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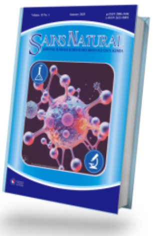

PERFORMANCE COMPARISON OF COAGULATION AND ADSORPTION FOR GAMBIER WASTEWATER TREATMENT USING POLY ALUMINIUM CHLORIDE (PAC), CALCIUM HYPOCHLORITE, AND ACTIVATED CARBON

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ABSTRACT

Industrial wastewater from gambier (Uncaria gambir Roxb.) extraction is characterized by high organic loads, intense coloration, and elevated levels of total dissolved solids (TDS), which often exceed regulatory discharge limits. This study evaluated the performance of two chemical coagulants, Poly Aluminium Chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$), and one physical adsorbent, coal-based activated carbon (CW 130 AR), in treating gambier wastewater. The experimental work assessed their effects on chemical oxygen demand (COD), TDS, and color, alongside adsorption equilibrium modeling using Langmuir and Freundlich isotherms. Results demonstrated that PAC achieved 89% COD removal, and calcium hypochlorite reached 82%. However, both coagulants were ineffective at reducing Total Dissolved Solids (TDS) and occasionally increased dissolved solids due to residual ionic species. In contrast, activated carbon achieved COD and color removal efficiencies exceeding 95%, though it provided only modest TDS removal (≈85%). Adsorption isotherm analysis confirmed that COD removal by activated carbon followed the Langmuir model ($R^2 = 0.9488$), indicating monolayer chemisorption on a homogeneous surface. Meanwhile, PAC and calcium hypochlorite showed weak conformity to Langmuir and Freundlich models, confirming coagulation/flocculation as their dominant removal mechanism. This study provides the first comparative performance evaluation of coagulation and adsorption processes for gambier industry wastewater, demonstrating that a hybrid or sequential treatment strategy can achieve more comprehensive pollutant removal. By enhancing treatment efficiency, reducing industrial effluent discharge, and enabling potential water reuse, this work supports Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 12 (Responsible Consumption and Production).

INTRODUCTION

Water is a fundamental chemical compound that plays a critical role in sustaining life and supporting various human activities. Approximately 71% of the Earth's surface is covered by water, of which only 2.5%-3% is freshwater, and the remaining 97%-97.5% is saline (Musie & Gonfa, 2023; Samsami et al., 2020). With the continued growth of the global population, demand for clean water has increased significantly for domestic, agricultural, and industrial uses (Boretti & Rosa, 2019; Ingrao et al., 2023; Khilchevskyi & Karamushka, 2022). (Boretti & Rosa, 2019; Ingrao et al., 2023; Khilchevskyi & Karamushka, 2022). This intensifying demand places considerable pressure on limited freshwater resources, underscoring the urgent need for practical, sustainable water management strategies.

In industrial operations, water serves as both a process medium and a cleaning agent. One example is the gambier (*Uncaria gambir* Roxb.) extraction industry, which utilizes approximately 63 m^3 of water daily for domestic and production purposes (Desfitri et al., 2024). These characteristics primarily originate from the leaching of plant-based polyphenolic compounds such as catechins and tannins during the extraction process, as well as from washing and handling activities that introduce fine particulates and dissolved inorganic residue. However, the wastewater generated by this process is characterized by high concentrations of organic matter, suspended solids, and total dissolved solids (TDS), as well as intense coloration. As a result, the effluent often fails to meet national discharge standards stipulated in the Indonesian Ministerial Regulation of Environment and Forestry No. 5 of 2014, particularly pH, chemical oxygen demand (COD), temperature, and color. Furthermore, under the more recent Government Regulation No. 22 of 2021, which emphasizes stricter environmental quality standards and integrated water pollution control, gambier wastewater poses an even greater challenge, as its high organic load and persistent coloration are increasingly incompatible with the regulation's stricter effluent management framework.

The insufficient quality of treated effluent can be attributed to limitations of existing wastewater treatment facilities, which often rely on closed, anaerobic systems. Such conditions inhibit the activity of aerobic microorganisms that are essential for the biodegradation of organic compounds. Additionally, the absence of chemical additives for pH adjustment, clarification, and disinfection further reduces treatment efficiency. These challenges underline the necessity for improved treatment technologies that are both effective and adaptable to local industrial contexts.

To address the challenges of treating high-strength industrial wastewater, chemical coagulation–flocculation and physical adsorption have been widely applied due to their effectiveness in removing suspended solids, color, and organic pollutants. Coagulation–flocculation destabilizes colloidal particles and promotes aggregation, enabling efficient removal of particulate and colloid-bound contaminants, while adsorption selectively targets dissolved organic compounds through surface interactions. Recent studies have demonstrated that integrated treatment systems combining coagulation, flocculation, and adsorption can achieve high pollutant removal efficiencies. For example, the combination of these processes has resulted in COD, TSS, and color removal efficiencies exceeding 95% in textile wastewater treatment (Badawi & Zaher, 2021). However, despite their proven effectiveness in other agro-industrial and textile effluents, such integrated coagulation–adsorption approaches have not yet been systematically applied or evaluated for gambier industry wastewater, which exhibits distinct chemical characteristics dominated by plant-based polyphenolic compounds.

Given the physicochemical similarity between gambier wastewater and textile effluents, both characterized by high organic loads and strong coloration, this study proposes a combined treatment approach involving chemical coagulation using poly aluminium chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$), and physical adsorption using coal-based activated carbon (CW 130 AR). Despite these similarities, gambier wastewater is dominated by naturally derived polyphenolic compounds, particularly catechins, tannins, and other flavonoid derivatives originating from plant extraction processes. In contrast, textile effluents typically contain synthetic dyes, surfactants, and auxiliary chemicals. These compositional differences influence pollutant behavior, removal mechanisms, and treatment efficiency. The specific objectives of this study are threefold: (1) to investigate the effect of PAC and calcium hypochlorite as coagulants on the reduction of TDS, COD, and color in gambier wastewater; (2) to examine the effectiveness of coal-based activated carbon in reducing the same parameters through adsorption; and (3) to calculate and compare the adsorption capacity coefficients between the chemical coagulants and the activated carbon.

