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Research Article

Comparative Performance Evaluation of Aeration, Coagulation, and Integrated Aeration Coagulation for Improving Tapioca Industrial Wastewater Quality

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Abstract

Tapioca processing industries generate wastewater containing high concentrations of organic matter and suspended solids that may adversely affect aquatic ecosystems if discharged without proper treatment. Although aeration and coagulation have been widely implemented as conventional wastewater treatment methods, comparative evidence regarding the effectiveness of their individual and integrated applications remains limited. This study aimed to comparatively evaluate the performance of aeration, coagulation, and integrated aeration–coagulation processes in improving the physicochemical quality of tapioca industrial wastewater. An experimental approach was employed by applying three treatment methods to wastewater samples and evaluating changes in Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity before and after treatment. The results demonstrated that all treatment methods improved wastewater quality, with the integrated aeration–coagulation process exhibiting the highest overall performance. The combined treatment increased dissolved oxygen to 24.6 mg/L, reduced ammonia concentration to 10 mg/L, and decreased turbidity to 2.95 NTU, while all measured parameters complied with the applicable wastewater quality standards. These findings indicate that integrating aeration and coagulation offers a more effective, environmentally sustainable, and practical treatment strategy than either process applied individually, making it a promising alternative for wastewater management in the tapioca processing industry.

Keywords: *Aeration; Coagulation; Integrated Aeration–Coagulation; Tapioca Industrial Wastewater; Wastewater Quality.*

How to Cite:

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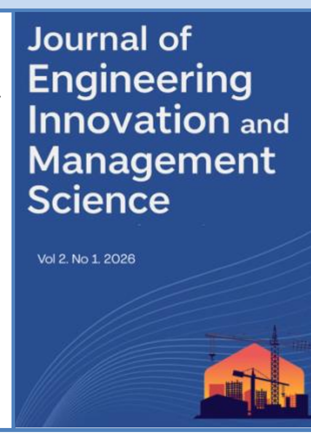

INTRODUCTION

The rapid growth of the food processing industry has contributed significantly to economic development by increasing agricultural productivity, generating employment opportunities, and supporting industrial expansion in many developing countries. Despite these economic benefits, food-processing industries also generate considerable volumes of wastewater that may pose serious environmental challenges when discharged without adequate treatment (Abdel-Fatah, 2023; Asgharnejad et al., 2021; Tripathy et al., 2025). Among agro-based industries, the tapioca processing industry is recognized as one of the major producers of wastewater because large quantities of water are required during washing, peeling, grinding, starch extraction, and purification processes (Budinarta et al., 2025; Pandit et al., 2021). As a consequence, substantial volumes of wastewater containing biodegradable organic matter, suspended solids, dissolved solids, and various inorganic compounds are continuously produced throughout the manufacturing process. Previous studies have reported that tapioca industrial wastewater is characterized by elevated concentrations of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS), indicating a high pollution potential if released directly into natural water bodies (Duque-Achipiz et al., 2025; Haryanto et al., 2020). The decomposition of excessive organic matter consumes dissolved oxygen in aquatic environments, resulting in oxygen depletion that adversely affects aquatic organisms and disrupts ecosystem stability. Furthermore, high concentrations of suspended particles increase turbidity, reduce light penetration, and impair the ecological functions of receiving water bodies. Continuous discharge of untreated wastewater may also contribute to unpleasant odors, deteriorated water quality, and reduced environmental carrying capacity in surrounding communities. Consequently, the implementation of efficient wastewater treatment technologies has become an essential requirement for minimizing environmental impacts while supporting sustainable industrial development. Therefore, improving the treatment efficiency of tapioca industrial wastewater remains an important environmental engineering challenge that requires practical, effective, and environmentally sustainable solutions.

Various wastewater treatment technologies have been developed to reduce pollutant concentrations and improve the quality of industrial effluents before environmental discharge. Among these technologies, biological treatment through aeration has become one of the most widely implemented methods because it enhances dissolved oxygen availability, thereby stimulating aerobic microbial activity responsible for degrading biodegradable organic compounds. Increasing dissolved oxygen concentrations also promotes more stable biological processes, accelerates organic matter decomposition, and improves the overall efficiency of wastewater treatment systems (Abdelfattah et al., 2023; Muloiwa et al., 2024; Xiao et al., 2021). Nevertheless, biological treatment alone may not effectively remove suspended solids, colloidal particles, or certain inorganic contaminants that remain stable within wastewater (Ahmed et al., 2022; Aragaw & Bogale, 2023; Li et al., 2020; Singla, 2022). Consequently, physicochemical treatment methods such as coagulation are frequently applied to complement biological treatment processes by destabilizing fine suspended particles and promoting their aggregation into larger flocs that can be more easily separated from wastewater. Coagulation has been widely recognized as an effective treatment process for reducing turbidity, suspended solids, and other particulate pollutants while improving wastewater clarity (Badawi et al., 2023; Zaki et al., 2023). Since aeration and coagulation operate through different treatment mechanisms, integrating these processes has the potential to produce complementary pollutant removal effects that enhance overall treatment performance. The combined application of biological oxygen enrichment and physicochemical particle removal is expected to improve multiple wastewater quality parameters simultaneously while maintaining relatively simple operational procedures. Such integrated treatment systems are particularly attractive for small- and medium-scale agro-industries because they offer technically feasible and economically affordable alternatives for wastewater management. Accordingly, investigating the combined performance of aeration and coagulation is essential for identifying treatment strategies capable of achieving higher pollutant removal efficiencies than individual treatment processes.

