns due to their poor biodegradability and potential to increase heavy metal content in the resulting sludge (Donovan et al., 2018; Wei et al., 2018). In addition to generating large quantities of chemically contaminated sludge, these coagulants can increase treatment costs and hinder sustainable waste management practices (Diver et al., 2023; Nayeri & Mousavi, 2022). These limitations underscore the importance of seeking safer, cost-effective alternatives that minimize environmental footprints while maintaining treatment performance.

Bioflocculants as An Environmentally Friendly Alternative

Bioflocculants are biodegradable, naturally occurring polymeric substances produced by microorganisms such as bacteria, fungi, and algae, which possess high particle-binding capacities in aqueous systems (Rebah et al., 2018). These biopolymers, typically composed of polysaccharides, proteins, and lipids, offer an environmentally benign alternative to synthetic flocculants due to their non-toxic and readily degradable nature (Maćczak et al., 2020; Salehizadeh et al., 2018). Bioflocculants have demonstrated significant efficiency in reducing suspended solids, turbidity, and COD levels in a wide range of industrial wastewaters, including those generated by the food and agricultural sectors (Maliehe et al., 2019; Rebah et al., 2018). Moreover, their production can be economically optimized by utilizing agro-industrial residues and wastewater as fermentation media, thereby reducing production costs and promoting circular economy principles (Siddeeg et al., 2020). The flocculation mechanisms of bioflocculants typically involve adsorption bridging, charge neutralization, and polymer entanglement, making them versatile and adaptable across various wastewater treatment contexts (Li et al., 2020).

Among microbial sources, *A. latus* has been identified as a particularly potent bioflocculant-producing bacterium. Studies have reported that bioflocculants derived from *A. latus* exhibit high removal efficiency for TSS and COD in food industry wastewater while maintaining activity across a broad pH and temperature range (Maliehe et al., 2016). These properties enhance their applicability in diverse industrial settings where operational conditions fluctuate. Compared to conventional chemical flocculants, *A. latus*-derived bioflocculants pose minimal environmental risk and offer a sustainable alternative to addressing industrial wastewater challenges (Selepe et al., 2022). Their high flocculating activity, low toxicity, and eco-friendly profile position them as strong candidates for large-scale implementation in industrial effluent treatment systems.

Synergy Between Bioflocculants and Inorganic Coagulants

Although individual applications of bioflocculants and inorganic coagulants have been well documented, research exploring their combined use remains relatively scarce. Emerging studies suggest that combining bioflocculants with conventional coagulants, such as alum, can enhance the removal efficiency of critical pollutants like BOD and COD more effectively than either agent (Rahmat et al., 2024). The synergy is attributed to improved floc structure, where bioflocculants facilitate the formation of denser and more stable flocs following initial charge neutralization by the coagulant (Tsoutsa et al., 2024). In addition, this combination has been shown to accelerate sedimentation rates and reduce sludge volume, thereby improving operational efficiency and lowering treatment costs (Joshi et al., 2019). Such synergistic systems are desirable for industrial applications, where cost-effectiveness and environmental compliance are key considerations.

The reduced requirement for inorganic coagulant dosage when introducing bioflocculants further contributes to minimizing the environmental impact of wastewater treatment processes (Jiang et al., 2009). This approach aligns with the growing demand for hybrid treatment technologies combining high efficiency and sustainability. Nonetheless, the application of *A. latus*-derived bioflocculants in combination with alum in tapioca wastewater treatment has not been extensively investigated. Understanding the interactive dynamics between these agents could pave the way for innovative treatment frameworks tailored for agro-industrial effluents.

This study addresses a critical gap by evaluating the synergistic potential of *A. latus* bioflocculants and alum coagulants in the treatment of tapioca industry wastewater. By assessing multiple performance parameters–including TSS, BOD_5, COD, cyanide, color, and pH–this research seeks to expand current knowledge on biologically integrated flocculation systems. The findings are expected to contribute to developing more effective, sustainable, and scalable wastewater treatment technologies suitable for industrial applications.

METHODOLOGY

Research Design

This study employed a laboratory-based experimental design with a two-factor factorial approach to evaluate the effectiveness of bioflocculants produced by *A. latus*, applied individually or in $Al_2(SO_4)_3$, in treating tapioca processing wastewater. The research was conducted in two stages: a preliminary study and a main experiment. The preliminary study aimed to determine the optimal dosage ranges for both bioflocculant and alum and supporting parameters, such as pH and agitation speed, influencing the flocculation process. The subsequent main experiment assessed the interaction between bioflocculant and alum dosages in improving pollutant removal efficiency through the coagulation-flocculation process. This factorial approach allows for a comprehensive evaluation of treatment variables' individual and interactive effects.

Research Location and Time

The experimental phase of this research was conducted over six months, from May to October 2022. Laboratory analyses and microbial cultivation were conducted in certified facilities under the department of agro-industrial technology, faculty of agricultural technology, Bogor Agricultural University (IPB). These included the bioindustry, chemical technology, quality control, and environmental technology laboratory. Additional advanced testing, including water quality and residue analysis, was conducted at BIOTROP Bogor and the Tanjungkarang Industrial Center laboratory in Lampung. Using multiple laboratories ensured the experimental data's accuracy, consistency, and validity.