By enhancing the effectiveness of industrial wastewater treatment and promoting the reuse of treated effluent, this research directly contributes to achieving Sustainable Development Goal (SDG) 6: Clean Water and Sanitation. Specifically, the study supports sustainable water resources management by reducing pollutant loads, increasing treatment efficiency, and enabling the recovery and reuse of water in industrial settings. In addition, the proposed treatment approach aligns with Sustainable Development Goal (SDG) 12: Responsible Consumption and Production by encouraging resource-efficient wastewater management, minimizing waste generation, and supporting cleaner production practices in agro-industrial processes. In this context, the development of innovative, low-cost, and efficient treatment strategies is essential for ensuring sustainable industrial growth while minimizing environmental degradation. The outcomes of this study are expected to provide a scientific basis for practical, scalable solutions that enhance circular water use and support cleaner production systems in agro-industrial sectors.

METHODOLOGY

This study was conducted to evaluate the performance of chemical coagulation using Poly Aluminium Chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$), and physical adsorption using coal-based activated carbon (CW 130 AR) in reducing pollutant parameters, namely total dissolved solids (TDS), chemical oxygen demand (COD), and color from gambier industry wastewater. All experimental procedures were designed to ensure repeatability and allow for performance comparison among the three treatment agents.

Equipment/Tool/ Material

The experimental work was conducted using standard laboratory equipment suitable for analyzing physicochemical wastewater treatment. The key equipment used included 1000 mL beaker glasses, 250 mL Erlenmeyer flasks, 1000 mL graduated cylinders, reaction tubes with racks, an analytical balance, a magnetic stirrer with spin bars, an ORP meter, a stopwatch, an oven, a desiccator, a pH meter, a TDS meter, and a spectrophotometer for COD and color measurements. Supporting tools, such as spatulas, filter paper, wash bottles, and pipettes were also used throughout the experiment.

The primary material used in this study was raw wastewater obtained from the gambier processing industry (PT. SRI, Sumatera Barat). For the coagulation process, two chemical agents were used: Polyaluminium Chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$). Quicklime (CaO) was added in each sample as a pH-neutralizing agent prior to coagulation and adsorption. The adsorbent material used for the adsorption experiments was coal-based activated carbon with the commercial code CW 130 AR. All chemical reagents were of analytical grade, and distilled water was used for cleaning and dilution as needed.

Procedures

The study was divided into two treatment scenarios: coagulation using PAC, coagulation using calcium hypochlorite ($Ca(OCl)_2$), and adsorption using coal-based activated carbon (CW 130 AR).

Coagulation Process

The coagulation experiments were conducted in batch mode following the standard jar test procedure, which is widely adopted for evaluating coagulation–flocculation performance in water and wastewater treatment systems (Standard Methods for the Examination of Water and Wastewater, APHA). Each experimental run used 200 mL of raw gambier wastewater. Before coagulant addition, 0.2 g of quicklime (CaO) was added to adjust the initial pH to a neutral range of 6.8–7.2. The samples were then subjected to rapid mixing at 300 rpm using a magnetic stirrer to ensure uniform dispersion of the coagulant, followed by the jar test sequence. Two coagulants, poly aluminium chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$), were evaluated at various dosages. After treatment, the supernatant was analyzed for pH, chemical oxygen demand (COD), total dissolved solids (TDS), and color to assess coagulation performance. The range of coagulant dosages applied in this study is summarized in Table 1.

Table 1. Dosage of Coagulant

Coagulant Type	Dosage (mg/L)
PAC	10, 15, 20, 25, 30, 40
$CA(OCl)_2$	10, 15, 20, 25, 30, 40

Adsorption Process

The adsorption experiments were conducted in batch mode using the same wastewater volume (200 mL) and lime dosage (0.2 g) as applied in the coagulation tests to maintain consistency in experimental conditions. Mixing was performed at a constant speed of 300 rpm using a magnetic stirrer. Coal-based activated carbon (CW 130 AR) was employed as the adsorbent and added to the wastewater at concentrations of 1000, 2000, 3000, 4000, and 5000 mg/L. This dosage range was selected to evaluate the adsorption performance of the activated carbon under varying adsorbent loadings. After adsorption, the treated samples were allowed to settle prior to further analysis.

The effectiveness of the adsorption process was evaluated by analyzing changes in key water quality parameters. The pH of the samples was measured using a calibrated pH meter. Chemical oxygen demand (COD) was determined using the closed reflux method in accordance with SNI 6989.2:2019. Total dissolved solids (TDS) were measured using a calibrated TDS meter. Color removal was assessed by comparing wastewater samples before and after treatment using a spectrophotometric approach. These analytical methods were applied consistently across all adsorption experiments to ensure data comparability and reliability.

These process parameters provided the foundation for identifying the optimum treatment conditions and comparing the performance of chemical coagulation and physical adsorption in reducing key pollutants from gambier wastewater.

RESULTS AND DISCUSSION

The performance of each treatment method, coagulation using PAC and calcium hypochlorite, and adsorption using coal-based activated carbon, was evaluated based on its ability to reduce the levels of COD, TDS, and color in gambier industry wastewater. The results are presented and discussed in detail to highlight the efficiency of each process, optimal operating conditions, and underlying removal mechanisms. Comparative analysis is also provided to determine the most effective treatment strategy for potential application in small-scale agro-industrial wastewater management. The findings are organized by treatment type and parameter response as follows.

Effect of PAC and Calcium Hypochlorite

Effect of PAC and Calcium Hypochlorite on COD

The effect of coagulant concentration using calcium hypochlorite and Poly Aluminium Chloride (PAC) on chemical oxygen demand (COD) reduction is illustrated in Figure 1. The data demonstrate that increasing the coagulant dosage initially leads to an increase in COD removal efficiency for both coagulants, followed by a decline beyond the optimum concentration.