Recent developments in environmental engineering have increasingly emphasized integrated wastewater treatment technologies as an effective approach for achieving higher pollutant removal efficiency while promoting sustainable water resource management. Numerous studies have demonstrated the effectiveness of aeration in enhancing biological degradation, whereas coagulation has consistently shown favorable performance in reducing suspended solids and improving wastewater clarification. Other investigations have explored hybrid treatment systems by integrating biological, physicochemical, membrane, electrochemical, and advanced oxidation processes to overcome the limitations associated with single-treatment technologies (Asheghmoalla & Mehrvar, 2024; Espinosa et al., 2026; Saadi et al., 2026). These findings indicate that integrating multiple treatment mechanisms can improve overall wastewater treatment performance while increasing operational flexibility under varying wastewater characteristics. However, the effectiveness of integrated treatment systems remains highly dependent on wastewater composition, operational conditions, and treatment configurations. In the case of tapioca industrial wastewater, considerable variations in pollutant characteristics require treatment strategies that are capable of simultaneously addressing multiple physicochemical parameters. Furthermore, previous investigations have generally focused on evaluating individual treatment technologies or advanced hybrid systems, whereas comparative assessments involving conventional aeration, coagulation, and their integrated application under identical operational conditions remain relatively limited (Jha & Mishra, 2024). Comprehensive evaluations involving Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity within a single experimental framework are also still rarely reported (Adjovu et al., 2023; Ngamile et al., 2025; Zainurin et al., 2022). Consequently, there remains a need for a systematic comparative evaluation capable of identifying the relative performance of each treatment strategy based on multiple physicochemical indicators. This study was therefore conducted to comparatively evaluate the effectiveness of aeration, coagulation, and integrated aeration–coagulation processes in improving the physicochemical quality of tapioca industrial wastewater and to provide scientific evidence supporting the development of practical, environmentally friendly, and sustainable wastewater treatment technologies for the tapioca processing industry.

Recent studies have demonstrated substantial progress in wastewater treatment technologies through the optimization of aeration processes for improving oxygen transfer efficiency, reducing energy consumption, and enhancing biological treatment performance, while coagulation-based technologies have also been extensively investigated to improve pollutant removal efficiency using both chemical and natural coagulants (Bahrodin et al., 2021; Gu et al., 2023; Nguyen et al., 2024; Sibiya et al., 2021; Skouteris et al., 2020). Furthermore, increasing attention has been directed toward integrated wastewater treatment systems that combine biological, physicochemical, membrane, electrocoagulation, and advanced oxidation processes to achieve higher treatment efficiencies and promote sustainable wastewater management (AlJaberi et al., 2022; Ceretta et al., 2021; Dhamorikar et al., 2024; Gopalakrishnan et al., 2023). Several investigations have also explored cassava-processing wastewater through resource recovery, anaerobic digestion, nutrient removal, adsorption, and circular economy approaches, highlighting the growing interest in sustainable management of wastewater generated by the cassava industry (Araujo et al., 2021; dos Santos et al., 2022; Duque-Achipiz et al., 2025; Lerdlattaporn et al., 2021). Nevertheless, existing studies have predominantly focused on individual treatment technologies or integrated systems involving advanced treatment processes, whereas direct comparative evaluations of conventional aeration, coagulation, and integrated aeration–coagulation under identical operational conditions remain relatively limited, particularly for tapioca industrial wastewater. Moreover, previous studies generally emphasized specific treatment objectives or a limited number of water quality indicators, making comprehensive assessments of multiple physicochemical parameters, including Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia, and turbidity, still scarce. Therefore, this study addresses this research gap by comparatively evaluating the performance of aeration, coagulation, and integrated aeration–coagulation processes using a comprehensive set of physicochemical indicators to identify the most effective, practical, and environmentally sustainable treatment strategy for improving tapioca industrial wastewater quality.

This study aims to comparatively evaluate the performance of aeration, coagulation, and integrated aeration–coagulation processes for improving the physicochemical quality of tapioca industrial wastewater. Specifically, the study investigates the effectiveness of each treatment method in reducing pollutant concentrations and enhancing wastewater quality under identical experimental conditions. The evaluation focuses on changes in Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity before and after treatment. Furthermore, this study compares the treatment performance of individual and integrated processes to determine the most effective approach for wastewater purification. The findings are expected to provide a comprehensive understanding of the advantages and limitations associated with each treatment strategy. In addition, this research seeks to identify whether integrating aeration and coagulation produces synergistic effects that enhance pollutant removal compared with the application of each process individually. The study also aims to generate scientific evidence supporting the implementation of simple and cost-effective wastewater treatment technologies for the tapioca processing industry. From an engineering perspective, the results are expected to contribute to the optimization of conventional wastewater treatment processes through an integrated treatment approach. Moreover, the findings may serve as a practical reference for improving wastewater management practices in agro-industrial sectors that generate wastewater with similar physicochemical characteristics. Ultimately, this study is expected to contribute to the advancement of sustainable industrial wastewater treatment by providing a comparative experimental evaluation that supports environmentally responsible and efficient wastewater management strategies.

METHODS

Research Design

This study employed an experimental research design to comparatively evaluate the performance of aeration, coagulation, and integrated aeration–coagulation processes in improving the physicochemical quality of tapioca industrial wastewater. The experimental approach was selected to enable a controlled comparison of treatment performance under identical operational conditions while minimizing external influences on wastewater characteristics. Three treatment configurations were investigated, namely aeration, coagulation, and integrated aeration–coagulation. Each treatment was independently applied to wastewater samples collected from the same wastewater source to ensure comparable initial characteristics. Treatment effectiveness was assessed by comparing physicochemical parameters before and after each treatment process. The evaluation focused on determining the capability of each treatment method to reduce pollutant concentrations and improve wastewater quality. A comparative approach was adopted to identify differences in treatment performance among the three treatment systems. The study emphasized the effectiveness of conventional treatment technologies that are technically feasible and economically applicable for small- and medium-scale tapioca industries. The experimental design also facilitated the assessment of potential synergistic effects resulting from integrating biological and physicochemical treatment processes. Overall, this design provided a systematic framework for evaluating alternative wastewater treatment strategies for sustainable industrial wastewater management.

Study Area

This study was conducted at the Environmental Engineering Laboratory, Department of Land and Environmental Resources Engineering, Politeknik Negeri Lampung, Indonesia. Wastewater samples were collected from a local tapioca processing industry located in Lampung Province, Indonesia, where tapioca production represents one of the major agro-industrial activities. Laboratory experiments were carried out under controlled conditions to ensure consistency throughout the treatment process. Representative wastewater samples were collected prior to entering the industrial wastewater treatment facility to ensure that the samples reflected actual wastewater characteristics generated during the production process. All laboratory analyses were performed immediately after sample collection to minimize physicochemical changes during storage. Wastewater samples were transported in clean polyethylene containers following standard sampling procedures. The laboratory environment was maintained under controlled conditions throughout the experimental period. All experimental treatments were conducted using identical operational procedures to ensure comparability among treatment methods. This experimental setting provided reliable conditions for evaluating the effectiveness of the investigated wastewater treatment processes.