Materials and Microorganisms

The primary material used in this study was raw liquid waste from a medium-scale tapioca processing facility, *PT Inti Sumber Agung Lancar*, located in Batanghari District, East Lampung Regency. This wastewater is generated from the processing of cassava tubers into starch. The bioflocculant-producing microorganism *A. latus* was obtained in lyophilized form from the Deutsche Sammlung von Mikroorganismen und Zellkulturen, Germany. This strain was chosen due to its known flocculation potential and environmental adaptability. All microbial cultivation and fermentation processes were carried out at the IPB bioindustry laboratory under aseptic and controlled conditions.

Bioflocculant Production

The production of bioflocculants began with the reactivation of *A. latus* cells using sterile Nutrient Broth as a liquid medium. The activated culture was streaked onto slanted Nutrient Agar to promote colony proliferation. After incubation at room temperature for 48 hours, active colonies were harvested and transferred into petri dishes containing fresh agar media to ensure robust cell growth. These cells were then inoculated into 100 mL of liquid medium within Erlenmeyer flasks and incubated in a shaker at 180 rpm for 48 hours at 30 °C to obtain seed culture. This culture was further scaled up in a 2-litre mini-fermenter containing 1.5 liters of the medium, maintained at 30 °C for seven days. A six-blade turbine impeller operating at 150 rpm provided uniform mixing and oxygenation, optimizing cell growth and bioflocculant production.

Flocculation Activity Testing

The flocculation activity of the produced bioflocculants was preliminarily evaluated using a kaolin suspension model. A standard test solution was prepared by mixing 80 mL of 5,000 ppm kaolin suspension, 10 mL of 10% $CaCl_2$ solution, and 0.5 mL of bioflocculant culture broth. The final volume was adjusted to 100 mL with distilled water, and the pH was standardized to 7.0 using NaOH or HCl. The mixture was stirred gently and allowed to settle for five minutes. The turbidity of the suspension was measured spectrophotometrically at a wavelength of 450 nm before and after the addition of the bioflocculant. The effectiveness of the flocculant was calculated using Eq. (1):

$$Flocculation\ activity = \frac{1}{A} - \frac{1}{B}, \quad (1)$$

where A and B denoting the OD_{450} of the treated sample and control, respectively, to assess bioflocculant effectiveness.

Initial Treatment of Waste Samples

Prior to coagulation-flocculation treatment, the raw tapioca wastewater underwent a standardized homogenization process to ensure consistency across replicates. The samples were shaken and filtered to remove large particulates, and their pH was adjusted from an initial range of 4.3-4.6 to a neutral pH of 7.2 using NaOH. This pH adjustment was necessary to align with the optimal range for bioflocculant activity and to ensure consistent chemical conditions for all

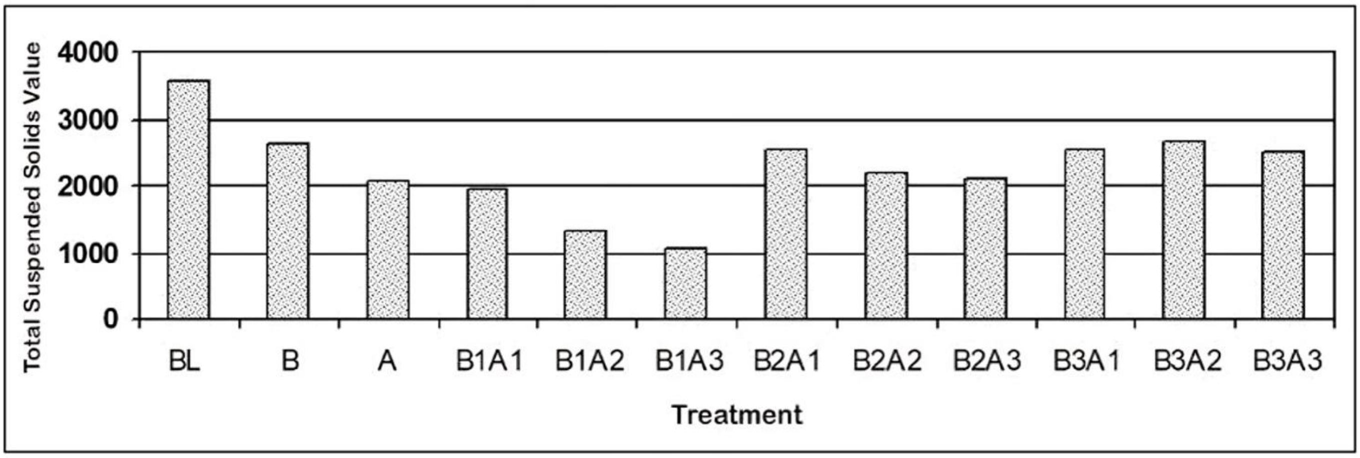

Figure 1. Waste TSS values after treatment with various combinations of bioflocculant and alum doses (BL = control; B = bioflocculant; A = alum; *B1A1* = [2 mL; 3 mg], *B1A2* = [2 mL; 6 mg], *B1A3* = [2 mL; 9 mg], *B2A1* = [4 mL; 3 mg], *B2A2* = [4 mL; 6 mg], *B2A3* = [4 mL; 9 mg], *B3A1* = [6 mL; 3 mg], *B3A2* = [6 mL; 6 mg], & *B3A3* = [6 mL; 9 mg]) (Source: Authors' own elaboration)

treatment combinations. The samples prepared were stored at 4 °C and used within 24 hours to maintain sample integrity.