Specifically, calcium hypochlorite achieved COD removal efficiencies of 55%, 58%, 59%, 70%, 82%, and 79% at concentrations of 10, 15, 20, 25, 30, and 40 mg/L, respectively. Meanwhile, PAC showed removal efficiencies of 82%, 63%, 89%, 74%, 59%, and 74% at the same respective concentrations. The maximum COD removal efficiency for PAC was 89% at 20 mg/L, while for calcium hypochlorite, the highest efficiency was 82% at 30 mg/L. The reduction in COD observed with calcium hypochlorite is primarily attributed to a combined coagulation-oxidation mechanism. Under the neutral pH conditions applied in this study (pH 6.8–7.2), calcium hypochlorite dissociates to form hypochlorous acid (HOCl), which acts as a mild oxidizing agent capable of partially oxidizing dissolved organic compounds, particularly phenolic compounds, which are dominant in gambier wastewater. Simultaneously, the presence of calcium ions (Ca^{2+}) contributes to charge neutralization and aggregation of colloidal organic matter, enhancing its removal through coagulation. The observed increase in COD removal efficiency with increasing $Ca(OCl)_2$ dosage up to 30 mg/L supports the role of oxidation in degrading soluble organics. In contrast, the decline at higher dosages may be due to excess residual oxidants and dissolved ionic species that limit further COD reduction.

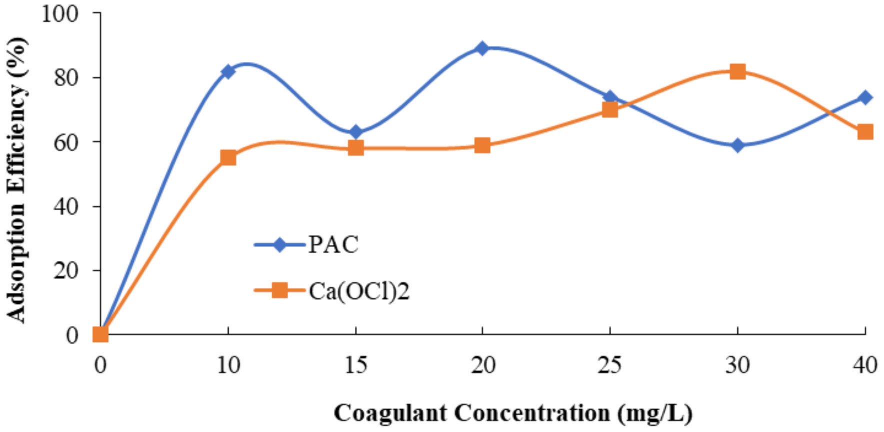


Figure 1. Effect of Coagulant Concentration on COD Adsorption Efficiency

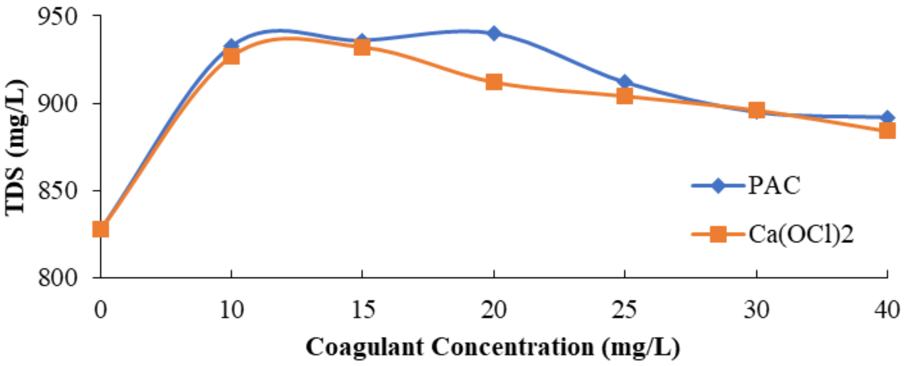


Figure 2. Effect of PAC and $Ca(OCl)_2$ on TDS

However, increasing the coagulant concentration beyond the optimum point resulted in a noticeable decline in treatment efficiency. This reduction is likely due to an overdose of positively charged coagulant ions, which exceed the amount needed to neutralize the negatively charged colloidal particles in the wastewater. As a result, charge reversal or re-stabilization occurs, leading to repulsive forces between particles and the breakdown of previously formed flocs. This phenomenon is known as deflocculation or restabilization (Husaini et al., 2018; Lestari, 2017). These findings contrast with those reported by Salsabila et al. (Salsabila et al., 2018), who found that PAC at 20 mg/L was only able to reduce COD by 39.94% in a different wastewater system. In addition, Badawi et al. (Badawi & Zaher, 2021) evaluated the coagulation-flocculation process for textile wastewater using ferric chloride ($FeCl_3$), with COD removal efficiencies ranging from 61.3% to 68.1%, depending on coagulant dosage.

The final COD values after treatment with both calcium hypochlorite and PAC were within the acceptable discharge limits established by the Indonesian Ministerial Regulation of Environment and Forestry No. 5 of 2014. The reduction in COD from coagulation results from the aggregation and settling of suspended and colloidal organic particles, thereby decreasing the amount of oxidizable material in the effluent. The positively charged coagulant ions facilitate the formation of flocs by binding with negatively charged organic molecules, effectively removing them from the aqueous phase. As the number of suspended particles decreases, the oxygen demand for biochemical oxidation also decreases, leading to a significant reduction in COD (Badawi & Zaher, 2021).

Effect of PAC and Calcium Hypochlorite on TDS

The influence of coagulant dosage, Poly Aluminium Chloride (PAC) and calcium hypochlorite ($Ca(OCl)_2$), on the total dissolved solids (TDS) concentration in gambier wastewater is presented in Figure 2. While coagulation is primarily designed to remove suspended and colloidal particles, it also influences dissolved solids due to the chemical nature of the coagulants and their reaction by-products.

The data show a general trend of increasing TDS values with higher coagulant dosages for both chemical agents, indicating that the coagulation-flocculation process does not effectively reduce dissolved solids in the wastewater matrix. For calcium hypochlorite, TDS values increased from an initial 828 mg/L to 927, 932, 912, 904, 896, and 884 mg/L at concentrations of 10, 15, 20, 25, 30, and 40 mg/L, respectively. Similarly, the use of PAC resulted in TDS values rising from 828 mg/L to 933, 936, 940, 912, 895, and 892 mg/L for the same concentration series. The highest TDS was observed at 15 mg/L of calcium hypochlorite (932 mg/L) and 20 mg/L of PAC (940 mg/L).