Materials and Equipment

The primary material used in this study was untreated tapioca industrial wastewater collected directly from the production process. Aluminum sulfate (alum) was used as the chemical coagulant during the coagulation treatment because of its widespread application in industrial wastewater treatment. Clean water was utilized for equipment washing and laboratory preparation throughout the experiment. The experimental equipment consisted of an aerator, coagulation container, beakers, measuring cylinders, glass stirring rods, sample containers, and other standard laboratory glassware. Physicochemical analyses were conducted using calibrated laboratory instruments for measuring Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity. Analytical balances, thermometers, pH meters, dissolved oxygen meters, turbidity meters, and supporting laboratory equipment were used throughout the experimental procedures. All instruments were inspected and calibrated prior to laboratory measurements to ensure measurement accuracy and consistency. The experimental setup was arranged according to standard laboratory safety procedures. All chemicals used in the experiments were analytical grade to minimize experimental errors. The selected materials and equipment enabled consistent implementation of each wastewater treatment process and accurate measurement of treatment performance.

Instruments and Data Collection

Primary data were obtained through direct laboratory measurements conducted before and after each wastewater treatment process. Initial wastewater characterization included measurements of Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity. These parameters were selected because they represent important indicators of physicochemical wastewater quality and environmental compliance. Following the initial characterization, wastewater samples were subjected to aeration, coagulation, and integrated aeration–coagulation treatments. After completion of each treatment process, the same physicochemical parameters were measured using identical analytical procedures. All measurements were conducted using calibrated laboratory instruments following standard analytical methods for wastewater quality assessment. Experimental observations were recorded systematically in laboratory worksheets immediately after each measurement. Data collection procedures were performed consistently for all treatment methods to ensure data comparability. Repeated observations were conducted where necessary to verify measurement consistency and minimize observational errors. The resulting dataset constituted the primary basis for evaluating the comparative performance of the investigated wastewater treatment methods.

Data Analysis

The collected data were analyzed using descriptive comparative analysis to evaluate the effectiveness of each treatment method in improving wastewater quality. Changes in Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity were calculated by comparing measurements before and after treatment. Comparative analyses were performed to determine the relative performance of aeration, coagulation, and integrated aeration–coagulation. Treatment performance was interpreted based on the magnitude of pollutant reduction and improvement of physicochemical water quality parameters. The obtained results were subsequently compared with applicable wastewater quality standards to evaluate environmental compliance. Data were presented in tables and graphical forms to facilitate interpretation and comparison among treatment methods. Trends observed during the experimental treatments were analyzed to identify the contribution of each treatment process to pollutant removal. The overall treatment effectiveness was determined by considering improvements across all measured physicochemical parameters. The comparative findings were interpreted within the context of sustainable industrial wastewater treatment. Finally, conclusions were drawn to identify the most effective treatment strategy for improving the quality of tapioca industrial wastewater.

Experimental Procedure

The experimental procedure began with the preparation of laboratory equipment and analytical materials required for wastewater treatment and physicochemical analyses. Representative wastewater samples were collected from the tapioca processing industry and transported to the laboratory using clean sampling containers. Initial measurements of Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity were conducted prior to treatment to determine the baseline wastewater characteristics. The wastewater samples were subsequently divided into three experimental groups corresponding to aeration, coagulation, and integrated aeration–coagulation treatments. Aeration treatment was carried out using an aerator to continuously supply oxygen throughout the treatment period. Coagulation treatment involved the addition of alum followed by mixing and sedimentation to facilitate floc formation and particle separation. For the integrated treatment, wastewater samples first underwent aeration and were subsequently subjected to coagulation to combine biological oxygen enrichment with physicochemical pollutant removal. After completion of each treatment process, all physicochemical parameters were measured again using the same analytical procedures employed during the initial characterization. The resulting data were compiled, compared, and interpreted to evaluate treatment performance across the three experimental methods. The overall experimental workflow implemented in this study is illustrated in **Figure 1**.

Figure 1. Research Method Flow

RESULT AND DISCUSSIONS

Results

Physicochemical Characteristics of Tapioca Industrial Wastewater Before and After Treatment

The physicochemical characteristics of tapioca industrial wastewater before and after aeration, coagulation, and integrated aeration–coagulation treatments are presented in **Table 1**. Seven physicochemical parameters were evaluated, including Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity. Prior to treatment, the wastewater exhibited relatively high concentrations of dissolved solids, ammonia, and turbidity, indicating the presence of pollutants that require treatment before environmental discharge. Following treatment, all investigated methods produced measurable changes in wastewater quality, although the magnitude of improvement varied among the evaluated parameters. Aeration achieved the greatest reduction in Total Dissolved Solids (TDS), whereas the integrated aeration–coagulation treatment produced the highest dissolved oxygen concentration and the lowest turbidity value. Coagulation also demonstrated considerable effectiveness in reducing turbidity, producing results comparable to those of the integrated treatment. Minor variations were observed in pH and temperature after treatment, while Total Suspended Solids (TSS) remained relatively stable throughout the experiment. In addition, ammonia concentration decreased consistently following all treatment methods, reaching the maximum allowable concentration specified by the wastewater quality standard. Overall, the results demonstrate that all investigated treatment methods improved wastewater quality and satisfied the applicable environmental quality standards. These findings provide an initial overview of the comparative performance of the investigated treatment processes, while detailed changes in each physicochemical parameter are presented in the following sections.

