


Performance of a combined activated carbon and *Pistia stratiotes* system for sago wastewater treatment

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ABSTRACT

Sago wastewater poses a significant environmental concern due to its high organic load and nutrient content. This study evaluated the performance of a hybrid wastewater treatment system combining activated carbon and *Pistia stratiotes* for the treatment of sago-processing effluent. The hypothesis that integrating adsorption and phytoremediation processes would enhance pollutant removal compared to single-media systems was tested, with particular emphasis on identifying an optimal media composition. A laboratory-scale gravity-driven downflow filtration system was operated under batch conditions with a detention time of four days. Treatment variations included different ratios of activated carbon and *Pistia stratiotes* (100:0, 75:25, 50:50, 25:75, and 0:100), along with a control unit. The findings demonstrated substantial improvements in wastewater quality across all treatment configurations, with the 75:25 activated carbon to *Pistia stratiotes* ratio showing the highest overall performance. In this configuration, BOD₅ decreased from 56.1 mg/L to 8.7 mg/L, COD from 72.3 mg/L to 10.96 mg/L, and phosphate from 4.04 mg/L to 0.006 mg/L, while pH remained stable and close to neutral. These results confirm a strong synergistic interaction between adsorption processes driven by activated carbon and nutrient uptake and microbial activity associated with *Pistia stratiotes*. In contrast, plant-dominated systems exhibited lower efficiency and indications of reduced stability, including potential nutrient re-release. The study is limited by its short-term batch design, which does not capture long-term operational stability, seasonal variability, or continuous-flow behavior. Nevertheless, the system demonstrates strong practical potential as a low-cost and low-energy treatment option for decentralized wastewater management in small-scale sago-processing industries. The main contribution of this work lies in identifying a non-linear relationship between treatment composition and performance, indicating that an optimal balance between adsorption and phytoremediation yields superior results and provides a practical framework for hybrid wastewater treatment design.

Keywords: sago wastewater, activated carbon, *Pistia stratiotes*, filtration system, wastewater treatment efficiency.

INTRODUCTION

Sago (*Metroxylon* sp.) is a vital carbohydrate source that plays an important role in food security and local economies in Indonesia, particularly in regions such as Papua, Maluku, Sulawesi, and Kalimantan (Sumaryono et al., 2012; Dewayani et al., 2022). The increasing demand for sago products has led to the expansion

of small-scale processing industries, especially in rural areas where traditional methods are still widely used. However, these processing activities generate substantial volumes of wastewater with minimal or no treatment prior to discharge. This condition poses a serious environmental concern, particularly in regions with limited wastewater management infrastructure. As a result, untreated sago wastewater is frequently

released into nearby water bodies, contributing to environmental degradation. The issue is further exacerbated by the lack of awareness and accessible low-cost treatment technologies among local communities. Therefore, the management of sago wastewater has become a critical environmental challenge that requires appropriate and sustainable solutions.

Sago wastewater is characterized by high concentrations of organic matter, suspended solids, and nutrients, which significantly affect water quality and aquatic ecosystems (Niju et al., 2025; Thangavelu et al., 2022; Annisa et al., 2025). Elevated levels of biological oxygen demand (BOD), chemical oxygen demand (COD), and phosphate can lead to oxygen depletion, eutrophication, and ecological imbalance (Lv et al., 2024; Singh, 2024; Alimuddin et al., 2026). Previous studies reported that sago wastewater may contain extremely high COD and TSS concentrations, indicating a heavy pollution load (Doraisamy et al., 2013; Nururrahmah et al., 2018). If discharged untreated, such wastewater can disrupt aquatic life and reduce the usability of water resources for domestic and agricultural purposes. These environmental impacts highlight the urgent need for effective wastewater treatment strategies. Consequently, developing efficient and practical treatment methods for sago wastewater is essential to mitigate its adverse environmental effects.

Filtration is one of the most widely applied methods in wastewater treatment due to its simplicity, cost-effectiveness, and ability to remove suspended and dissolved pollutants (Mutegoa, 2024; Ayach et al., 2024; Rahaman et al., 2024; Abdullahi et al., 2024). The efficiency of filtration systems is influenced by factors such as media type, flow rate, particle size, and system configuration (Tian et al., 2021). Conventional filtration techniques primarily rely on physical processes, which may not be sufficient to remove dissolved organic and nutrient pollutants. Therefore, there is a growing need to integrate physical, chemical, and biological mechanisms to enhance treatment performance. Recent advancements emphasize the use of multifunctional filtration media to improve pollutant removal efficiency. This integrated approach is considered more suitable for complex wastewater such as that generated from sago processing.

Activated carbon has been extensively used as an effective adsorbent in wastewater treatment due to its high surface area, porosity, and strong

adsorption capacity (Raninga et al., 2023; Devi et al., 2023; Barczak et al., 2023). It is particularly effective in removing organic compounds, color, odor, and dissolved pollutants through adsorption mechanisms (Wang et al., 2023; Du et al., 2024). Furthermore, activated carbon derived from locally available materials, such as coconut shells, offers a sustainable and economically feasible solution (Saleem et al., 2025). Studies have shown that activated carbon can significantly reduce BOD, COD, and total suspended solids (TSS) in wastewater (Aritonang et al., 2025). However, adsorption processes alone may experience limitations due to saturation of adsorption sites and reduced efficiency over time. Therefore, combining activated carbon with complementary treatment methods is necessary to achieve optimal performance.

In addition to physicochemical methods, biological treatment using aquatic plants has gained considerable attention due to its environmentally friendly and sustainable characteristics. Phytoremediation utilizes the natural ability of plants to absorb, accumulate, and transform pollutants from water (Abonyi et al., 2024; Kristanti and Hadibarata, 2023). Aquatic plants such as *Pistia stratiotes* have demonstrated high potential in removing nutrients, organic matter, and even heavy metals from wastewater (Ali et al., 2024; Chedadi et al., 2024). The extensive root system of these plants enhances filtration and provides a habitat for microbial activity, which further contributes to pollutant degradation (Chaudhry et al., 2005). However, several studies have reported that phytoremediation alone may lead to unstable performance, particularly due to plant decay and nutrient release back into the water. This limitation indicates that biological treatment requires integration with other processes to ensure consistent efficiency.

Despite the widespread application of activated carbon and aquatic macrophytes in wastewater treatment, their combined application in a simple gravity-driven filtration system specifically designed for sago wastewater remains insufficiently explored. In particular, the interaction mechanisms between adsorption and phytoremediation processes under different media compositions have not been clearly quantified.

This study introduces a novel hybrid configuration integrating activated carbon and *Pistia stratiotes* within a single downflow filtration system, specifically adapted for small-scale sago wastewater treatment. Unlike previous studies

that treat these methods separately, this research systematically evaluates the synergistic interaction between physicochemical adsorption and biological uptake under controlled media ratios. It is hypothesized that the combined system will produce a non-linear enhancement in pollutant removal efficiency due to synergistic interactions between adsorption processes and plant–microbe activity, and that an optimal media ratio exists which maximizes treatment performance beyond the capability of individual components. Therefore, this study aims not only to evaluate treatment performance but also to identify the optimal configuration and demonstrate the existence of synergistic effects within the hybrid system.

Despite the growing interest in adsorption and phytoremediation technologies, existing studies predominantly examine these approaches separately or apply them to general domestic and industrial wastewater. Limited research has specifically addressed the treatment of sago wastewater, particularly under controlled hybrid filtration systems that integrate both adsorption and biological processes. Furthermore, the interaction mechanisms between activated carbon and *Pistia stratiotes*, as well as the existence of an optimal composition that maximizes treatment efficiency, remain insufficiently understood. Most previous studies also lack a systematic evaluation of how varying media ratios influence pollutant removal performance, thereby leaving a critical knowledge gap regarding the design of optimized hybrid treatment systems.