This increase in TDS indicates that neither PAC nor calcium hypochlorite is effective in at reducing dissolved solids in wastewater. Instead, both coagulants are more effective at removing suspended solids (TSS) and turbidity through charge neutralization and particle aggregation. The increase in TDS is likely due to the introduction of ionic species from the coagulants themselves, such as Ca^{2+}, Al^{3+}, Cl^{-}, and OCl^{-}, which dissolve into the water and contribute to the total ionic load (Mwewa et al., 2019). These ions do not precipitate or form insoluble flocs, so they remain in solution and increase the measured TDS.

Furthermore, the presence of unreacted coagulant residues and their hydrolysis by-products may also contribute to the TDS levels, particularly at higher dosages. This finding is consistent with previous studies (Butler & Ford, 2018), which reported that coagulation processes are primarily effective for particulate removal rather than dissolved contaminants. These studies also highlighted that sedimentation time plays a critical role in improving TSS removal efficiency, but has a limited impact on dissolved constituents, such as TDS. Additionally, research on tofu industry wastewater (Butler & Ford, 2018) showed that TDS tended to increase post-coagulation due to residual coagulant ions, and on study evaluating the effectiveness of coagulation-floculation treatment using aluminium sulfate found that inorganic coagulants such as alum can add dissolved ions and raise TDS, reinforcing that coagulation targets particulates more than dissolved substances.

In summary, while coagulation-flocculation is a reliable method for reducing suspended solids and improving visual clarity, it has minimal impact or, in some cases, an adverse effect on TDS. Therefore, additional treatment steps such as adsorption, ion exchange, or membrane filtration would be necessary to target and reduce the dissolved fraction in the effluent if compliance with strict TDS discharge limits is required.

Effect of Coagulant Concentration (PAC and Ca(OCl)$_2$) on Color Removal

The influence of coagulant concentration on the color of gambier wastewater is illustrated in Figure 3. Visual observations were made before and after coagulation-flocculation using calcium hypochlorite and Poly Aluminium Chloride (PAC) at varying concentrations.

Figure 3 shows a clear transformation in the visual appearance in the wastewater's visual appearance. Subfigure (a) shows the raw wastewater prior to treatment, which exhibits a distinct yellow hue due to the high content of dissolved organic compounds, primarily tannins. Panels (b) and (c) demonstrate the visual changes after the addition of calcium hypochlorite and PAC, respectively, at concentrations of 10, 15, 20, 25, 30, and 40 mg/L. In both cases, the wastewater transitioned from a yellowish to nearly colorless appearance, indicating a substantial reduction in apparent color intensity. To support these qualitative observations, the visual characteristics of the treated wastewater at each coagulant dosage are summarized in Table 2. The table highlights the progressive reduction in color intensity and turbidity with increasing coagulant dosage, with optimal clarification observed at 30 mg/L for calcium hypochlorite and 20 mg/L for PAC, consistent with the COD and color removal trends discussed previously.

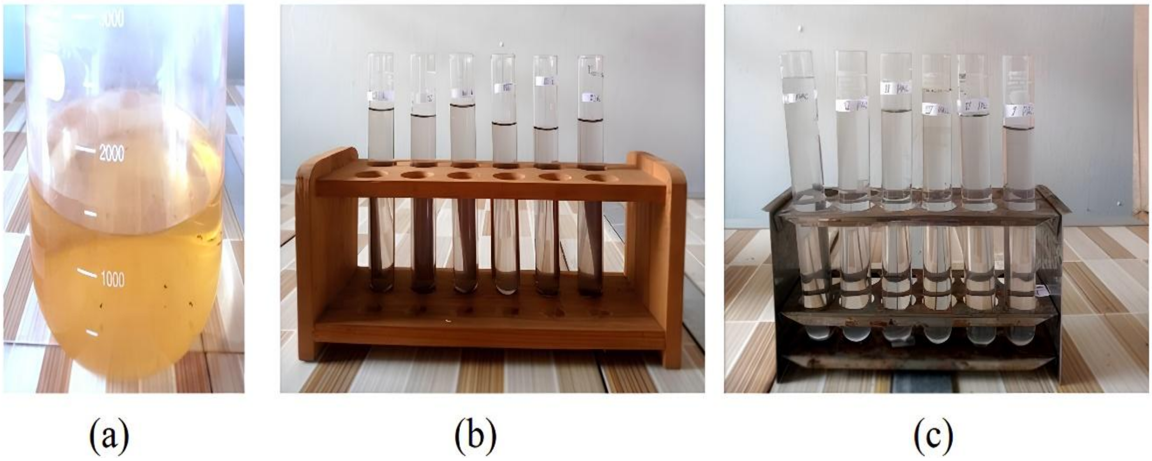


Figure 3. (a) Wastewater before coagulation-flocculation; (b) after addition of Ca(OCl)$_2$; (c) after addition of PAC

Table 2. Visual characteristics of gambier wastewater after coagulation

Treatment	Dosage (mg/L)	Visual Appearance	Interpretation
Raw wastewater	0	Dark yellow, opaque	High dissolved tannins and suspended matter
$Ca(OCl)_2$	10	Yellow, turbid	Initial destabilization of colloids
	15	Yellow, reduced turbidity	Partial coagulation and oxidation
	20	Light yellow	Improved removal of dissolved organics
	25	Pale yellow, clearer	Enhanced coagulation–oxidation effect
	30	Almost colorless, clear	Optimal color and organic matter removal
	40	Slight haze observed	Possible excess residual ions
PAC	10	Yellow-brown, turbid	Initial floc formation
	15	Yellow, reduced turbidity	Improved flocculation
	20	Nearly colorless, clear	Optimal coagulation performance
	25	Slight turbidity	Overdosing effect begins
	30	Yellowish, visible flocs	Restabilization of particles
	40	Turbid, floc residue	Excess coagulant