Table 1. Physicochemical characteristics of tapioca industrial wastewater before and after treatment

Parameter	**Unit**	**Before Treatment**	**Aeration**	**Coagulation**	**Integrated Aeration–Coagulation**
Total Dissolved Solids (TDS)	mg/L	846	395	675	452
Total Suspended Solids (TSS)	mg/L	0.7938	0.8005	0.8006	0.8020
pH	–	6.85	6.84	6.01	6.62
Dissolved Oxygen (DO)	mg/L	10.5	12.7	12.9	24.6
Temperature	°C	27.0	28.7	28.3	28.3
Ammonia	mg/L	20	10	10	10
Turbidity	NTU	19.53	14.92	3.47	2.95

Changes in Total Dissolved Solids (TDS)

The changes in Total Dissolved Solids (TDS) following wastewater treatment are illustrated in Figure 2, while the corresponding numerical values are summarized in Table 1. Before treatment, the wastewater contained a TDS concentration of 846 mg/L, representing the highest dissolved solid content measured during the experiment. Among the three treatment methods, aeration produced the greatest reduction in TDS, decreasing the concentration to 395 mg/L. This reduction corresponds to approximately 53.3% of the initial concentration, representing the lowest TDS value obtained among all investigated treatments. The integrated aeration–coagulation treatment also substantially reduced TDS, reaching 452 mg/L, which corresponds to a reduction of approximately 46.6% relative to the untreated wastewater. In comparison, coagulation alone produced a more moderate decrease, reducing TDS from 846 mg/L to 675 mg/L, equivalent to approximately 20.2%. Although differences were observed among treatment methods, all final TDS concentrations remained considerably below the maximum permissible limit of 2000 mg/L established by the applicable wastewater quality standard. The comparative results indicate that both aeration and integrated aeration–coagulation treatments were more effective in reducing dissolved solids than coagulation alone. Furthermore, the relatively small difference between aeration and the integrated treatment suggests that both approaches substantially improved dissolved solid removal under the investigated experimental conditions. The overall trend observed in Figure 2 confirms that all treatment methods successfully reduced dissolved solids, with aeration exhibiting the highest reduction efficiency among the evaluated processes.

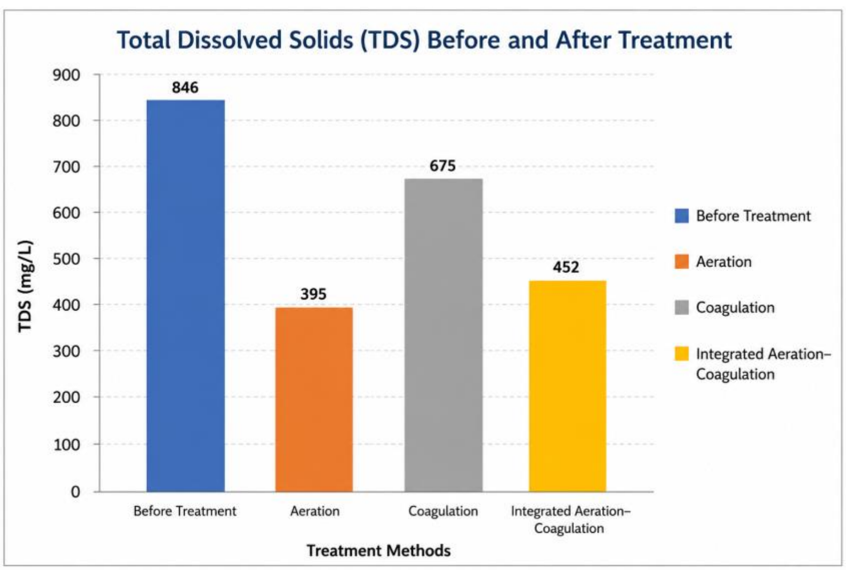

Figure 2. Total Dissolved Solids (TDS) before and after aeration, coagulation, and integrated aeration coagulation treatments.

Changes in Total Suspended Solids (TSS)

The changes in Total Suspended Solids (TSS) following wastewater treatment are summarized in Table 1. Prior to treatment, the wastewater exhibited a TSS concentration of 0.7938 mg/L. Following aeration, coagulation, and integrated aeration–coagulation treatments, the measured

TSS concentrations were 0.8005 mg/L, 0.8006 mg/L, and 0.8020 mg/L, respectively. Compared with the untreated wastewater, only slight variations in TSS values were observed among the investigated treatment methods. The measured concentrations remained relatively constant throughout the experimental treatments, with differences of less than 0.01 mg/L among the three treatment processes. Furthermore, all measured TSS values were substantially lower than the applicable wastewater quality standard of 200 mg/L. The relatively consistent TSS concentrations indicate that suspended solid levels remained within environmentally acceptable limits throughout the experimental period. Although differences among treatments were minimal, the measured values demonstrate that all treatment methods maintained satisfactory suspended solid concentrations after treatment. The consistency observed in TSS measurements suggests that the investigated treatment processes did not adversely affect suspended solid concentrations. Overall, the results presented in Table 1 indicate that all wastewater samples satisfied the regulatory requirement for Total Suspended Solids after treatment.

Changes in pH

The pH values of tapioca industrial wastewater before and after treatment are presented in Table 1. Before treatment, the wastewater exhibited a pH value of 6.85, indicating slightly acidic conditions while remaining within the acceptable wastewater quality range. Following aeration treatment, the pH remained nearly unchanged at 6.84, representing the smallest variation among the investigated treatment methods. Coagulation treatment produced the lowest pH value of 6.01, whereas the integrated aeration–coagulation process resulted in a pH of 6.62. Despite these differences, all measured pH values remained within the regulatory range of 6–9 established for industrial wastewater discharge. The variation observed among treatment methods did not exceed one pH unit, indicating relatively stable wastewater acidity throughout the experiment. Among the investigated treatments, coagulation generated the greatest decrease in pH, while aeration maintained the initial wastewater condition more consistently. The integrated treatment produced an intermediate pH value between those obtained after aeration and coagulation. Overall, the results demonstrate that all treatment methods maintained wastewater pH within the permissible environmental standard after treatment.