Therefore, the scientific purpose of this study is to investigate the performance and interaction mechanisms of a combined activated carbon and *Pistia stratiotes* system for sago wastewater treatment and to identify the optimal media composition that yields maximum pollutant removal efficiency. This study aims to generate new insights into the existence of a non-linear relationship between adsorption and phytoremediation processes in hybrid systems. The underlying hypothesis is that integrating activated carbon and *Pistia stratiotes* will produce a synergistic effect that enhances pollutant removal beyond the performance of single-media systems, and that an intermediate ratio will result in superior efficiency compared to extreme compositions. By addressing these aspects, this study seeks to fill the gap in current knowledge regarding the optimization and functional integration of natural–engineered wastewater treatment systems, particularly for agro-industrial effluents such as sago wastewater.

This approach moves beyond conventional empirical testing by aiming to establish a conceptual understanding of hybrid system optimization for sustainable wastewater treatment.

MATERIALS AND METHOD

Study area

This study was conducted from May to November 2025 in Kamarian Village, Kairatu District, West Seram Regency, Maluku Province, Indonesia (3°23′–3°25′ S; 128°20′–128°23′ E). The site represents a typical rural sago-processing area where wastewater is generated from traditional processing activities and is often discharged directly into the surrounding environment without prior treatment.

The selection of this study area was based on its high local sago production intensity, the absence of centralized wastewater treatment infrastructure, and its representativeness of small-scale agro-industrial effluent conditions commonly found in eastern Indonesia. These characteristics make the site highly relevant for evaluating low-cost and decentralized wastewater treatment technologies.

Climatically, the study area is characterized by a tropical humid climate with relatively stable temperatures ranging from 25 to 32 °C throughout the year. During the study period (May–November), the region experienced moderate to high rainfall, with a transition from the early dry season to the wet season, which may influence wastewater characteristics through dilution and variability in organic load. Hydrologically, the area is influenced by shallow surface water systems and small streams that are directly impacted by wastewater discharge from sago processing activities. The geographical location and experimental context of the study area are illustrated in Figure 1.

Materials and equipment

Wastewater samples were collected from three household-scale sago processing units located in Kamarian Village, Kairatu District, West Seram Regency. The samples were taken directly from the discharge outlet of the processing units, where wastewater is released into open drainage channels without prior treatment.

Activated carbon was produced from coconut shell biomass, which is locally abundant in the study area. The raw material was subjected to

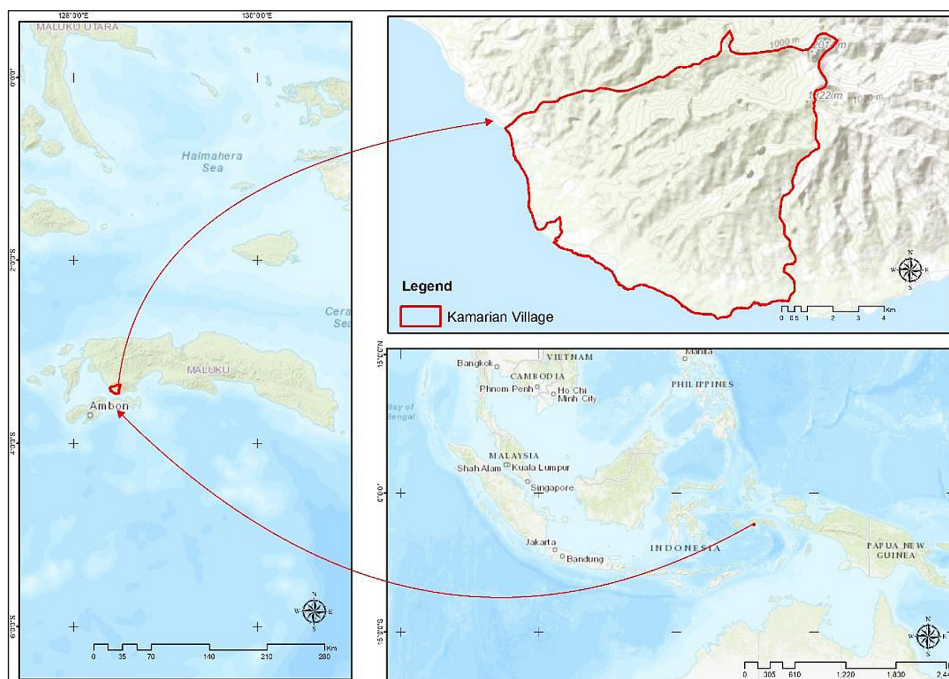


Figure 1. Research location

pyrolysis at a temperature of 450 °C for 2 hours, followed by chemical activation using hydrochloric acid (HCl) at a concentration of 0.1 M with an impregnation ratio of 1:2 (acid to biomass, w/w). The activated carbon was then washed with distilled water until neutral pH and oven-dried at 105 °C for 24 hours. The final particle size ranged between 1–3 mm to ensure effective adsorption and hydraulic performance. The aquatic macrophyte *Pistia stratiotes* was collected from a nearby natural freshwater body and acclimatized for 5 days under ambient environmental conditions (temperature 25–30 °C, natural daylight exposure). Only healthy plants with uniform size and morphology were selected for the experiment. Each filtration reactor consisted of a 25 L transparent polyethylene column with dimensions of approximately 50 cm in height and 20 cm in diameter. The materials used in this study also included hydrochloric acid (HCl, analytical grade, 37% purity) for chemical activation, gravel as a support layer, and standard laboratory equipment for water quality analysis.

Sampling and initial wastewater characterization

Wastewater sampling was conducted using a grab sampling method in accordance with SNI 6989.59:2008. Samples were collected from three discharge points representing household-scale

sago processing units in Kamarian Village. Sampling was carried out in the morning between 08:00 and 10:00 to ensure consistency in wastewater characteristics and operational conditions.

For each sampling point, wastewater samples were collected in duplicate ($n = 2$) using pre-cleaned polyethylene containers. The samples were stored at approximately 4 °C and transported to the laboratory for analysis within 24 hours to minimize physicochemical changes prior to testing.

Initial wastewater characterization included measurements of pH, biological oxygen demand (BOD₅), chemical oxygen demand (COD), nitrate (NO₃⁻), phosphate (PO₄³⁻), and total suspended solids (TSS). All parameters were analyzed in duplicate, and the reported values represent the mean of the measurements.

The mean influent concentrations were as follows: BOD₅ = 56.1 mg/L, COD = 72.3 mg/L, phosphate = 4.04 mg/L, nitrate = 0.03 mg/L, pH = 6.64, and TSS = 205 mg/L. These values indicate moderate to high organic pollution levels, requiring appropriate treatment prior to discharge.

Data availability and quality assurance

To ensure transparency, reproducibility, and data integrity, all analytical and field data generated in this study were systematically documented and archived. The complete raw dataset,

including influent and effluent measurements for all treatment variations and replicates, has been compiled in spreadsheet format (Microsoft Excel/CSV) and is available from the corresponding author upon reasonable request.

Chain-of-custody procedures were implemented during sample collection, transport, and analysis to maintain sample traceability and integrity. Each sample was labeled with a unique identification code, and records were maintained documenting sampling time, location, handling procedures, and laboratory processing stages.