This discoloration is primarily due to the interaction between negatively charged particles in the wastewater and the positively charged species released by the coagulants. These electrostatic interactions play a pivotal role in the formation of flocs, which are aggregates of fine particles suspended in a liquid (Wang et al., 2015). The resulting flocs settle out of suspension, thereby removing both visible color and associated colloidal organic matter from the solution. Similar findings were reported by previous research (Rusydi et al., 2017), treated textile wastewater using a combination of coagulants, including calcium hypochlorite, lime, clay, and alum. Observed that coagulation-flocculation effectively reduced color from intensely dark to clear, alongside a decrease in COD from 615 mg/L to 130 mg/L, and (Badawi & Zaher, 2021) achieved color removal efficiencies up to 82% using ferric chloride ($FeCl_3$) in textile effluent treatment, further validating the role of coagulation in the decolorization of industrial wastewaters. In the present study, COD concentrations were reduced from 169.99 mg/L to between 71.43 mg/L and 31.25 mg/L, while TDS remained below 1000 mg/L. Most importantly, the treated effluent became visually apparent, indicating effective removal of chromophoric substances. These results demonstrate that the treated wastewater met the Indonesian effluent discharge standards specified in Ministerial Regulation No. 5 of 2014. Therefore, the post-treatment effluent is deemed safe for discharge into the environment or for reuse within the industrial process (Keskin et al., 2021).

Effect of Activated Carbon

The effect of adsorbent dosage on the removal of COD, TDS, and color was examined to evaluate its performance and feasibility as a physical treatment option. Activated carbon was applied in varying dosages: 1000, 2000, 3000, 4000, and 5000 mg/L, with a fixed contact time of 60 minutes under continuous stirring. The removal mechanisms, effectiveness, and implications of using activated carbon in agro-industrial wastewater treatment are discussed below.

Effect of Activated Carbon on COD

The relationship between the dosage of coal-based activated carbon (CW 130 AR) and the reduction of chemical oxygen demand (COD) in gambier wastewater is illustrated in Fig. 4. The adsorbent was applied at various concentrations: 1000, 2000, 3000, 4000, and 5000 mg/L, with a constant contact time of 60 minutes under continuous stirring. The resulting COD removal efficiencies were 96%, 93%, 89%, 77%, and 98%, respectively.

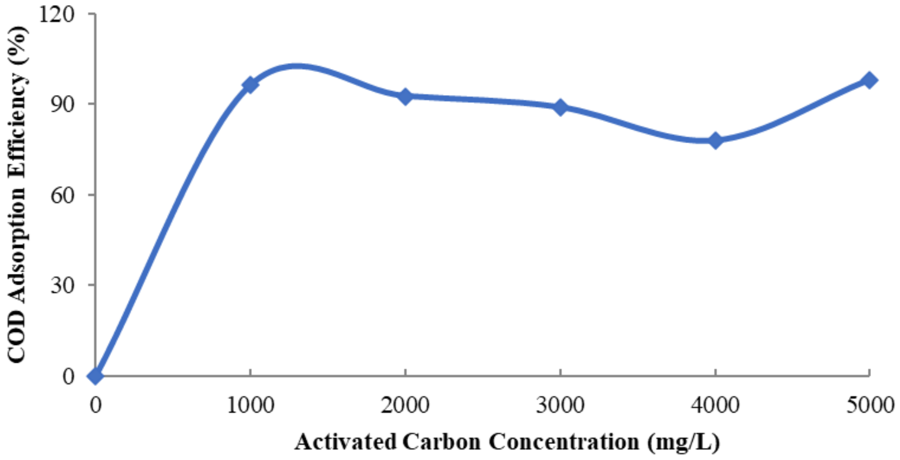


Figure 4. Effect of Activated Carbon Concentration on COD Adsorption Efficiency

As shown in Fig. 4, the COD adsorption efficiency generally increased with increasing activated carbon dosage, reaching a maximum removal efficiency of 98% at 5000 mg/L. At low adsorbent concentrations (1000 mg/L), the increase in removal efficiency can be attributed to the availability of abundant active sites on the activated carbon surface, allowing effective adsorption of dissolved organic compounds. However, a slight decline in COD removal efficiency was observed at intermediate dosages (2000–4000 mg/L). This phenomenon can be explained by particle aggregation and overlapping of adsorption sites, which reduces the effective surface area available for adsorption. At higher adsorbent loadings, excessive activated carbon particles may also lead to increased solution turbidity and mass-transfer limitations, hindering the diffusion of organic molecules into the adsorbent's internal pores. At the highest dosage of 5000 mg/L, the adsorption efficiency increased again, reaching its maximum value. This improvement is likely due to the dominance of total available adsorption sites over aggregation effects, as the substantially larger amount of activated carbon provided sufficient active surface area to compensate for particle interactions and restore effective adsorption. Additionally, at this concentration, enhanced contact probability between adsorbent particles and organic pollutants may further contribute to the observed increase in COD removal.

This indicates a strong dose-response relationship, where more adsorption sites were available at higher concentrations, enhancing the binding and removal of dissolved organic pollutants. These organics, which include tannins and phenolic compounds from gambier extract residues, contribute significantly to COD and are effectively adsorbed due to their high affinity for the porous carbon surface. This behaviour aligns with adsorption theory, which suggests that adsorption efficiency increases with greater adsorbent surface area, enabling more extensive interactions between the adsorbent and adsorbate (Satyam & Patra, 2024). The results are also consistent with those reported by another researcher (Badawi & Zaher, 2021) , who observed similar trends in COD removal from textile wastewater using nano zero-valent iron (nZVI), achieving efficiencies of 91% to 97%.

Importantly, the final COD concentrations after activated carbon treatment met the effluent quality standards stipulated in Indonesian Ministerial Regulation No. 5 of 2014. This suggests that the treated wastewater is environmentally compliant and may be suitable for safe discharge or potential reuse. As emphasised by previous researchers (Zahmatkesh et al., 2022), the decrease in COD indicates effective removal of oxygen-demanding substances, which is essential for reducing the environmental impact of industrial effluents.