Changes in Dissolved Oxygen (DO)

The dissolved oxygen (DO) concentrations measured before and after wastewater treatment are presented in Table 1, while the overall trend is illustrated in Figure 3. Untreated wastewater exhibited an initial dissolved oxygen concentration of 10.5 mg/L. Following aeration treatment, the DO concentration increased to 12.7 mg/L, corresponding to an increase of approximately 20.9% relative to the untreated wastewater. Coagulation treatment produced a comparable result, increasing the dissolved oxygen concentration to 12.9 mg/L, equivalent to an improvement of approximately 22.9%. The integrated aeration–coagulation treatment produced the highest dissolved oxygen concentration of 24.6 mg/L, representing an increase of approximately 134.3% compared with the initial wastewater condition. This value was nearly twice that observed after either aeration or coagulation applied individually. All measured dissolved oxygen concentrations exceeded the minimum wastewater quality requirement of 4 mg/L, indicating satisfactory oxygen availability following treatment. Among the investigated treatment methods, the integrated process exhibited the highest dissolved oxygen concentration, whereas aeration and coagulation produced relatively similar improvements. The comparative trend presented in Figure 3 clearly demonstrates the superior performance of the integrated aeration–coagulation treatment in increasing dissolved oxygen concentration under the investigated experimental conditions.

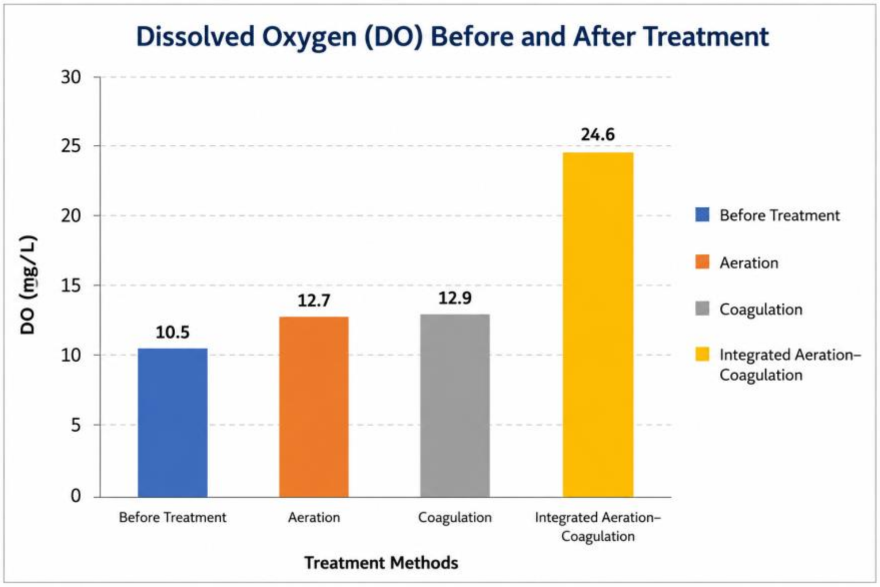

Figure 3. Dissolved Oxygen (DO) concentration before and after aeration, coagulation, and integrated aeration–coagulation treatments.

Changes in Temperature

Wastewater temperature before and after treatment is summarized in Table 1. The untreated wastewater exhibited an initial temperature of 27.0°C. Following aeration treatment, the temperature increased slightly to 28.7°C, while coagulation and integrated aeration–coagulation treatments both resulted in temperatures of 28.3°C. The observed temperature increases ranged from 1.3°C to 1.7°C relative to the untreated wastewater. Despite these slight increases, all measured temperatures remained below the maximum allowable wastewater discharge limit of 30°C. The temperature differences among treatment methods were relatively small, with a maximum difference of only 0.4°C. These observations indicate that all treatment processes maintained wastewater temperature within acceptable environmental limits throughout the experiment. Overall, temperature remained relatively stable regardless of the treatment method applied.

Changes in Ammonia Concentration

The ammonia concentrations before and after wastewater treatment are presented in Table 1. Prior to treatment, the wastewater contained an ammonia concentration of 20 mg/L, indicating the presence of nitrogenous compounds that require treatment before environmental discharge. Following aeration treatment, the ammonia concentration decreased to 10 mg/L, representing a

50% reduction relative to the untreated wastewater. A similar reduction was observed after coagulation treatment, with the final ammonia concentration also reaching 10 mg/L. Likewise, the integrated aeration–coagulation treatment reduced ammonia concentration to 10 mg/L, producing the same final concentration as the individual treatment methods. Although all investigated treatments achieved identical final ammonia concentrations, each treatment successfully reduced ammonia to the maximum allowable concentration specified by the applicable wastewater quality standard. The uniform reduction observed across all treatments indicates that ammonia concentration decreased consistently following wastewater treatment. Furthermore, the treated wastewater satisfied the environmental discharge requirement of ≤10 mg/L, demonstrating compliance with the applicable wastewater quality regulation. The comparative results indicate that no substantial differences were observed among the investigated treatment methods with respect to the final ammonia concentration. Overall, all treatment processes effectively reduced ammonia concentration to the acceptable regulatory limit under the investigated experimental conditions.

Changes in Turbidity

The turbidity values before and after wastewater treatment are summarized in Table 1, while the comparative trend is illustrated in Figure 4. The untreated wastewater exhibited an initial turbidity of 19.53 NTU, indicating the presence of suspended particles that reduced water clarity. Following aeration treatment, turbidity decreased to 14.92 NTU, corresponding to a reduction of approximately 23.6% relative to the untreated wastewater. Coagulation treatment produced a considerably greater reduction, decreasing turbidity to 3.47 NTU, equivalent to an approximate 82.2% reduction. The integrated aeration–coagulation treatment achieved the lowest turbidity value of 2.95 NTU, corresponding to an approximate 84.9% reduction compared with the initial wastewater condition. Among the investigated treatment methods, the integrated treatment produced the greatest reduction in turbidity, followed closely by coagulation alone. In contrast, aeration exhibited a more moderate reduction in turbidity than the coagulation-based treatments. Nevertheless, all treated wastewater samples exhibited turbidity values well below the applicable wastewater quality standard of 25 NTU, indicating satisfactory clarification following treatment. The comparative trend presented in Figure 4 clearly demonstrates the superior turbidity reduction achieved by the integrated aeration–coagulation treatment under the investigated experimental conditions. Overall, the results indicate that all treatment methods improved wastewater clarity, with the integrated treatment exhibiting the highest overall performance.