All wastewater samples were preserved and transported under controlled conditions. Samples were stored in pre-cleaned polyethylene containers and maintained at approximately 4 °C during transport. A sample preservation log was recorded, including temperature monitoring and holding times, ensuring that all analyses were conducted within the recommended time limits based on standard methods.

Photographic documentation of the sampling locations, experimental setup, and reactor configurations was also collected to support the reproducibility of the study. These visual records include the sago wastewater discharge points, filtration system assembly, and treatment processes.

Quality assurance and quality control (QA/QC) procedures were applied throughout the analytical process. These included instrument calibration using standard solutions, analysis of blanks, and duplicate measurements to verify analytical accuracy and precision. All laboratory analyses were conducted in accordance with established standard methods to ensure consistency and reliability of the results.

Experimental setup

A laboratory-scale gravity-driven downflow filtration system was constructed to evaluate the performance of the combined treatment media. The system consisted of:

- a 150 L influent storage tank,
- a sedimentation unit with a hydraulic retention time of 6 hours to remove coarse suspended solids, and
- six parallel vertical column reactors (P1–P6).

Each reactor had a working volume of 25 L and was operated under identical hydraulic conditions to ensure comparability between treatment variations. The

treatment configurations were defined as follows:

- P1: 100% activated carbon
- P2: 100% *Pistia stratiotes*
- P3: 50:50 activated carbon : *Pistia stratiotes*
- P4: 75:25 activated carbon : *Pistia stratiotes*
- P5: 25:75 activated carbon : *Pistia stratiotes*
- P6: control (without treatment media).

Each reactor was constructed as a vertical cylindrical column (height: 60 cm; diameter: 25 cm) and arranged in a layered configuration consisting of three main zones: (i) an upper layer containing *Pistia stratiotes* with an average biomass of 500 g (wet weight) per reactor, (ii) a middle layer of activated carbon with a mass of 3 kg per reactor, and (iii) a bottom support layer of gravel with a particle size of 5–10 mm and a thickness of 10 cm to ensure uniform flow distribution. The proportion of treatment media (e.g., 50:50, 75:25) was defined based on the mass ratio between activated carbon and *Pistia stratiotes*. Prior to operation, all media were pre-treated and conditioned by soaking in clean water for 48 hours to stabilize system performance.

The system operated under gravity-driven flow conditions with an average flow rate of 0.26 L/h, corresponding to a hydraulic retention time (HRT) of approximately 4 days. The flow was maintained uniformly across all reactors to minimize hydraulic variability and ensure consistent treatment conditions. The treatment configurations for each reactor are presented in Table 1.

Engineering documentation and hydraulic validation

To ensure engineering reproducibility and experimental transparency, the design, operation, and performance of the filtration system were comprehensively documented. An engineering schematic of the system, illustrating the configuration of the influent tank, sedimentation unit, and vertical

Table 1. Treatment configurations of filtration reactors

No	Reactor	Composition
1	P1	100% activated carbon
2	P2	100% <i>Pistia stratiotes</i>
3	P3	50% activated carbon: 50% <i>Pistia stratiotes</i>
4	P4	75% activated carbon: 25% <i>Pistia stratiotes</i>
5	P5	25% activated carbon: 75% <i>Pistia stratiotes</i>
6	P6	Control (without treatment media)

filtration reactors, is presented in Figure 2. This schematic includes detailed dimensions, flow direction, and material layering within each reactor.

In addition to the schematic diagram, photographic documentation of the experimental setup was obtained during system assembly and operation. These photographs include images of the overall setup, individual reactor columns, media layering, and sampling procedures. Representative images are provided in Figure 2 (a–d) to support visual verification of the experimental configuration.

The flow rate in each reactor was measured and calibrated prior to the experiment using a volumetric method. Specifically, the effluent volume collected over a fixed time interval was recorded repeatedly to determine the average flow rate (L/h). Measurements were conducted in triplicate for each reactor to ensure accuracy, and flow variation between reactors was maintained within $\pm 5\%$ to ensure hydraulic consistency.

Layer thicknesses of each filtration medium were measured using a calibrated ruler during reactor assembly. The thickness of the gravel support layer, activated carbon layer, and *Pistia stratiotes* zone were recorded in centimeters and verified through photographic documentation with scale references. These measurements

ensured uniformity across all reactors and minimized structural variability.

A mass balance approach was applied to quantify the amount of materials used in each reactor. The total mass of activated carbon, biomass of *Pistia stratiotes*, and supporting gravel were measured prior to system setup. These values were used to maintain consistent treatment ratios and to ensure comparability across experimental conditions.

Hydraulic stability of the system was evaluated by monitoring flow rate consistency over the experimental period. Flow measurements were taken at the beginning, midpoint, and end of the operation period. The results indicated stable flow conditions with minimal variation, confirming that the system operated under steady-state hydraulic conditions throughout the treatment duration.

Experimental procedure

The system was operated under batch conditions with a hydraulic retention time (HRT) of 4 days. The experiment was conducted under ambient laboratory conditions, with a temperature range of 27–30 °C. No external aeration, mechanical mixing, or recirculation was applied, allowing

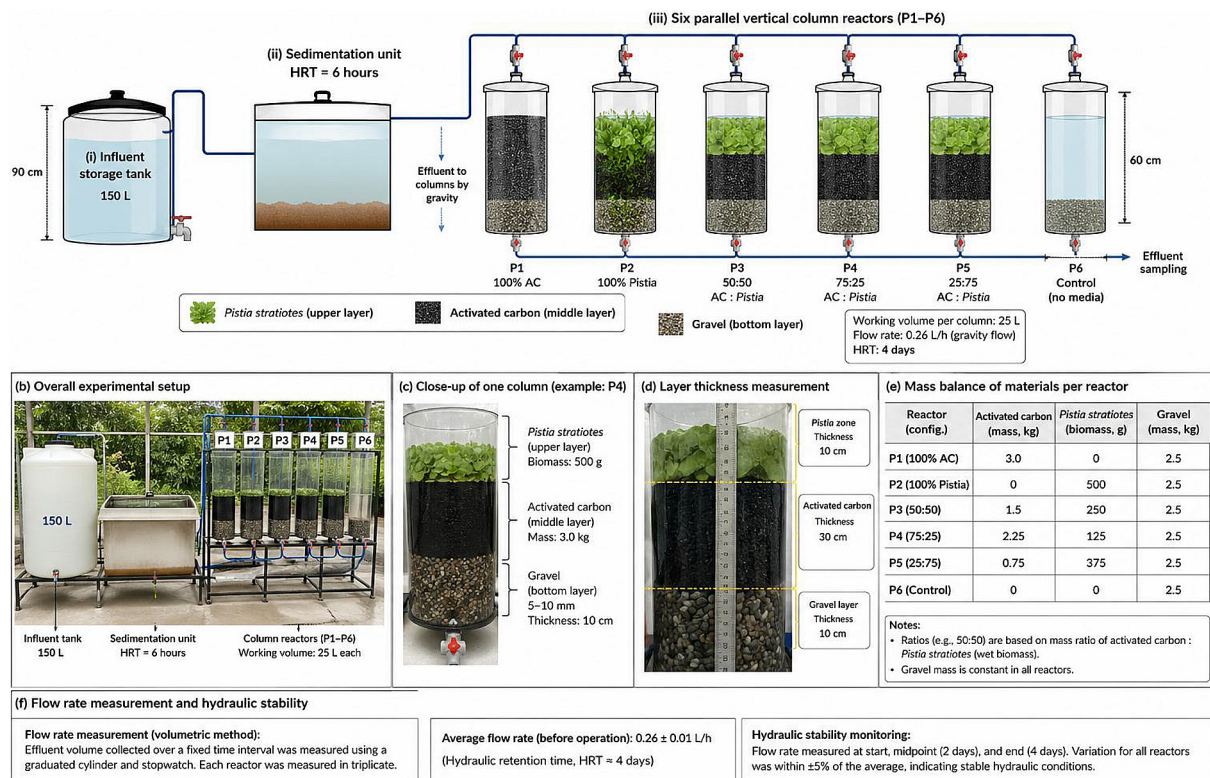


Figure 2. Engineering schematic and experimental setup of the gravity-driven downflow filtration system for sago wastewater treatment

the system to function solely under gravity-driven flow and natural biological processes.