Effect of Activated Carbon on TDS

The influence of activated carbon dosage on the removal of total dissolved solids (TDS) from gambier wastewater is shown in Figure 5. The adsorbent used was coal-based activated carbon (CW 130 AR), applied at concentrations of 1000, 2000, 3000, 4000, and 5000 mg/L. The corresponding TDS removal efficiencies were 84%, 85%, 85%, 84%, and 85%, respectively.

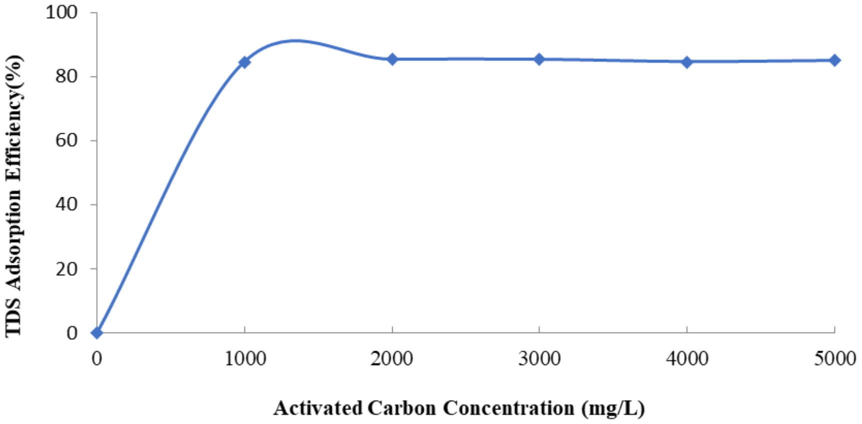


Figure 5. Effect of Activated Carbon Concentration on TDS Adsorption Efficiency

As presented in Figure 5, there was no significant improvement in TDS removal with increasing adsorbent concentration beyond 2000 mg/L. This plateau in efficiency suggests that adsorption of dissolved solids, primarily inorganic ions such as Ca^{2+}, Mg^{2+}, and Cl^{-}, was limited by the nature of the adsorbent and the operational conditions. Activated carbon generally has low affinity for small ionic species, particularly when unmodified, and is more suited for the removal of non-polar or moderately polar organic compounds. One contributing factor to the limited TDS removal was the relatively short contact time of 30 minutes and a mixing speed of 300 rpm. These operational parameters may have restricted the diffusion of ionic species into the internal pore structure of the activated carbon. As noted by previous researchers (Badawi et al., 2024), increasing the amount of activated carbon without extending the contact time does not guarantee improved adsorption efficiency for TDS. This observation is consistent with previous findings (Indihani et al., 2017) demonstrated that longer contact times ranging from 90 to 180 minutes significantly enhanced the adsorption of TDS from batik wastewater using activated charcoal.

Although the removal of TDS remained relatively constant across the range of dosages, all final TDS values were maintained below the regulatory threshold of 1000 mg/L, indicating compliance with national discharge standards (Ministerial Regulation of Environment and Forestry No. 5 of 2014). However, when strict TDS control is required, the adsorption process may need to be supplemented with other technologies such as ion exchange, reverse osmosis, or membrane filtration to achieve deeper reductions. In conclusion, while CW 130 AR activated carbon is highly effective in removing organic pollutants from gambier wastewater, its application for TDS reduction is limited under the tested conditions. These results highlight the importance of optimizing operational parameters, such as contact time and stirring speed, especially when targeting the removal of dissolved inorganic species.

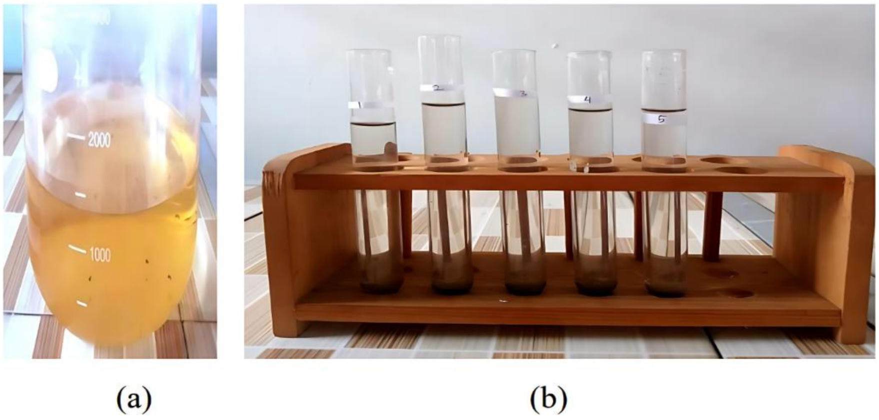


Figure 6. (a) Wastewater Before Adsorption; (b) Wastewater After Adsorption

Effect of Activated Carbon on Colour Removal

The influence of activated carbon dosage on the visual colour of gambier wastewater was evaluated through both qualitative observation and quantitative reduction in chromophoric intensity. Figure 6 illustrates the visible change in wastewater before and after adsorption treatment using coal-based activated carbon (CW 130 AR). Subfigure (a) shows the raw wastewater with a strong yellow colouration, while subfigure (b) depicts the clear effluent following adsorption

Visual inspection confirmed that the yellowish-brown hue of the untreated wastewater was significantly reduced across all tested concentrations, 1000, 2000, 3000, 4000, and 5000 mg/L. At every dosage level, the treated samples became progressively clearer, and at higher concentrations, the wastewater appeared nearly colorless. This indicates that CW 130 AR is highly effective at removing color-causing compounds from gambier effluent through physical adsorption. The strong decolorization capability of activated carbon is primarily attributed to its large specific surface area, well-developed microporous structure, and substantial mesopore volume. These properties enable the adsorbent to capture a wide range of dissolved organic molecules, including tannins, polyphenols, and other chromophores that contribute to the intense coloration of the wastewater. As noted by previous researcher (Badawi et al., 2024), the extended pore networks of activated carbon provide sufficient adsorption space for these organic pollutants, enhancing overall color removal performance.