Experimental Design

The main experiment employed a two-factor factorial design arranged in a completely randomized design (CRD) with two replicates per treatment. The two experimental factors were the dosage of bioflocculant and alum, each tested at three levels. The resulting nine treatment combinations were applied to evaluate their effects on key water quality parameters, including TSS, BOD_5, COD, color, cyanide concentration, and pH. The factorial design facilitated the identification of main effects and interactions between treatment variables, contributing to a robust analysis of treatment efficacy.

Data Analysis

The data collected were subjected to statistical analysis using analysis of variance for factorial design under CRD to determine the significance of main effects and interaction effects between treatments. The statistical model used was as follows:

$$Y_{ijkr} = \mu + A_i + B_j + (AB)_{ij} + \varepsilon_{ijkr}, \quad (2)$$

where Y_{ijkr} is the observation value, μ is the overall mean, A_i is the effect of the i-th level of factor A (bioflocculant dose), B_j is the effect of the j-th level of factor B (alum dose), $(AB)_{ij}$ is the interaction between A and B, and ε_{ijkr} is the random error. The indices i, j, k = 1, 2, 3, represent the levels of each factor, and r = 1, 2, denotes the number of replications. The statistical software analysis was conducted, and significance was determined at the 95% confidence level (α = 0.05). When significant differences were found, post hoc tests were conducted to determine pairwise differences among treatment means.

RESULTS

This study evaluated the effectiveness of bioflocculants produced by *A. latus* in the flocculation of tapioca industrial wastewater, both as a standalone treatment and in $Al_2(SO_4)_3$. The assessment was based on six key parameters of wastewater quality: TSS, BOD_5, COD, colour, cyanide content, and pH variation.

Total Suspended Solids

TSS represents the concentration of insoluble particles in the wastewater, commonly consisting of residual starch granules, cassava peels, and other organic fractions from the washing and extraction stages of tapioca processing. Elevated TSS levels contribute to increased turbidity and can interfere with downstream treatment efficiency. **Figure 1** illustrates the influence of various combinations of bioflocculant and alum dosages on TSS reduction.

As shown in **Figure 1**, the highest TSS level was recorded in the untreated control (BL) at approximately 3,700 mg/L. Bioflocculant-only treatment reduced TSS to around 2,600 mg/L, whereas alum alone achieved a greater reduction, lowering TSS to approximately 2,100 mg/L. The most effective treatment was the *B1A3* combination (2 mL bioflocculant + 9 mg alum), reducing TSS to around 1,000 mg/L. Treatments *B1A1* and *B1A2* also demonstrated substantial TSS reductions, falling within the 1,200 - 1,500 mg/L range. In contrast, combinations with higher bioflocculant doses (B2 and B3 series) yielded less favorable outcomes, showing TSS levels comparable to or higher than single treatments.

Biological Oxygen Demand Over 5 Days

BOD_5 indicates the amount of microbial oxygen populations require to decompose organic material within five days. Tapioca wastewater typically exhibits high BOD_5 levels due to its starch-rich composition, which is readily biodegradable. The influence of treatment combinations on BOD_5 values is presented in **Figure 2**

As observed in **Figure 2**, the baseline BOD_5 of 2,881.3 mg/L was significantly reduced across all treatments. Bioflocculant treatment alone decreased BOD_5 to approximately 1,756.3 mg/L, while alum alone achieved a reduction of around 1,385.2 mg/L. The most substantial decrease was observed in the *B1A2* (491.4 mg/L) and *B1A3* (621.9 mg/L) combinations. Treatments with bioflocculant doses exceeding 2 mL led to higher BOD_5