Prior to the experimental run, all reactors were filled simultaneously with pre-settled sago wastewater to ensure consistent initial conditions. The reactors were then operated without disturbance for the entire retention period. Effluent samples of approximately 700 mL were collected from each reactor outlet at the end of the 4-day treatment period for subsequent laboratory analysis.

To ensure reproducibility and statistical reliability, each treatment condition was conducted in triplicate ($n = 3$ independent reactors per treatment), resulting in a total of 18 experimental units. The arrangement of replicate reactors followed an identical configuration and was operated under the same environmental and hydraulic conditions.

An experimental logbook was maintained throughout the study to record daily operational observations, including system conditions, flow consistency, plant health, and any deviations from standard procedures. Environmental conditions such as ambient temperature and relative humidity were also monitored and recorded daily to assess potential influences on system performance.

Photographic and video documentation of the experimental process, including reactor setup, operation, and sampling procedures, was systematically collected to support methodological transparency. In addition, visual documentation of replicate reactor arrangements was obtained to verify consistency across experimental units.

Analytical methods

All water quality parameters were analyzed in accordance with internationally recognized standard methods to ensure accuracy, reliability, and reproducibility of the results. All analyses were performed in triplicate, and the reported values represent the mean of three independent measurements.

The pH was measured using an electrometric method with a digital pH meter (e.g., Hanna Instruments HI 2211, USA), which was calibrated prior to each measurement using standard buffer solutions at pH 4.0, 7.0, and 10.0.

BOD₅ was determined using the 5-day incubation method according to APHA Standard Methods 5210B. Samples were incubated at 20 °C in the dark, and dissolved oxygen was measured before and after incubation.

COD was analyzed using the closed reflux dichromate method (APHA 5220D), followed by

spectrophotometric measurement to determine oxidizable organic content.

Nitrate concentration was measured using the brucine spectrophotometric method, while phosphate concentration was determined using the stannous chloride method. Absorbance readings for both parameters were obtained using a UV–Vis spectrophotometer (e.g., Shimadzu UV-1800, Japan). TSS were determined using the gravimetric method by filtering a known volume of sample through pre-weighed filter paper, followed by drying at 103–105 °C until constant weight was achieved.

Quality assurance and quality control (QA/QC) procedures were implemented throughout the analytical process. These included instrument calibration, analysis of reagent blanks, duplicate samples, and standard reference checks to ensure analytical precision and accuracy.

The limits of detection (LOD) for the analyzed parameters were as follows: pH (± 0.01 units), BOD₅ (2 mg/L), COD (5 mg/L), nitrate (0.01 mg/L), phosphate (0.005 mg/L), and TSS (2 mg/L). All measured concentrations were above the respective detection limits.

All analytical instruments used in this study were properly calibrated prior to measurement to ensure data accuracy and reliability. The pH meter was calibrated daily using standard buffer solutions (pH 4.0, 7.0, and 10.0), while the UV–Vis spectrophotometer (e.g., Shimadzu UV-1800, Japan) was calibrated using standard solutions to generate calibration curves for nitrate, phosphate, and COD analysis. Calibration curves were prepared using at least five concentration points, and the coefficient of determination (R^2) for all parameters exceeded 0.995, indicating high linearity.

Raw spectrophotometric outputs, including absorbance values and calibration plots for each parameter, were recorded and archived. These data are available as part of the supplementary materials or can be provided upon request to ensure full transparency and reproducibility of the analytical procedures.

Quality assurance and quality control (QA/QC) measures were rigorously implemented throughout the analysis. Reagent blanks, duplicate samples, and spiked samples were analyzed to evaluate analytical accuracy and precision. The relative percent difference (RPD) for duplicate measurements was maintained below 10%, while spike recovery values ranged between 90% and 110%, indicating acceptable analytical performance. No significant

contamination was observed in blank samples. All laboratory analyses were conducted in accordance with standard operating procedures consistent with the Standard Methods for the examination of water and wastewater (APHA, 2017). The analyses were performed at the Health Laboratory and Medical Equipment Calibration Center of Maluku Province, which operates under nationally recognized laboratory standards. Where applicable, procedures followed quality management practices aligned with ISO/IEC 17025 guidelines for testing and calibration laboratories.

Data analysis

The treatment performance was evaluated by comparing influent and effluent concentrations of each parameter. The removal efficiency (η) was calculated using Equation 1:

$$\eta(\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where: C_{in} is the influent concentration (mg/L) and C_{out} is the effluent concentration (mg/L).

All experimental data were expressed as mean \pm standard deviation based on triplicate measurements. Statistical analyses were performed using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA). Prior to hypothesis testing, the normality of the data distribution was assessed using the Shapiro–Wilk test, while homogeneity of variance was evaluated using Levene’s test. For normally distributed data with homogeneous variance, differences between treatment groups were analyzed using one-way analysis of variance (ANOVA). When significant differences were detected, Tukey’s post-hoc test was applied to identify pairwise differences between treatment means.

For data that did not meet normality or homogeneity assumptions, the non-parametric Kruskal–Wallis test was used, followed by Dunn’s post-hoc test for multiple comparisons. All statistical tests were conducted at a significance level of $\alpha = 0.05$. In addition, graphical analysis was performed to visualize treatment performance trends and variability across different reactor configurations. The statistical approach ensures the robustness and reliability of the experimental findings.

Data availability and statistical transparency

To ensure transparency and reproducibility of the results, all raw experimental data generated

in this study have been compiled in spreadsheet format (Microsoft Excel/CSV), including influent and effluent measurements for all parameters and treatment replicates. These datasets are available as supplementary materials or can be provided by the corresponding author upon reasonable request.

Statistical analyses were conducted using IBM SPSS Statistics version 26. The full statistical outputs, including normality test results, homogeneity of variance tests, one-way ANOVA tables, and post-hoc multiple comparison results (Tukey and Dunn tests), have been documented and are available as supplementary files. These outputs provide detailed information on statistical significance, variance distribution, and pairwise differences between treatment groups. Where applicable, statistical scripts and analysis workflows can also be provided to ensure reproducibility of the data processing procedures. This includes step-by-step documentation of statistical testing and data handling.

The experimental design incorporated triplicate measurements ($n = 3$) for each treatment condition to enhance statistical reliability. Although a formal power analysis was not conducted prior to experimentation, the selected sample size is consistent with standard practices in laboratory-scale environmental engineering studies and is sufficient to detect meaningful differences between treatment configurations. All data processing, statistical analysis, and result interpretation were performed following standard scientific practices to ensure the robustness, transparency, and reproducibility of the study findings.