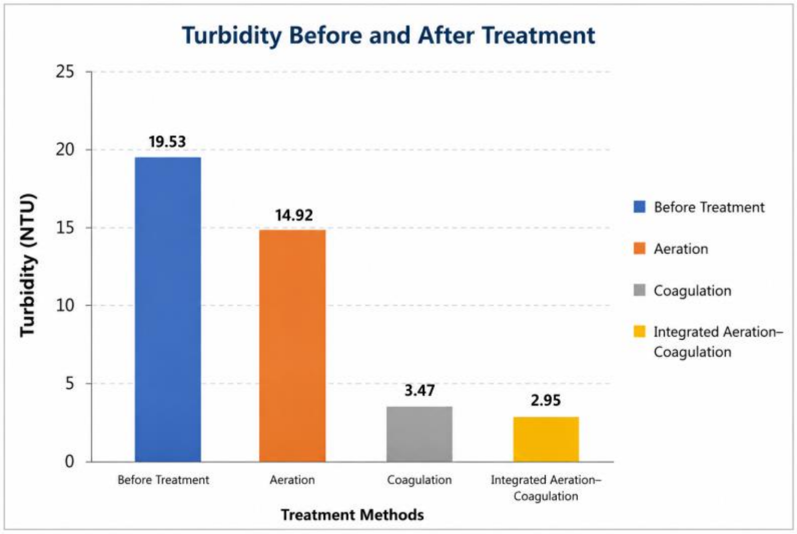

Figure 4. Turbidity before and after aeration, coagulation, and integrated aeration–coagulation treatments.

Summary of Experimental Findings

The comparative evaluation of aeration, coagulation, and integrated aeration–coagulation treatments demonstrated that each treatment method improved the physicochemical quality of tapioca industrial wastewater to varying degrees. As summarized in Table 1, aeration achieved the greatest reduction in Total Dissolved Solids (TDS), decreasing the concentration from 846 mg/L to 395 mg/L, whereas the integrated treatment reduced TDS to 452 mg/L. In contrast, the integrated aeration–coagulation process exhibited the highest dissolved oxygen concentration, increasing DO from 10.5 mg/L to 24.6 mg/L, while aeration and coagulation individually increased DO to 12.7 mg/L and 12.9 mg/L, respectively. Ammonia concentration decreased uniformly from 20 mg/L to 10 mg/L following all treatment methods, indicating consistent nitrogen reduction performance across the investigated treatments. Turbidity exhibited the greatest improvement following the integrated treatment, decreasing from 19.53 NTU to 2.95 NTU, whereas coagulation alone reduced turbidity to 3.47 NTU and aeration to 14.92 NTU. Throughout the experiment, pH remained within the regulatory range of 6–9, while wastewater temperature remained below 30°C, indicating stable physicochemical conditions after treatment. Total Suspended Solids (TSS) also remained well below the regulatory limit during all treatment processes. Collectively, these findings demonstrate that all treatment methods successfully improved wastewater quality and achieved compliance with the applicable environmental standards. Among the investigated treatments, the integrated aeration–coagulation process exhibited the most balanced performance by simultaneously improving multiple physicochemical parameters. The detailed implications and scientific interpretation of these findings are discussed in the following section.

Discussion

The findings of this study demonstrate that aeration, coagulation, and integrated aeration–coagulation treatments all contributed to improving the physicochemical quality of tapioca industrial wastewater, although their effectiveness differed depending on the evaluated parameter. The integrated aeration–coagulation process exhibited the most balanced performance by simultaneously improving dissolved oxygen concentration, reducing turbidity, and lowering ammonia concentration while maintaining all measured parameters within the applicable wastewater quality standards. These findings suggest that combining biological and physicochemical treatment mechanisms provides broader pollutant removal capability than applying either treatment individually (Liu et al., 2026; Loganathan et al., 2023; N Lotha et al., 2024). The complementary performance observed in the integrated treatment is consistent with the concept of hybrid wastewater treatment systems, in which different removal mechanisms operate simultaneously to enhance overall treatment efficiency. Biological oxidation primarily targets biodegradable organic compounds, whereas coagulation effectively destabilizes suspended and colloidal particles, allowing both processes to complement one another during wastewater treatment (Abderrezzaq et al., 2024; Aragaw & Bogale, 2023; Ouadrhiri et al., 2025). Such complementary interactions explain why the integrated treatment produced improvements across several physicochemical parameters rather than only one specific indicator. Similar observations have been reported in previous studies demonstrating that integrated wastewater treatment systems generally outperform single-treatment processes because they combine multiple pollutant removal pathways (Asheghmoalla & Mehrvar, 2024; Gkika et al., 2026; Saadi et al., 2026). Recent developments in environmental engineering have increasingly emphasized hybrid treatment technologies as practical alternatives for improving wastewater quality while maintaining operational simplicity and cost efficiency. The present findings therefore strengthen previous evidence supporting the integration of conventional treatment technologies for agro-industrial wastewater management. Collectively, these results indicate that integrating aeration and coagulation represents a promising engineering approach for improving the environmental performance of tapioca industrial wastewater treatment.

The substantial reduction in Total Dissolved Solids observed after aeration treatment indicates that biological treatment can effectively improve wastewater quality through enhanced oxygen transfer and microbial activity. Aeration increased dissolved oxygen availability, creating favorable conditions for aerobic microorganisms responsible for degrading dissolved biodegradable compounds within wastewater. This mechanism contributes to reductions in dissolved organic substances, which subsequently influence the measured Total Dissolved Solids concentration. Previous studies have consistently reported that optimized aeration systems improve oxygen transfer efficiency, accelerate organic matter degradation, and enhance the biological stability of industrial wastewater (Jamaludin et al., 2024; Shukla et al., 2025; Skouteris et al., 2020). Advances in aeration technology, including fine-bubble diffusers, membrane-aerated biofilm reactors, and intelligent aeration control systems, have further demonstrated the importance of oxygen availability in improving biological treatment efficiency (He et al., 2021; Kahaduwa et al., 2026). Although the present study employed a conventional aeration system, the observed reduction in dissolved solids supports previous findings regarding the effectiveness of oxygen enrichment in biological wastewater treatment. Compared with coagulation, aeration achieved greater TDS reduction, suggesting that dissolved pollutants present in tapioca wastewater are more responsive to biological oxidation than physicochemical particle removal alone. Nevertheless, aeration produced only moderate improvements in turbidity because suspended particles cannot be completely removed through biological oxidation processes. This observation agrees with previous investigations indicating that aeration alone is generally insufficient for removing colloidal particles and therefore often requires complementary physicochemical treatment processes. Consequently, the present findings reinforce the role of aeration as an essential biological treatment process while also highlighting the need for integration with other technologies to achieve comprehensive wastewater purification.