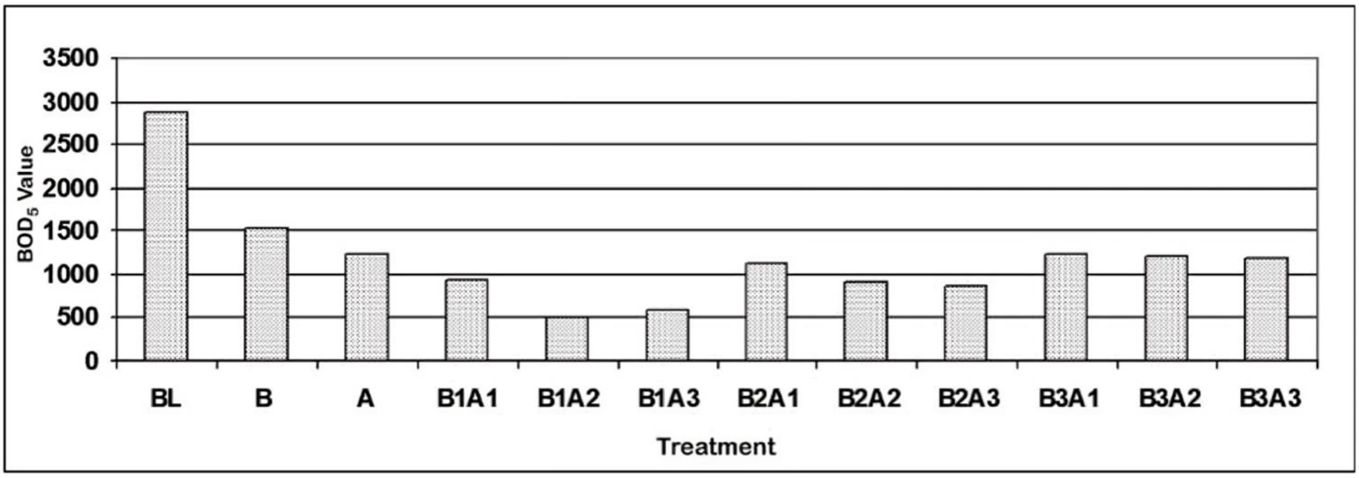

Figure 2. Waste *BOD_5* value after treatment with various combinations of bioflocculant and alum doses (Source: Authors' own elaboration)

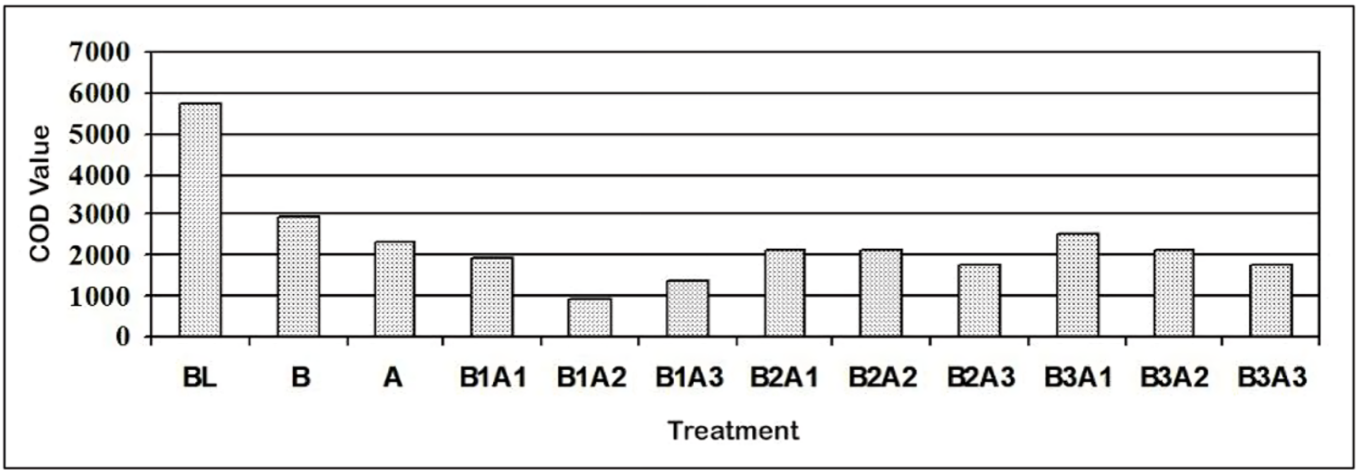

Figure 3. Waste COD values after treatment with various dosage combinations of bioflocculant and alum (Source: Authors' own elaboration)

values (1,000 - 1,200 mg/L), indicating that an excessive bioflocculant dose may not enhance performance and could potentially inhibit microbial degradation dynamics.

Chemical Oxygen Demand

COD measures the total oxygen demand required to chemically oxidize organic and inorganic substances in wastewater, including compounds resistant to biological breakdown. COD values are typically higher than *BOD_5* due to the inclusion of more complex, recalcitrant compounds. The treatment effect on COD levels is shown in **Figure 3**.

Figure 3 reveals a notable reduction in the initial COD level of 5,742.3 mg/L in all treatments. Applying bioflocculant alone reduced COD to approximately 2,500 mg/L, while alum alone reduced around 2,000 mg/L. The *B1A2* treatment exhibited the highest COD removal efficiency, achieving a value below 1,000 mg/L. *B1A1* and *B1A3* combinations also showed effective reductions, reaching 1,000 - 1,300 mg/L. In contrast, treatments with higher bioflocculant concentrations (4 - 6 mL) did not further improve COD removal, indicating a plateau or possible inhibition at higher doses.

Cyanide Content

Cyanide in tapioca wastewater originates from linamarin and lotaustralin, cyanogenic glycosides that degrade into hydrocyanic acid during cassava processing. These compounds are acutely toxic and must be reduced to safe levels before discharge. The effect of treatments on cyanide content is shown in **Figure 4**.

Figure 4 shows that all treatment scenarios' initial cyanide concentrations of 0.35 mg/L decreased. Bioflocculant alone reduced cyanide to 0.29 mg/L, while alum alone achieved a slightly better reduction to 0.27 mg/L. The *B1A2* and *B2A3* combinations provided the most significant reductions, reaching values close to 0.20 mg/L. Other combinations also showed superior performance compared to single treatments, with most values falling below 0.25 mg/L, indicating the benefit of combined treatment approaches.