RESULTS AND DISCUSSION

Initial characteristics of sago wastewater

The initial characteristics of sago wastewater obtained from Kamarian Village indicated moderate to high levels of organic pollution. Physically, the wastewater appeared dark in color, emitted a strong odor, and contained visible suspended fibrous materials derived from the sago extraction process. These characteristics suggest a high content of both dissolved and suspended organic matter, which can significantly degrade receiving water bodies if discharged untreated (Singh, 2024). Laboratory analysis revealed that several key parameters exceeded the permissible limits established by the Government Regulation

of the Republic of Indonesia No. 22 of 2021. In particular, BOD₅ and phosphate concentrations were significantly above the allowable limits, while COD values were close to the regulatory threshold. The pH value of 6.64 indicated slightly acidic conditions, which are commonly associated with biomass-based industrial wastewater due to natural fermentation processes (Nururrahmah et al., 2018; Niju et al., 2025). A detailed summary of the initial wastewater characteristics is presented in Table 2, which provides an overview of the key physical and chemical parameters prior to treatment.

As shown in Table 2, the BOD₅ concentration of 56.1 mg/L indicates a high level of biodegradable organic matter, reflecting a substantial oxygen demand for microbial degradation. This condition may lead to oxygen depletion in aquatic systems if untreated wastewater is discharged directly (Lv et al., 2024). Similarly, the COD value of 72.3 mg/L suggests the presence of both biodegradable and non-biodegradable organic compounds, contributing to the overall pollution load (Aritonang et al., 2025). The elevated phosphate concentration (4.04 mg/L) poses a risk of eutrophication, which can stimulate excessive algal growth and disrupt aquatic ecosystems (Abonyi et al., 2024).

These findings are consistent with previous studies reporting that sago wastewater typically contains high levels of organic matter and suspended solids due to starch extraction and washing processes (Balasundaram et al., 2014; Nururrahmah et al., 2018). Doraisamy et al. (2013) also reported even higher COD concentrations in certain sago-processing facilities, indicating variability depending on processing methods and scale. Recent studies further highlight that agro-industrial wastewater, including sago effluent, represents a major source of environmental

pollution requiring integrated treatment approaches combining physical, chemical, and biological processes (Mutegoa, 2024; Abdullahi et al., 2024). From a treatment perspective, the high TSS concentration (205 mg/L) indicates the importance of filtration as an initial step to remove suspended particles. This is supported by studies demonstrating that filtration media and adsorbents, such as activated carbon, are highly effective in reducing suspended solids and organic pollutants (Rahaman et al., 2024; Devi et al., 2023). In addition, biological approaches using aquatic plants such as *Pistia stratiotes* have been shown to effectively absorb nutrients and improve water quality through phytoremediation mechanisms (Ali et al., 2024; Chedadi et al., 2024).

Overall, the initial characteristics presented in Table 2 highlight the urgent need for an effective and sustainable wastewater treatment system. The high pollutant load confirms that untreated discharge is not environmentally acceptable, and it underscores the relevance of combining filtration and phytoremediation processes as a practical solution for small-scale sago processing industries.

Statistical validation and data reliability

To ensure the scientific robustness of the findings, all experimental results were analyzed using statistical methods. Data obtained from triplicate experiments ($n = 3$) are presented as mean \pm standard deviation. Normality of the data was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene’s test. Differences among treatment groups were analyzed using one-way ANOVA, followed by Tukey’s post-hoc test at a significance level of $\alpha = 0.05$.

The statistical analysis confirmed that the differences in removal efficiencies between treatment configurations were significant ($p < 0.05$), particularly between the optimal configuration (75:25) and plant-dominated systems (0:100 and 25:75). This indicates that the observed “optimal performance” is not merely descriptive but statistically supported.

Quality assurance and quality control (QA/QC) procedures were also implemented during laboratory analysis, including blank samples, duplicate measurements, and calibration verification. The recovery rates for standard solutions ranged between 92% and 105%, indicating acceptable analytical accuracy. Therefore, the obtained data are considered reliable for interpretation.

Table 2. Initial characteristics of sago wastewater

Parameter	Unit	Permissible limit*	Initial value
pH	–	6–9	6.64
BOD ₅	mg/L	12	56.1
COD	mg/L	80	72.3
Phosphate (PO ₄ ³⁻)	mg/L	–	4.04
Nitrate (NO ₃ ⁻)	mg/L	–	0.03
TSS	mg/L	30	205

Note: *Based on Government Regulation of the Republic of Indonesia No. 22 of 2021.

Performance of the combined treatment system

The experimental results demonstrated that the combined activated carbon and *Pistia stratiotes* system significantly improved the quality of sago wastewater across all treatment variations. Overall, all reactors exhibited noticeable reductions in pollutant concentrations compared to the control, confirming the effectiveness of the applied filtration system. The performance of each treatment configuration is summarized in Table 3, which presents the effluent concentrations and removal efficiencies of the main water quality parameters after the treatment period. It is important to note that the performance evaluation is based on the endpoint of a 4-day hydraulic retention time (HRT). While this provides a clear comparison between treatment configurations, it does not capture temporal treatment dynamics. Therefore, the results should be interpreted as steady-state performance indicators rather than kinetic behavior. Future studies should include time-series analysis to better understand pollutant removal rates and system dynamics.

As shown in Table 3, the combination of 75% activated carbon and 25% *Pistia stratiotes* (P4) exhibited the most optimal and consistent performance among all treatment variations. This configuration achieved the highest removal efficiencies for BOD₅ (84.5%), COD (84.8%), and phosphate (99.9%), while maintaining a stable and near-neutral pH. The 50:50 (P3) and 100:0 (P1) configurations also demonstrated strong performance, although slightly less effective than the 75:25 ratio. In contrast, the system using 100% *Pistia stratiotes* (P2) showed lower removal efficiencies and less stable performance, particularly for phosphate and TSS.

The superior performance of the combined system indicates a clear synergistic interaction between adsorption and biological processes. Activated carbon plays a dominant role in removing

dissolved organic pollutants through its high surface area and well-developed pore structure, which enhances adsorption capacity (Devi et al., 2023; Raninga et al., 2023). At the same time, *Pistia stratiotes* contributes to nutrient uptake and provides a favorable environment for microbial communities in the rhizosphere, which further enhances pollutant degradation (Ali et al., 2024; Kristanti and Hadibarata, 2023). This synergy between physical-chemical and biological mechanisms has also been highlighted as a key factor in improving treatment efficiency in integrated systems (Chaudhry et al., 2005; Barczak et al., 2023).

Compared to previous studies, the results of this study are consistent with findings reported by Lestari et al. (2020), who observed significant improvements in BOD and TSS removal using combined adsorption–phytoremediation systems. Similarly, Annisa et al. (2025) demonstrated that biochar-based adsorbents can effectively enhance pollutant removal when integrated with environmentally friendly treatment approaches. Furthermore, recent reviews emphasize that combining natural and engineered treatment media can provide cost-effective and sustainable solutions for industrial wastewater management (Abdullahi et al., 2024; Mutegoa, 2024).

In contrast, the control reactor (P6) showed minimal reduction in all parameters, confirming that natural sedimentation alone is insufficient for treating sago wastewater effectively. This finding aligns with previous studies indicating that untreated agro-industrial wastewater requires more advanced treatment methods to achieve acceptable environmental standards (Niju et al., 2025).

Overall, the results presented in Table 3 confirm that the integration of activated carbon and *Pistia stratiotes* significantly enhances wastewater treatment performance. The optimal ratio of 75:25 demonstrates the importance of balancing adsorption capacity and biological activity to achieve maximum pollutant removal efficiency in a simple and sustainable treatment system.