The coagulation treatment demonstrated superior performance in reducing wastewater turbidity compared with aeration, indicating that physicochemical particle destabilization remains highly effective for removing suspended materials from tapioca industrial wastewater. Coagulant addition promotes charge neutralization and floc formation, enabling fine suspended particles to aggregate into larger particles that can be separated more efficiently during sedimentation. This mechanism explains the substantial reduction in turbidity observed after coagulation treatment and the further improvement obtained when coagulation was integrated with aeration. Similar results have been reported in numerous studies evaluating aluminum sulfate and other chemical coagulants for industrial wastewater treatment, where significant reductions in turbidity and suspended solids were consistently achieved (Adebayo et al., 2021; Sibiya et al., 2022; Tsoutsa et al., 2024). Recent investigations have also shown that coagulation performance depends on several operational factors, including coagulant dosage, wastewater pH, mixing intensity, settling time, and wastewater composition. Although coagulation effectively removed suspended particles, its influence on dissolved pollutants was less pronounced than that of aeration, reflecting the different pollutant removal mechanisms associated with physicochemical treatment. This finding is consistent with previous reports indicating that coagulation primarily targets particulate contaminants rather than dissolved biodegradable organic compounds (Knap-Bałdyga & Żubrowska-Sudoł, 2023; Saxena et al., 2020). Consequently, coagulation alone may not provide sufficient treatment efficiency for wastewater containing high concentrations of dissolved organic matter, such as tapioca industrial wastewater. The improved performance observed in the integrated treatment suggests that combining coagulation with biological oxidation allows each process to compensate for the limitations of the other. Therefore, the present study provides additional evidence that coagulation remains an indispensable component of integrated wastewater treatment systems designed to improve multiple physicochemical water quality parameters simultaneously.

The superior performance of the integrated aeration–coagulation treatment observed in this study highlights the synergistic interaction between biological oxidation and physicochemical separation during wastewater treatment. Aeration increases dissolved oxygen availability and stimulates aerobic microbial metabolism, whereas coagulation destabilizes suspended particles through charge neutralization and floc formation, allowing contaminants that cannot be efficiently removed by biological treatment alone to be separated more effectively. The simultaneous improvement in dissolved oxygen concentration, turbidity reduction, and ammonia removal observed in the integrated treatment demonstrates that combining complementary treatment mechanisms can enhance the overall treatment efficiency beyond that achieved by individual processes. Similar synergistic effects have been reported in integrated wastewater treatment systems combining biological, physicochemical, membrane, or advanced oxidation technologies, where pollutant removal efficiencies were consistently higher than those obtained using single-treatment approaches (Saadi et al., 2026; Seifi et al., 2025; Yang et al., 2022). However, many previous investigations have focused on sophisticated hybrid technologies requiring relatively high investment costs and complex operational control, limiting their applicability in small- and medium-scale agro-industries (Divate et al., 2026; Melas et al., 2025; Teixeira et al., 2025). In contrast, the integrated aeration–coagulation process evaluated in the present study utilizes conventional treatment technologies that are technically simple, economically feasible, and relatively easy to implement under practical industrial conditions. This practical characteristic represents an important advantage for tapioca processing industries, particularly in developing countries where financial and technological resources may be limited. Furthermore, the present findings demonstrate that substantial improvements in wastewater quality can be achieved without employing highly advanced treatment technologies, provided that complementary treatment mechanisms are appropriately integrated. Therefore, the novelty of this study lies not only in the comparative evaluation of aeration, coagulation, and integrated aeration–coagulation under identical operational conditions, but also in demonstrating that the integration of two conventional treatment methods can produce balanced improvements across multiple physicochemical wastewater quality parameters. These findings provide additional scientific evidence supporting the application of integrated conventional treatment systems as practical alternatives for sustainable wastewater management in agro-industrial sectors.

From an environmental engineering perspective, the findings of this study provide important implications for improving wastewater treatment strategies within the tapioca processing industry. The successful reduction of dissolved solids, ammonia concentration, and turbidity, together with the substantial increase in dissolved oxygen concentration, indicates that integrated treatment systems can simultaneously address several critical indicators of wastewater quality. Such improvements are expected to reduce the environmental risks associated with untreated industrial wastewater, including oxygen depletion, eutrophication, excessive suspended solids, and deterioration of aquatic ecosystem functions. Compliance with applicable wastewater quality standards further demonstrates the feasibility of implementing integrated aeration–coagulation treatment as an environmentally responsible wastewater management strategy. In addition to environmental benefits, the use of conventional aeration and coagulation technologies offers practical advantages because both processes are already widely available in industrial wastewater treatment facilities and do not require sophisticated operational expertise. Consequently, the proposed treatment approach may be adopted by small- and medium-scale tapioca industries seeking cost-effective solutions for wastewater quality improvement. The comparative evaluation presented in this study also provides useful technical information for engineers and environmental managers when selecting wastewater treatment technologies based on target pollutant characteristics and operational objectives. Although the present investigation focused on physicochemical water quality parameters, future studies should incorporate additional indicators such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), microbial populations, sludge characteristics, and long-term operational performance to obtain a more comprehensive assessment of treatment efficiency. Economic evaluation, life-cycle assessment, and process optimization should also be considered in future research to strengthen the practical applicability of integrated wastewater treatment systems under industrial operating conditions. Overall, this study contributes to the growing body of knowledge on sustainable industrial wastewater treatment by providing experimental evidence that supports the integration of conventional biological and physicochemical processes as an effective and practical approach for improving the quality of tapioca industrial wastewater.