Color (Decolorization)

Color is a key aesthetic parameter in wastewater, often associated with phenolic compounds and pigmented organic materials derived from cassava peels and organic degradation. Effective color reduction improves the visual and chemical

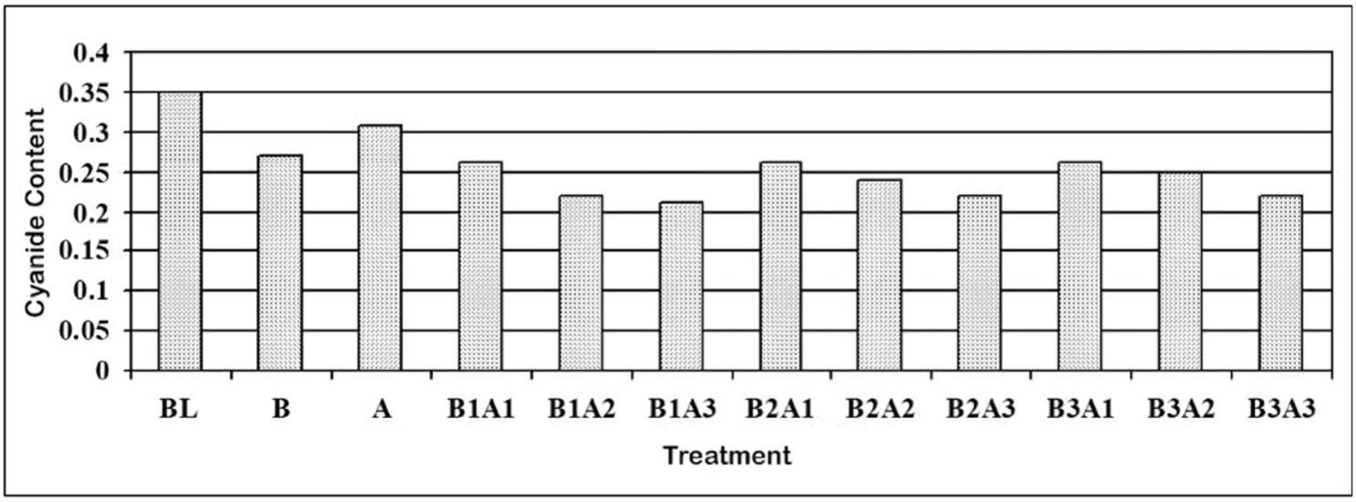

Figure 4. Value of waste cyanide content after treatment with various combinations of bioflocculant and alum doses (Source: Authors' own elaboration)

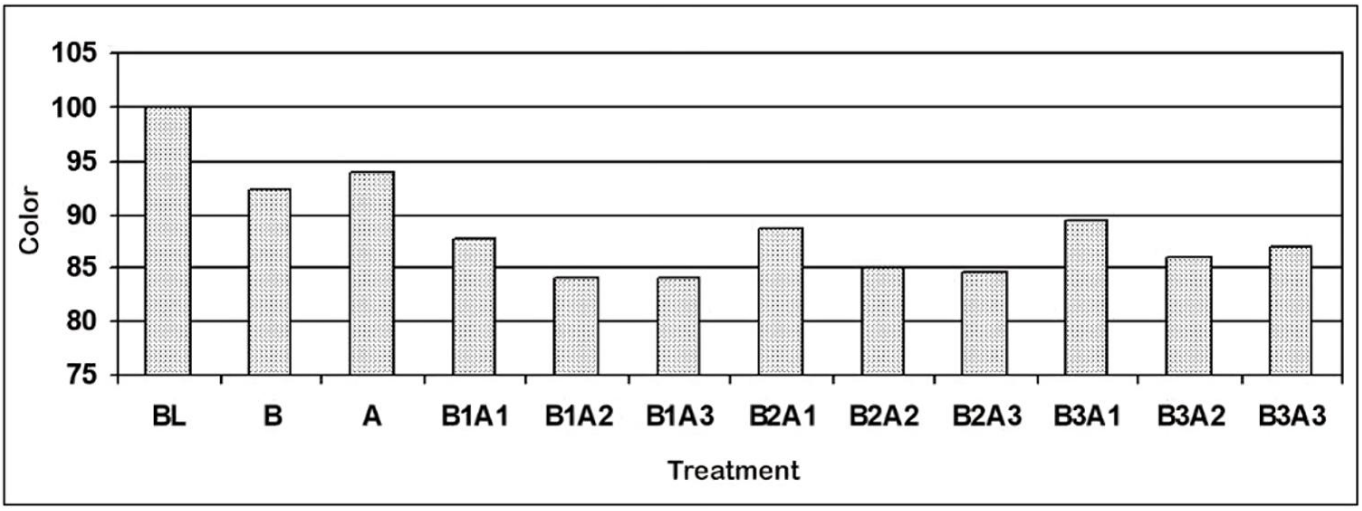

Figure 5. Value the color of the waste after treatment with various combinations of bioflocculant and alum doses (Source: Authors' own elaboration)

quality of treated effluent. Decolorization results from different treatment combinations are presented in **Figure 5**.