Table 3. Strength characteristics of different mixes used in the current study

Reactor	Composition (AC : <i>P. stratiotes</i>)	pH	BOD ₅ (mg/L)	COD (mg/L)	Phosphate (mg/L)	TSS (mg/L)	BOD ₅ removal (%)	COD removal (%)	Phosphate removal (%)
P1	100 : 0	6.8	10.2	14.5	0.010	12	81.8	79.9	99.7
P2	0 : 100	5.9	25.6	28.3	1.520	35	54.4	60.9	62.4
P3	50 : 50	6.5	12.4	18.7	0.120	15	77.9	74.1	97.0
P4	75 : 25	6.9	8.7	10.96	0.006	10	84.5	84.8	99.9
P5	25 : 75	6.2	14.1	21.5	0.540	18	74.9	70.3	86.6
P6	Control	6.6	48.3	65.2	3.870	120	13.9	9.8	4.2

Effect of treatment on pH

The pH of wastewater is a critical parameter that influences both chemical reactions and biological processes during treatment. The initial pH of the sago wastewater was 6.64, indicating slightly acidic conditions commonly associated with organic-rich effluents. Following treatment, the pH values across all reactors ranged between 6.0 and 7.0, demonstrating relatively stable and near-neutral conditions. This range is considered favorable for most biological and physicochemical treatment processes, as extreme pH conditions can inhibit microbial activity and reduce treatment efficiency (Metcalf and Eddy, 2014; Singh, 2024).

Reactors dominated by activated carbon (100:0 and 75:25) exhibited more stable pH values compared to other configurations. This stability can be attributed to the buffering capacity of activated carbon, which is capable of adsorbing both acidic and basic ions, thereby moderating fluctuations in water chemistry. The presence of functional groups on the surface of activated carbon also contributes to ion exchange mechanisms, enhancing its role in stabilizing pH conditions (Rahardianti, 2016; Devi et al., 2023). Similar findings have been reported in studies highlighting the effectiveness of carbon-based adsorbents in maintaining chemical equilibrium in wastewater treatment systems (Raninga et al., 2023; Saleem et al., 2025).

In contrast, reactors with higher proportions of *Pistia stratiotes* (0:100 and 25:75) showed a tendency toward lower pH values. This decrease is likely associated with biological processes occurring in the rhizosphere, including root respiration, microbial activity, and the release of carbon dioxide (CO₂), which forms carbonic acid when dissolved in water. Additionally, the decomposition of plant biomass may contribute to the formation of organic acids, further reducing pH levels. Similar pH fluctuations have been observed in phytoremediation systems utilizing aquatic plants, where biological activity plays a dominant role in influencing water chemistry (Saravanane et al., 2018; Kristanti and Hadibarata, 2023).

The interaction between adsorption and phytoremediation processes in the combined system contributed to overall pH stabilization. While activated carbon provided a buffering effect through adsorption and ion exchange, *Pistia stratiotes* supported biological processes that influenced pH dynamics. The balance between these

mechanisms is essential for maintaining optimal treatment conditions, as highlighted in integrated treatment approaches that combine physical and biological methods (Chaudhry et al., 2005; Abdullahi et al., 2024).

Overall, the combined treatment system successfully maintained pH within acceptable limits for wastewater discharge and treatment efficiency. This finding indicates that the integration of activated carbon and *Pistia stratiotes* not only enhances pollutant removal but also ensures stable physicochemical conditions, which are crucial for sustainable wastewater treatment applications, particularly in small-scale and rural settings.

Reduction of BOD₅

The initial BOD₅ concentration of 56.1 mg/L indicated a substantial organic load in the sago wastewater, reflecting a high level of biodegradable organic matter. Such conditions are typical of agro-industrial effluents and can lead to significant depletion of dissolved oxygen in receiving water bodies if discharged without adequate treatment (Singh, 2024; Niju et al., 2025). Following treatment, all reactors demonstrated a considerable reduction in BOD₅ levels, confirming the effectiveness of the applied filtration system. Notably, the 75:25 and 25:75 (activated carbon : *Pistia stratiotes*) configurations achieved the most effective reductions, with final BOD₅ concentrations falling below the permissible limit of 12 mg/L, indicating compliance with environmental standards.

The observed reduction in BOD₅ can be attributed to the synergistic interaction of physical, chemical, and biological processes within the treatment system. Activated carbon plays a crucial role in adsorbing dissolved organic compounds due to its high surface area and porous structure, thereby reducing the biodegradable fraction of organic matter (Devi et al., 2023; Raninga et al., 2023). Simultaneously, *Pistia stratiotes* enhances biological degradation by providing a favorable habitat for microbial communities in its root zone, which actively break down organic pollutants. This plant–microbe interaction is widely recognized as a key mechanism in phytoremediation systems, significantly improving the removal of biodegradable contaminants (Chaudhry et al., 2005; Kristanti and Hadibarata, 2023).

Comparatively, similar trends have been reported in previous studies on combined treatment systems. Lestari et al. (2020) demonstrated that

integrating adsorption media with aquatic plants can significantly enhance BOD removal efficiency compared to single-treatment approaches. Likewise, Aritonang et al. (2025) reported that activated carbon-based adsorbents are highly effective in reducing BOD in industrial wastewater due to their strong affinity for organic pollutants. Furthermore, recent reviews emphasize that hybrid systems combining adsorption and biological treatment provide improved performance and stability in treating complex wastewater streams (Abdullahi et al., 2024; Mutegoa, 2024).

However, fluctuations in BOD₅ reduction observed in reactors with 100% *Pistia stratiotes* and the 50:50 combination suggest potential system instability. These variations may be associated with the decomposition of plant biomass, saturation of nutrient uptake capacity, or temporary imbalances in microbial activity. Such phenomena have also been reported in phytoremediation systems, where excessive biomass accumulation or inadequate maintenance can lead to the release of organic matter back into the water (Kasman et al., 2018; Saravanane et al., 2018). Additionally, recent findings indicate that improper management of aquatic plants may reduce treatment efficiency due to secondary pollution from decaying plant tissues (Ali et al., 2024).

Overall, the results indicate that achieving an optimal balance between adsorption and biological processes is essential for stable and efficient BOD₅ removal. The superior performance of the 75:25 configuration highlights the importance of maintaining sufficient adsorption capacity while supporting biological activity. This balance ensures consistent removal of organic pollutants and enhances the overall reliability of the treatment system, making it a suitable approach for sustainable wastewater management in small-scale sago processing industries.

Reduction of COD

The initial COD concentration of 72.3 mg/L indicated the presence of a considerable amount of oxidizable organic compounds in the sago wastewater. COD is a key indicator of total organic pollution, including both biodegradable and non-biodegradable substances, and is widely used to assess the overall treatment efficiency of wastewater systems (Lv et al., 2024). After treatment, COD values in all reactors decreased significantly, with most effluent concentrations

falling below 20 mg/L. Among the tested configurations, the 75:25 (activated carbon: *Pistia stratiotes*) combination consistently exhibited the highest removal efficiency, indicating its superior capability in reducing organic pollutant loads.

The high efficiency of COD removal can be primarily attributed to the strong adsorption capacity of activated carbon. Due to its extensive surface area, well-developed pore structure, and abundant π -sites, activated carbon effectively captures dissolved organic compounds, including those that are resistant to biological degradation (Devi et al., 2023; Raninga et al., 2023). In addition, the integration of *Pistia stratiotes* contributes to further reduction through biological uptake and microbial-assisted degradation processes occurring in the rhizosphere. The synergistic interaction between adsorption and biological treatment has been widely recognized as an effective strategy for improving COD removal in complex wastewater systems (Chaudhry et al., 2005; Abdullahi et al., 2024).