Implication

The findings of this study provide important theoretical and practical implications for the development of sustainable industrial wastewater treatment technologies in the agro-processing sector. From a scientific perspective, the study demonstrates that integrating biological and physicochemical treatment processes can achieve more balanced improvements across multiple physicochemical wastewater quality parameters than applying individual treatment methods alone. The comparative evaluation also enriches the existing body of knowledge by providing experimental evidence on the relative performance of aeration, coagulation, and integrated aeration–coagulation under identical operational conditions, thereby supporting future comparative studies in industrial wastewater treatment. The results further confirm that conventional treatment technologies remain highly relevant when appropriately integrated to maximize pollutant removal efficiency without requiring sophisticated treatment systems. From an engineering perspective, the integrated aeration–coagulation process offers a practical and technically feasible alternative for improving wastewater quality in tapioca processing industries, particularly for small- and medium-scale enterprises with limited financial and technological resources. The substantial improvements in dissolved oxygen concentration, turbidity, ammonia concentration, and dissolved solids indicate that the proposed treatment strategy can contribute to more effective compliance with environmental discharge standards. The implementation of this integrated treatment approach may also reduce the environmental risks associated with untreated industrial effluents, including deterioration of water quality, oxygen depletion, and ecosystem degradation. In addition, the study provides valuable technical information that can assist environmental engineers, wastewater treatment operators, and industrial managers in selecting treatment technologies according to specific wastewater characteristics and operational objectives. The comparative dataset generated in this research may also serve as a useful reference for optimizing conventional wastewater treatment systems through the integration of complementary treatment mechanisms. Furthermore, the findings support current efforts toward cleaner production and sustainable wastewater management by promoting efficient resource utilization through relatively simple treatment technologies. The study also provides an empirical foundation for future research investigating process optimization, operational scaling, and integration with other environmentally friendly treatment technologies. Overall, this research contributes to advancing sustainable wastewater treatment practices by demonstrating that integrated aeration–coagulation represents an effective, practical, and environmentally responsible solution for improving the physicochemical quality of tapioca industrial wastewater while supporting long-term environmental sustainability and industrial compliance.

Limitation and Suggestion for Further Research

This study has several limitations that should be considered when interpreting the findings and planning future investigations. First, the experimental evaluation was conducted using wastewater samples collected from a single tapioca processing industry, which may limit the generalizability of the results to other industries with different production processes and wastewater characteristics. Second, the assessment focused exclusively on selected physicochemical parameters, including Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Dissolved Oxygen (DO), temperature, ammonia concentration, and turbidity, without evaluating other important indicators such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), total nitrogen, total phosphorus, microbial populations, or sludge characteristics. Third, the study investigated treatment performance under a single operational configuration without examining the influence of key process variables such as aeration duration, airflow rate, coagulant dosage, mixing intensity, sedimentation time, or hydraulic retention time on treatment efficiency. Furthermore, no statistical optimization or predictive modeling was performed to determine the optimal operating conditions for the integrated treatment process. The economic feasibility, operational cost, energy consumption, and life-cycle environmental impacts of the proposed treatment system were also beyond the scope of this study. In addition, the experimental investigation was conducted at a laboratory scale, and therefore the performance of the integrated aeration–coagulation process under continuous industrial operating conditions remains to be validated. Future research should investigate the optimization of operational parameters using statistical experimental designs such as Response Surface Methodology (RSM) or Design of Experiments (DOE) to maximize treatment efficiency. Subsequent studies are also encouraged to evaluate additional physicochemical, biological, and microbiological indicators to obtain a more comprehensive understanding of wastewater treatment performance. Moreover, pilot-scale and full-scale validation studies should be conducted to assess the long-term operational stability, scalability, and practical applicability of the integrated treatment system in industrial environments. Future investigations should further compare integrated aeration–coagulation with emerging treatment technologies, including electrocoagulation, membrane filtration, advanced oxidation processes, and nature-based treatment systems, to identify the most efficient and sustainable treatment strategy. Collectively, these future research directions will strengthen the scientific foundation and practical implementation of integrated wastewater treatment technologies while supporting the development of environmentally sustainable management systems for tapioca industrial wastewater.

CONCLUSION

This study comparatively evaluated the performance of aeration, coagulation, and integrated aeration–coagulation processes in improving the physicochemical quality of tapioca industrial wastewater. The experimental results demonstrated that all treatment methods contributed to measurable improvements in wastewater quality, although the degree of effectiveness varied among the evaluated physicochemical parameters. Aeration achieved the greatest reduction in Total Dissolved Solids (TDS), while coagulation exhibited substantial effectiveness in reducing turbidity through the removal of suspended particles. The integrated aeration–coagulation treatment demonstrated the most balanced overall performance by simultaneously increasing dissolved oxygen concentration and reducing ammonia concentration, turbidity, and dissolved solids to environmentally acceptable levels. All treated wastewater samples complied with the applicable wastewater quality standards, indicating that the investigated treatment methods were capable of improving wastewater quality prior to environmental discharge. These findings confirm that integrating biological and physicochemical treatment mechanisms can provide broader pollutant removal capability than applying either treatment process individually. The comparative evaluation also demonstrates that conventional treatment technologies remain highly effective when appropriately integrated under identical operational conditions. From an engineering perspective, the integrated aeration–coagulation process represents a technically feasible, operationally simple, and economically practical alternative for wastewater treatment in the tapioca processing industry. The study contributes to the existing knowledge by providing experimental evidence regarding the comparative performance of three conventional treatment strategies using multiple physicochemical indicators within a single evaluation framework. Furthermore, the findings provide valuable technical information that can support engineers, environmental practitioners, and industrial managers in selecting wastewater treatment technologies according to treatment objectives and wastewater characteristics. The integrated treatment approach also supports cleaner production practices by improving wastewater quality through environmentally responsible and sustainable treatment processes. Overall, this study demonstrates that integrated aeration–coagulation is an effective and promising strategy for enhancing the physicochemical quality of tapioca industrial wastewater while contributing to the advancement of sustainable industrial wastewater management and environmental protection.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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