As shown in **Figure 5**, the original color intensity measured at 100 units decreased under all treatment conditions. Single treatments reduced color to approximately 90 units. Greater reductions were observed in combined treatments, particularly *B1A2*, *B2A2*, and *B2A3*, which yielded values between 80 and 85 units. *B3A1* demonstrated the highest decolorization efficiency, reaching a color value near 80 units. These findings suggest moderate dosing strategies enhance pigment removal efficiency without excessive reagent use.

pH Changes

pH is an important parameter in coagulation-flocculation dynamics, influencing the chemical behavior of coagulants and the physical stability of flocs. In this study, the initial pH of the wastewater was standardized to 7.2 to align with the optimal range for alum performance (5.5 - 8.0). The effects of treatments on final pH values are shown in **Figure 6**.

Figure 6 indicates that all post-treatment pH values remain within the acceptable environmental range of 6.0 - 9.0. Treatments involving bioflocculant alone did not significantly alter pH, maintaining it near the initial value. Alum-only treatment resulted in a modest pH reduction to around 6.83. Combined treatments effectively maintained pH stability, with *B2A2* and *B2A3* yielding the highest post-treatment pH values (close to 6.94). The *B3A3* combination was the only treatment that resulted in a slightly more pronounced pH drop, though still within regulatory limits.

DISCUSSION

Effectiveness of the Combination of Bioflocculants and Alum on Tapioca Waste Parameters

The findings of this study demonstrate that the combination of bioflocculants produced by *A. latus* with $Al_2(SO_4)_3$ significantly enhances wastewater treatment performance compared to single treatments. The improvement results from the synergistic interaction between the bridging ability of bioflocculants and the charge-neutralizing effect of alum, which facilitates the formation of

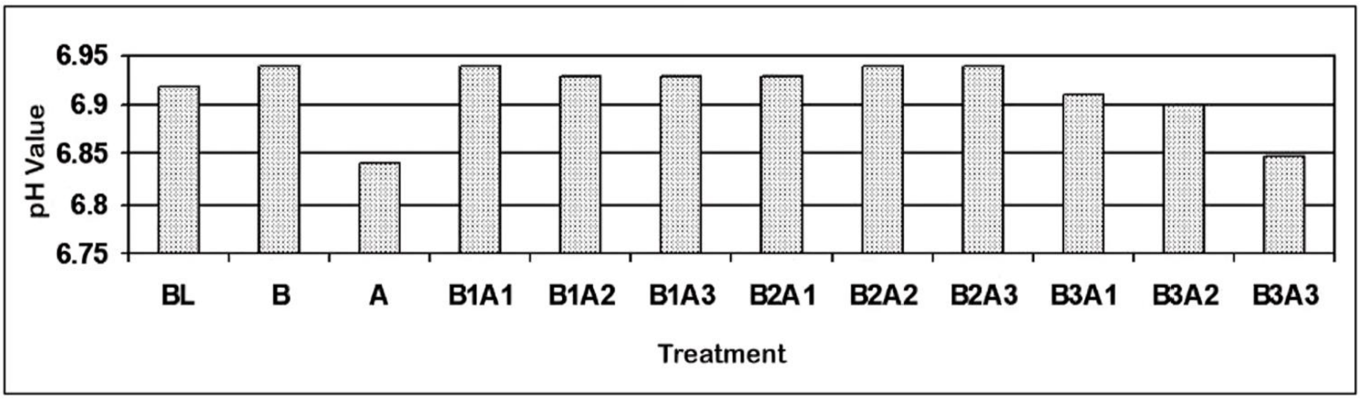

Figure 6. pH value of waste after treatment with various combinations of bioflocculant and alum doses (Source: Authors' own elaboration)

larger, denser, and more stable flocs. This synergism promotes efficient sedimentation, thereby reducing suspended solids and organic pollutant concentrations (Rahmat et al., 2024; Tsoutsa et al., 2024). Such enhancement not only improves water clarity but also reduces pollutant loads that directly contribute to achieving SDG 6's goals (clean water and sanitation), emphasizing the role of integrated eco-friendly technologies in ensuring sustainable water management in industrial processes (Das et al., 2021; Kurniawan et al., 2020).

The combination treatment, particularly *B1A2* (2 mL bioflocculant + 6 mg alum), achieved the highest removal efficiencies for TSS (70.15%), COD (83.80%), and BOD_5 (67.38%), underscoring the effectiveness of a balanced dosage ratio. These results align with the principle of integrated chemical-biological flocculation, wherein bioflocculant polymers enhance the performance of inorganic coagulants (Maćczak et al., 2020; Sun et al., 2021). The consistent superiority of this dosage combination across multiple water quality parameters indicates a robust and adaptable system for agro-industrial wastewater treatment. Furthermore, by lowering the need for high doses of chemical coagulants, the hybrid system supports SDG 12's goals (responsible consumption and production) through reduced chemical dependency and safer industrial effluent management (Diver et al., 2023; Obaideen et al., 2022).

Conversely, increasing the bioflocculant dose beyond 2 mL diminished treatment efficiency. This decline is likely due to the excessive presence of organic macromolecules, which can increase dissolved organic matter and interfere with floc formation. Arulraj et al. (2022) reported that overdosing bio-based flocculants may restabilize particles and inhibit aggregation due to saturation effects of the polymer. Therefore, the optimization of bioflocculant-coagulant ratios is essential to maintain treatment stability and efficiency while minimizing reagent consumption. Optimized dosage use not only enhances process performance but also embodies the resource efficiency principles central to SDG 12, which promotes minimizing waste and maximizing resource effectiveness in industrial operations.