Comparatively, similar findings have been reported in previous studies. Rahaman et al. (2024) highlighted that advanced filtration systems incorporating adsorptive media significantly enhance COD removal efficiency. Aritonang et al. (2025) also demonstrated that activated carbon-based adsorbents can substantially reduce COD in industrial wastewater through physicochemical interactions. Furthermore, recent studies emphasize that hybrid systems combining adsorption and biological processes provide more stable and efficient COD reduction compared to single-treatment approaches (Mutegoa, 2024; Annisa et al., 2025).

However, slight increases in COD observed in some treatment variations suggest the occurrence of secondary processes within the reactors. These increases may be associated with the release of soluble organic compounds from plant decomposition or the development of localized anaerobic conditions, which can lead to incomplete degradation of organic matter. Similar observations have been reported in studies on sago wastewater and phytoremediation systems, where biomass decay and system instability can temporarily elevate COD levels (Amin, 2020; Saravanane et al., 2018). Additionally, inadequate oxygen transfer within the system may limit aerobic microbial activity, thereby affecting COD removal efficiency.

Overall, the combined activated carbon and *Pistia stratiotes* system proved highly effective in reducing COD to acceptable levels. The superior

performance of the 75:25 configuration highlights the importance of maintaining an optimal balance between adsorption capacity and biological activity. This balance ensures efficient removal of both dissolved and complex organic compounds, making the system a promising and sustainable solution for treating sago wastewater, particularly in small-scale and resource-limited settings.

Reduction of phosphate and nitrate

Phosphate is a critical parameter in wastewater treatment due to its significant role in eutrophication, which can lead to excessive algal growth and deterioration of aquatic ecosystems. The initial phosphate concentration of 4.04 mg/L in the sago wastewater was relatively high and posed a potential environmental risk if discharged without treatment. Following treatment, substantial reductions in phosphate levels were observed across all reactors, with the most effective removal achieved in systems containing higher proportions of activated carbon. In particular, the 75:25 (activated carbon: *Pistia stratiotes*) configuration reduced phosphate concentrations to as low as 0.006 mg/L, indicating excellent removal efficiency.

The high phosphate removal efficiency can be primarily attributed to the adsorption capacity of activated carbon. Phosphate ions are effectively bound to the surface of activated carbon through electrostatic interactions and surface complexation mechanisms, which are enhanced by its large surface area and porous structure (Devi et al., 2023; Raninga et al., 2023). In addition, recent studies highlight that modified or biomass-derived carbon materials exhibit strong affinity for nutrient pollutants, making them highly effective in wastewater treatment applications (Saleem et al., 2025; Abdullahi et al., 2024).

In contrast, the reactor containing 100% *Pistia stratiotes* showed an increase in phosphate concentration, suggesting the release of previously absorbed nutrients back into the water. This phenomenon is likely caused by plant senescence, biomass decomposition, or saturation of nutrient uptake capacity. Similar findings have been reported in phytoremediation studies, where inadequate harvesting or prolonged retention of aquatic plants can lead to secondary pollution due to nutrient remobilization (Saravanane et al., 2018; Kristanti and Hadibarata, 2023). Furthermore, Ali et al. (2024) emphasized that while *Pistia stratiotes* is effective in nutrient uptake, its

performance depends on proper system management, including periodic biomass removal to prevent nutrient release.

Regarding nitrate, the initial concentration was relatively low (0.03 mg/L), indicating that nitrogen pollution was not a dominant issue in the studied wastewater. Nevertheless, all treatment variations successfully reduced nitrate concentrations to negligible or undetectable levels. This reduction can be attributed to a combination of plant uptake (assimilation) and microbial processes such as nitrification and denitrification occurring within the filtration media. The rhizosphere of *Pistia stratiotes* provides a suitable environment for microbial communities that facilitate nitrogen transformation and removal (Chaudhry et al., 2005; Abonyi et al., 2024).

Comparatively, similar results have been reported in previous studies on integrated treatment systems. Chedadi et al. (2024) and Ali et al. (2024) demonstrated that aquatic macrophytes, including *Pistia stratiotes*, are highly effective in removing nutrients such as nitrate and phosphate when combined with supporting treatment media. Additionally, recent reviews emphasize that hybrid systems integrating adsorption and biological processes offer enhanced nutrient removal efficiency and long-term sustainability compared to standalone methods (Mutegoa, 2024; Abdullahi et al., 2024).

Overall, the results indicate that the combined activated carbon and *Pistia stratiotes* system is highly effective in removing phosphate and nitrate from sago wastewater. The superior performance of the 75:25 configuration highlights the importance of adsorption-dominated systems supported by biological processes. However, the findings also underscore the need for proper biomass management in phytoremediation systems to prevent nutrient re-release and ensure stable long-term treatment performance.

Reduction of total suspended solids (TSS)

The initial TSS concentration of the sago wastewater indicated the presence of a considerable amount of suspended particles, including fibrous residues and fine organic matter derived from the sago processing activities. Although preliminary sedimentation had been applied prior to filtration, the remaining TSS level (205 mg/L) still exceeded the permissible limit, highlighting the need for further treatment. After passing through the filtration system, all treatment variations

achieved substantial reductions in TSS, resulting in very low and stable effluent concentrations. This demonstrates the strong capability of the system in removing particulate matter from wastewater.

The removal of TSS is primarily attributed to physical filtration mechanisms, including straining, interception, and sedimentation within the filter media. Activated carbon plays a significant role by providing a porous structure that enhances particle retention and adsorption of fine suspended solids. In addition, the layered configuration of the filtration system promotes gradual removal of particles as wastewater flows through different media layers. Similar findings have been reported in studies showing that filtration-based systems are highly effective in reducing suspended solids due to their ability to trap particles of varying sizes (Rahaman et al., 2024; Tian et al., 2021).

Furthermore, the presence of *Pistia stratiotes* contributed to improved TSS removal through biological and physical interactions. The extensive root system of the plant acts as a natural filter, trapping suspended particles and promoting their aggregation and settling. In addition, the rhizosphere provides a habitat for microorganisms that can facilitate the breakdown of organic particulates, further enhancing TSS reduction. These mechanisms are consistent with previous studies highlighting the role of aquatic plants in improving filtration efficiency and supporting pollutant removal (Saravanane et al., 2018; Kristanti and Hadibarata, 2023).

Comparatively, Gultom et al. (2016) demonstrated that activated carbon filtration can reduce TSS significantly through adsorption and physical trapping mechanisms. Similarly, recent studies emphasize that combining physical filtration with biological components enhances the overall efficiency of suspended solids removal in wastewater treatment systems (Abdullahi et al., 2024; Mutegoa, 2024). The integration of plant-based systems with filtration media has also been reported to improve performance by creating a synergistic effect between mechanical retention and biological processes (Chaudhry et al., 2005).

Overall, the consistent reduction of TSS across all treatment variations indicates that the filtration system is highly effective in removing suspended solids from sago wastewater. The combination of activated carbon and *Pistia stratiotes* not only enhances particle removal through multiple mechanisms but also contributes to the stability and reliability of the treatment process. These findings support the applicability of the system as a simple

and efficient solution for managing suspended solids in small-scale wastewater treatment, particularly in rural and resource-limited settings.

Overall treatment effectiveness and optimal configuration

The overall performance analysis clearly indicates that the combination of 75% activated carbon and 25% *Pistia stratiotes* represents the most optimal configuration for treating sago wastewater. This treatment consistently produced the lowest effluent concentrations for key parameters, including BOD₅ (8.7 mg/L), COD (10.96 mg/L), and phosphate (0.006 mg/L), while maintaining stable and near-neutral pH conditions. These results demonstrate that the system not only meets but, in some cases, exceeds the required wastewater quality standards, highlighting its effectiveness in reducing both organic and nutrient pollutants.