In conclusion, coal-based activated carbon demonstrates excellent performance in removing color from gambier wastewater, making it a suitable option for polishing treatment or as a standalone method in systems where minimal chemical use is desired. The simplicity of the process, combined with its effectiveness, supports its potential for broader implementation in small to medium-scale agro-industrial wastewater treatment settings.

Adsorption Isotherms of Langmuir and Freundlich

Performance of PAC, calcium hypochlorite ($Ca(OCl)_2$), and coal-based activated carbon (CW 130 AR) was further evaluated using two commonly applied isotherm models: Langmuir and Freundlich. These models are used to describe the equilibrium relationship between the concentration of adsorbate in the liquid phase and the amount adsorbed onto the solid phase at constant temperature. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with finite and identical sites, where no interaction occurs between adsorbed molecules. In contrast, the Freundlich isotherm is an empirical model that applies to heterogeneous surfaces and multilayer adsorption, as shown in Table 3.

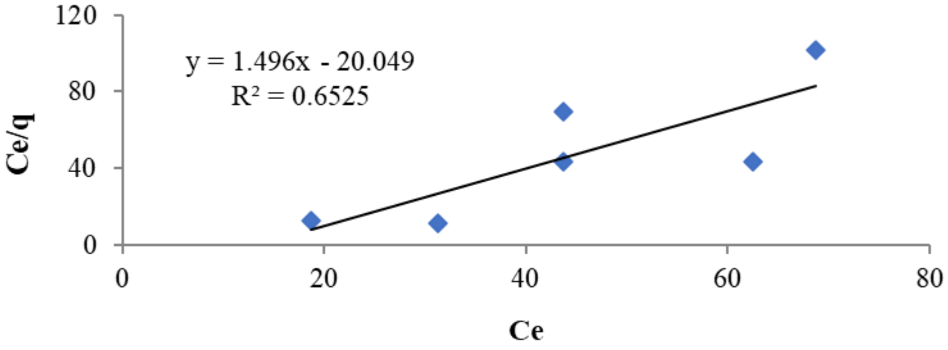
The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with finite and identical sites, where no interaction occurs between adsorbed molecules. In contrast, the Freundlich isotherm is an empirical model that applies to heterogeneous surfaces and multilayer adsorption. The experimental data were plotted based on the linearized equations of each model and are presented in Figure 7 (Langmuir) and Figure 8 (Freundlich). The determination coefficient (R^2) was used as an indicator of model fit for each adsorbent/coagulant.

Table 3. Langmuir and Freundlich Isotherm Equations

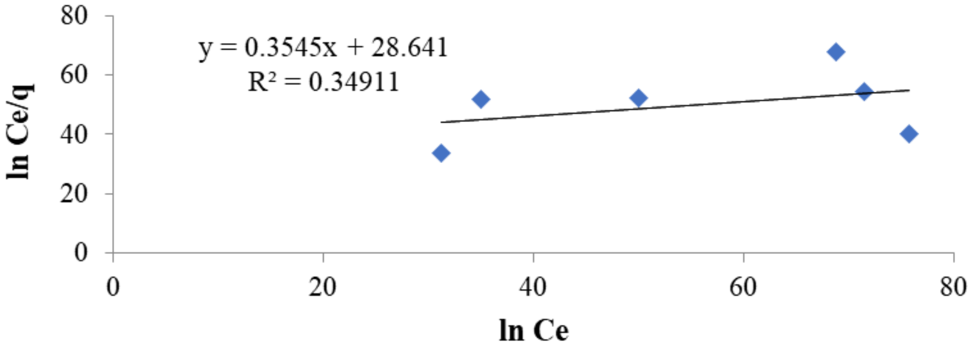
Isotherm	Equation
Langmuir	$\frac{C_e}{q} = \frac{1}{q_m} C_e + \frac{1}{K_L x\, q_m}$
Freundlich	$\boldsymbol{\ln q_e = \frac{1}{n} \ln C_e + \ln(K_f)}$

As shown in Fig. 7, the Langmuir adsorption isotherm describes the relationship between the equilibrium concentration of COD in the solution (Ce) and the amount of COD adsorbed per unit mass of adsorbent (qe). Among the three treatment agents tested, coal-based activated carbon exhibited the best linear correlation with the Langmuir model, achieving a determination coefficient (R^2) of 0.9488, indicating that COD removal follows monolayer adsorption behaviour on a homogeneous surface. In contrast, PAC showed a moderate correlation ($R^2 = 0.6525$), suggesting that while some adsorption interactions occur, the predominant mechanisms are coagulation and charge neutralisation rather than true surface adsorption. Calcium hypochlorite exhibited the weakest Langmuir fit with an R^2 value of 0.3491, further confirming that its primary function is coagulation/flocculation rather than adsorption.

a) PAC



b) Ca(OCl₂)



c) Activated Carbon

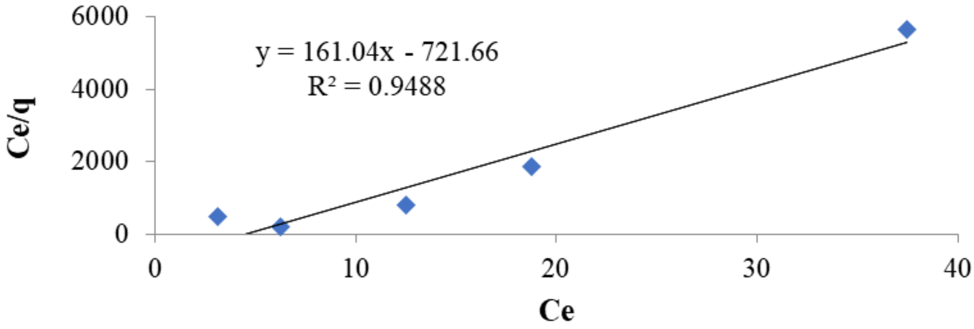
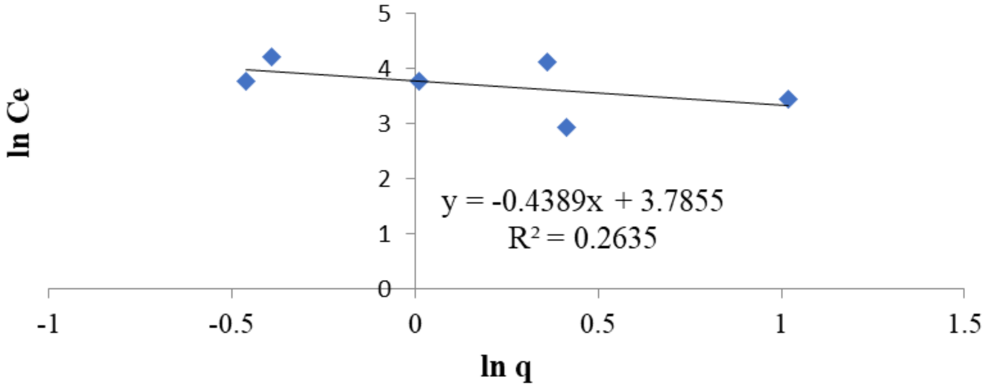