While reductions in color and cyanide content were not as pronounced as those in organic parameters, they remained substantial and environmentally relevant. The hybrid treatment reduced cyanide by 31.29% and color by 15.98%, indicating its ability to mitigate both the aesthetic and toxicological impacts of tapioca effluent. The mechanism involves the adsorption of phenolic and low-molecular-weight compounds by bioflocculants, while alum assists in particle aggregation by reducing the zeta potential (Jiang et al., 2009). These outcomes highlight the potential of the bioflocculant and alum system to address toxic compounds such as cyanogenic glycosides, thus protecting aquatic ecosystems and aligning with SDG 14's goals (life below water) by reducing chemical contamination that threatens biodiversity in downstream water bodies.

pH Stability and Advantages of the Hybrid Coagulation-Flocculation Approach

An additional advantage of the combined treatment system lies in its ability to maintain pH stability within the optimal range for floc formation. The post-treatment pH remained between 6.85 and 6.94 across all combinations, fulfilling regulatory standards (6.0 - 9.0) while preserving the chemical conditions required for effective coagulation. Maintaining this pH range is crucial for preserving the activity of Al^{3+} ions and ensuring the integrity of bioflocculant compounds during flocculation (Eckenfelder, 2000). From a sustainability perspective, stable pH control reflects responsible water management practices that support SDG 6's goals by maintaining effluent quality suitable for safe discharge and reuse in industrial cycles (Das et al., 2021; Kurniawan et al., 2020).

The buffering capability of *A. latus*-derived bioflocculants effectively counteracted the acidity introduced by alum, thereby preserving pH equilibrium and minimizing the potential ecological harm of acidic discharges. The *B2A2* and *B2A3* combinations exhibited the most stable pH outcomes, suggesting that these dosage levels promote both coagulation efficiency and chemical balance. This stability enhances process reliability and reduces infrastructure corrosion, thereby contributing to a longer operational lifespan and lower maintenance costs. Moreover, by preventing acidification and maintaining near-neutral effluent conditions, the hybrid system minimizes disturbances to aquatic ecosystems. This outcome aligns with SDG 14's goals, which emphasize the reduction of land-based pollutants that impact marine and freshwater biodiversity.

Furthermore, maintaining stable pH conditions reduces the dependency on auxiliary chemicals, such as buffers or alkalis, thereby improving the overall cost efficiency and environmental performance of the system. As noted by Diver et al. (2023), minimizing chemical additives not only lowers operational costs but also decreases the risk of residual contamination in treated water. Consequently, this hybrid bioflocculant and alum approach exemplifies an eco-efficient wastewater treatment strategy consistent with SDG 12's goals by promoting cleaner production and resource efficiency within industrial wastewater management frameworks.

Optimal Dose Validation and Applicative Relevance for Industry

The combination of 2 mL bioflocculant with 6 mg alum (*B1A2*) was validated as the optimal formulation, consistently producing the highest removal efficiencies across all treatment parameters. This dosage achieved maximum reductions in COD and TSS–critical indicators of organic pollution–while maintaining stable pH and minimizing the use of chemical coagulants. The optimized ratio demonstrates a balanced interaction between biological and chemical mechanisms, ensuring both high treatment efficiency and environmental compatibility. Such optimization directly contributes to SDG 6's goals by improving the effectiveness and reliability of wastewater purification processes in industrial contexts (Das et al., 2021; Kurniawan et al., 2020).

The findings of this research are consistent with those of previous studies by Joshi et al. (2019) and Tsoutsa et al. (2024), which confirmed that hybrid coagulation-flocculation systems enhance pollutant removal efficiency while reducing the dosage of inorganic coagulants required. Beyond improved efficiency, this approach also reduces sludge generation, simplifies post-treatment management, and lowers disposal costs–issues that are often significant operational challenges in industrial wastewater treatment (Li et al., 2020). Considering the high organic load and volume typical of tapioca effluents, the bioflocculant and alum combination presents a scalable and contextually relevant solution that supports SDG 12's goals through waste minimization, reduced hazardous chemical use, and process optimization (Arulraj et al., 2022; Diver et al., 2023).

Moreover, the selection of *A. latus* as a bioflocculant source further strengthens the sustainability dimension of the proposed treatment system. Its proven stability, cost-effective cultivation, and wide pH tolerance make it a viable candidate for large-scale industrial application (Maliehe et al., 2019; Selepe et al., 2022). The organism's ability to produce non-toxic and biodegradable polymers ensures environmental safety and aligns with the principles of green technology. By substituting hazardous synthetic agents with biologically derived flocculants, this study advances the goals of SDG 9 (industry, innovation, and infrastructure) through the development of cleaner and more innovative industrial technologies that foster sustainable production cycles (Rebah et al., 2018).