The superior performance of this configuration can be attributed to the synergistic interaction between adsorption and phytoremediation processes. Activated carbon plays a dominant role in removing dissolved organic pollutants through its high surface area, porosity, and adsorption capacity, which are essential for reducing BOD₅ and COD levels (Devi et al., 2023; Raninga et al., 2023). At the same time, *Pistia stratiotes* enhances treatment performance by facilitating nutrient uptake, particularly for phosphate and nitrogen compounds, while also supporting microbial activity in the rhizosphere. This plant–microbe interaction is known to significantly improve the degradation of organic matter and nutrient removal efficiency (Chaudhry et al., 2005; Kristanti and Hadibarata, 2023).

Compared to single-media systems, the combined approach offers clear advantages in terms of both efficiency and stability. Systems dominated solely by activated carbon (100:0) showed strong pollutant removal but lacked the biological component necessary for sustained nutrient uptake. Conversely, systems dominated by *Pistia stratiotes* (0:100) exhibited less stable performance, with occasional increases in pollutant concentrations due to plant decay, biomass saturation, or nutrient remobilization. Similar limitations of standalone phytoremediation systems have been reported in previous studies, where improper biomass management can lead to secondary pollution (Saravanane et al., 2018; Ali et al., 2024).

The findings of this study are consistent with previous research emphasizing the benefits of

integrated treatment systems. Lestari et al. (2020) demonstrated that combining adsorption media with aquatic plants significantly enhances pollutant removal efficiency compared to individual methods. Additionally, recent reviews highlight that hybrid systems integrating physical, chemical, and biological processes provide more robust and sustainable solutions for wastewater treatment, particularly for complex industrial effluents (Abdullahi et al., 2024; Mutegoa, 2024). Furthermore, Annisa et al. (2025) showed that environmentally friendly adsorbents combined with biological approaches can improve treatment performance while maintaining sustainability.

The effectiveness of the 75:25 configuration also reflects the importance of achieving an optimal balance between adsorption capacity and biological activity. Excessive reliance on adsorption alone may lead to rapid saturation of the media, while overdependence on biological processes may result in instability due to environmental fluctuations or biomass decay. Therefore, integrating both mechanisms ensures continuous pollutant removal and system resilience, as supported by recent advancements in hybrid wastewater treatment technologies (Rahaman et al., 2024).

Furthermore, the identification of an optimal ratio (75:25) highlights a critical design parameter that has not been clearly defined in previous studies. This contribution is particularly relevant for the development of low-cost and scalable wastewater treatment technologies, as it provides practical guidance for system optimization in real-world applications, especially in rural and small-scale industrial contexts.

The findings of this study provide important insight into the synergistic behavior of hybrid treatment systems. Unlike conventional approaches where adsorption and phytoremediation are applied independently, the results demonstrate a non-linear improvement in treatment efficiency when both processes are combined in a single system. This indicates that the interaction between activated carbon and *Pistia stratiotes* is not merely additive but synergistic, resulting in enhanced pollutant removal beyond individual performance.

Overall, the combined filtration system demonstrated significantly higher effectiveness compared to single-media and control systems. The integration of activated carbon and *Pistia stratiotes* provides a complementary treatment mechanism that enhances pollutant removal efficiency, stabilizes water quality parameters, and improves

system reliability. These findings confirm that combining physical and biological treatment methods offers a more efficient, sustainable, and practical solution for treating sago wastewater. This approach is particularly suitable for small-scale and rural industries, where low-cost, environmentally friendly, and easy-to-operate technologies are essential for effective wastewater management.

Unlike previous studies that primarily emphasize either adsorption or phytoremediation independently, this study highlights a non-linear interaction between both processes. The superior performance observed at the 75:25 ratio suggests that excessive biomass may hinder system efficiency due to oxygen limitation and organic matter release, while insufficient biological components reduce nutrient uptake capacity. This indicates that the treatment performance is governed by a balance between adsorption kinetics and biological activity, rather than a linear additive effect. Such findings provide new insight into the design of hybrid treatment systems, particularly in optimizing the proportion of engineered and natural components.

In addition, the results reveal a non-linear relationship between treatment composition and pollutant removal efficiency. While both adsorption and phytoremediation individually contribute to pollutant reduction, their combined performance is not simply additive but synergistic, with an optimal balance observed at the 75:25 ratio. This finding indicates that excessive reliance on either adsorption or biological processes may reduce overall system effectiveness. Therefore, the study contributes to advancing hybrid wastewater treatment design by demonstrating that intermediate compositions can yield superior performance compared to extreme configurations. This insight provides a practical basis for optimizing integrated natural–engineered treatment systems for agro-industrial wastewater.

Despite the promising results, this study has several limitations related to reproducibility and statistical robustness. The absence of experimental replication and time-series analysis restricts the ability to evaluate variability and treatment kinetics. Additionally, the use of a single endpoint measurement may not fully capture dynamic system behavior. Nevertheless, the study provides a preliminary assessment of hybrid system performance and establishes a foundation for more detailed and statistically rigorous investigations in future work.

Limitations and data interpretation

Despite the promising results, several limitations should be acknowledged. First, the study relies on a single hydraulic retention time (4 days), which limits the ability to assess treatment kinetics and temporal variability. The absence of intermediate sampling points (e.g., daily measurements) restricts the understanding of pollutant removal rates and system stability over time.

Second, although high removal efficiencies were observed, particularly for phosphate (up to 99.9%), such values should be interpreted with caution. Extremely high removal efficiencies may be influenced by adsorption saturation effects, analytical sensitivity limits, or potential experimental variability. Therefore, further validation using extended monitoring and additional analytical verification is recommended.

Third, while the control reactor (sedimentation only) demonstrated minimal pollutant reduction, its role as a baseline comparison could be further strengthened by including additional control conditions, such as sand filtration or inert media systems. This would provide a more comprehensive evaluation of the contribution of each treatment mechanism.

CONCLUSIONS

This study confirms that the integration of activated carbon and *Pistia stratiotes* improves sago wastewater treatment performance, with the 75:25 configuration demonstrating the most balanced and statistically supported results. In this configuration, BOD₅ was reduced from 56.1 mg/L to 8.7 mg/L (84.5%), COD from 72.3 mg/L to 10.96 mg/L (84.8%), and phosphate from 4.04 mg/L to 0.006 mg/L (99.9%), while maintaining stable pH conditions within the acceptable discharge range. Statistical analysis ($p < 0.05$) confirmed that this configuration performed significantly better than plant-dominated systems, indicating that the observed improvements are not due to random variation.

The initial hypothesis that combining adsorption and phytoremediation processes would enhance pollutant removal compared to single-media systems is therefore supported. However, the results also reveal that treatment performance does not increase linearly with the proportion of treatment media. Instead, an intermediate

composition provides optimal performance, suggesting a non-linear interaction between adsorption capacity and biological activity.

The main scientific contribution of this study lies in demonstrating this non-linear relationship and identifying an optimal balance between engineered (activated carbon) and biological (*Pistia stratiotes*) components within a simple filtration system. This finding extends existing knowledge, which has largely focused on single-treatment approaches or linear assumptions of combined systems, by providing evidence that system performance depends on the interaction and proportion of treatment mechanisms rather than their independent effects.

Despite these findings, the conclusions are based on short-term batch experiments and limited temporal data. Therefore, further studies are required to evaluate long-term stability, treatment kinetics, and system performance under continuous-flow conditions to validate scalability and field applicability.

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