Overall, this study provides quantitative validation of the efficacy and industrial feasibility of combining *A. latus*-based bioflocculants with alum for treating tapioca wastewater. The hybrid system represents a sustainable, high-performance alternative to conventional methods, promoting resource-efficient and eco-friendly wastewater management. Furthermore, it addresses long-term environmental concerns associated with the persistence and toxicity of synthetic coagulants, offering a biodegradable and low-impact solution that supports multiple sustainability objectives. This finding reinforces the role of biotechnological innovation in advancing the global sustainability agenda

Implications of the Study

The findings of this study have significant implications for both sustainable industrial practices and environmental education. The hybrid bioflocculant-alum system developed in this research offers a practical approach for improving the quality of tapioca wastewater while reducing chemical dependence and environmental risks. By enhancing pollutant removal efficiency and promoting eco-friendly treatment, this approach directly supports the goals of SDG 6 and SDG 12. Similar to the findings of Kurniawan et al. (2020) and Das et al. (2021), this study reinforces the importance of integrating green technologies into wastewater management systems to achieve cleaner production and sustainable industrial development.

Beyond its industrial relevance, the results of this study can serve as valuable enrichment material for higher education, particularly in courses related to environmental biology, environmental biotechnology, or education for sustainable development. The bioflocculation process using *A. latus* provides a compelling example of how microorganisms can be utilized to mitigate pollution while maintaining ecological balance. Incorporating these findings into educational practice encourages learners to apply scientific knowledge to address environmental problems.

Furthermore, the study's outcomes contribute to the development of environmentally based education that fosters interdisciplinary learning among science, technology, and sustainability. The implementation of bioflocculant-based wastewater treatment can be explored in laboratory experiments or project-based learning activities, allowing students to experience the principles of circular economy and resource efficiency in action. This approach aligns with SDG 9's goals by fostering innovation through environmentally responsible technologies.

From a broader educational perspective, disseminating the results of this study supports the cultivation of environmental literacy and responsible citizenship among future professionals. Embedding this topic into science and environmental education curricula promotes critical reflection on the social and ecological impacts of industrial activities. In line with the goals of SDG 4 (quality education) and SDG 14, the pedagogical application of this research can help students understand how sustainable wastewater management protects aquatic ecosystems while advancing global sustainability objectives.

CONCLUSIONS

This study demonstrates that the combination of bioflocculants produced by *A. latus* with $Al_2(SO_4)_3$ is highly effective in reducing key pollutant parameters in tapioca industrial wastewater. The optimal treatment dose of 2 mL bioflocculant and 6 mg alum achieved the highest removal efficiencies for COD (83.80%), TSS (70.15%), and BOD_5 (67.38%), while also reducing cyanide content (31.29%) and color (15.98%). Furthermore, this treatment combination maintained the final effluent pH within a neutral range (6.85 - 6.94), fulfilling environmental standards and supporting operational stability. These results highlight the strong synergistic effect between biological and inorganic flocculating agents, confirming that hybrid coagulation-flocculation is an efficient and sustainable approach to treating organic-rich industrial effluents.

The outcomes of this research contribute directly to several of the SDGs. The improvement of water quality and reduction of chemical dependency support the SDG 6 goals. The reduction in hazardous coagulant use and waste generation aligns with SDG 12, and the development of bioflocculant-based technology exemplifies innovation in sustainable industry practices, contributing to SDG 9. Additionally, by mitigating toxic discharges that threaten aquatic ecosystems, the study also reinforces SDG 14, highlighting the ecological importance of adopting green treatment technologies in the agro-industrial sector.

Despite its promising outcomes, several limitations should be acknowledged. First, this study was conducted under controlled laboratory conditions; further validation is needed at the pilot or industrial scale to confirm its real-world applicability. Second, the bioflocculant used was in its crude form without purification; therefore, the specific contributions of its active components–such as polysaccharides and proteins–remain to be elucidated. Third, operational parameters such as mixing speed, flocculation time, and hydrodynamic conditions were not comprehensively optimized. Future studies should address these gaps by conducting kinetic analyses, scaling-up experiments, and characterizing the composition of bioflocculant materials to enhance process understanding and improve performance consistency.

In practical terms, the combination of 2 mL *A. latus* bioflocculant and 6 mg alum can be recommended for medium- to large-scale tapioca wastewater treatment systems due to its verified efficiency and environmental compatibility. The demonstrated reduction in chemical usage supports the transition toward cost-effective, resource-efficient, and sustainable treatment practices. Furthermore, the development of bioflocculant products from locally sourced microorganisms, such as *A. latus*, represents a strategic pathway for reducing dependence on imported synthetic polymers and strengthening regional bioeconomy initiatives. This innovation not only advances sustainable industrial operations but also creates opportunities for knowledge transfer and capacity-building in environmental biotechnology.

From an educational perspective, the findings of this study can be integrated into courses such as environmental biology or environmental-based education to enhance students' understanding of the interconnection between biotechnology, sustainability, and environmental protection. The hybrid bioflocculant-alum system provides a real-world example of how microbiological principles can be applied to address global environmental issues, encouraging inquiry-based learning and interdisciplinary problem-solving. Embedding this topic into higher education curricula supports SDG 4's goals by promoting environmental literacy, scientific reasoning, and innovation-oriented learning, thereby preparing future professionals to contribute actively to achieving the SDGs.

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