Figure 7. Langmuir adsorption isotherm plots for (a) PAC, (b) $Ca(OCl_2)$, and (c) coal-based activated carbon (CW130 AR)

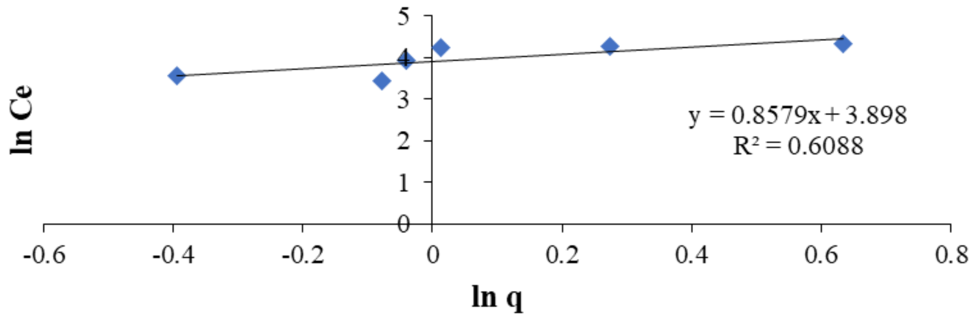
The results suggest that activated carbon removal is primarily governed by chemisorption, a process involving specific interactions between adsorbate molecules and active sites on the carbon surface, resulting in monolayer coverage. Conversely, PAC and calcium hypochlorite remove COD mainly through particle destabilisation and floc formation. These differences in mechanistic behavior highlight the complementary roles of adsorption and coagulation in wastewater treatment systems. For coal-based activated carbon, the Freundlich plot yielded a very low determination coefficient ($R^2 = 0.0567$), indicating a poor fit to this model.

As illustrated in Figure 8, the Freundlich isotherm model describes the adsorption process on heterogeneous surfaces and allows for the possibility of multilayer adsorption. However, the adsorption of COD from gambier wastewater onto the tested treatment agents showed varying degrees of agreement with this model. For coal-based activated carbon, the Freundlich plot yielded a very low determination coefficient ($R^2 = 0.0567$), indicating a poor fit to this model. This result suggests that adsorption on activated carbon is better represented by the Langmuir isotherm, confirming that COD removal occurs predominantly through monolayer adsorption on a homogeneous surface with uniform adsorption energy. In contrast, PAC and calcium hypochlorite demonstrated slightly better linearity with the Freundlich model compared to their Langmuir fits. It suggests that for PAC had an R^2 of 0.2635, while calcium hypochlorite achieved an R^2 of 0.6088, indicating a moderate fit. It suggests that for PAC and calcium hypochlorite, COD removal may involve a combination of mechanisms, including limited surface adsorption alongside coagulation and flocculation.

a) PAC



b) $Ca(OCl_2)$



c) Activated Carbon

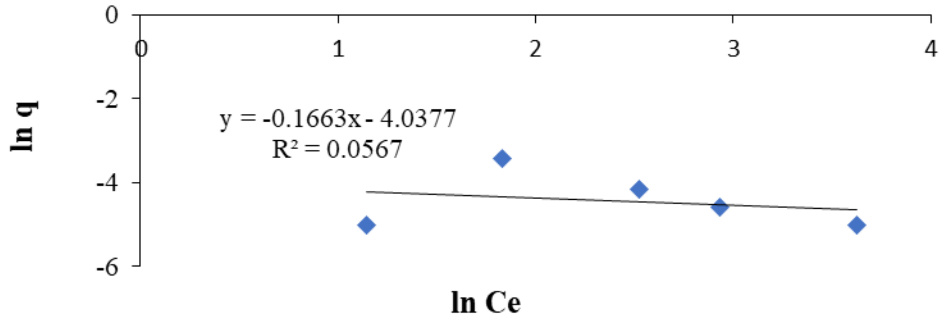


Figure 8. Freundlich adsorption isotherm plots for (a) PAC, (b) calcium hypochlorite, and (c) coal-based activated carbon (CW 130 AR)

Table 4. Isotherm Constants and Correlation Coefficients (R^2)

Agent	Model	R^2	Mechanism Interpretation
Activated Carbon (CW 130 AR)	Langmuir	0.9488	Strong monolayer chemisorption
	Freundlich	0.0567	Weak multilayer adsorption
PAC	Langmuir	0.6525	Moderate, partial surface interaction
	Freundlich	0.2635	Low, minimal multilayer adsorption
Calcium Hypochlorite	Langmuir	0.3491	Poor surface adsorption fit
	Freundlich	0.6088	Moderate heterogeneous adsorption, but likely coagulation-dominated

These findings further reinforce the conclusion that activated carbon operates through an actual adsorption mechanism, while PAC and calcium hypochlorite primarily function through colloidal destabilization and particle aggregation rather than extensive adsorption interactions.

Adsorption Isotherm Analysis: Comparative Mechanisms

Figure 7 and Figure 8 present the linearized plots for the adsorption isotherms (Langmuir and Freundlich) of COD removal for three treatment agents: calcium hypochlorite ($Ca(OCl)_2$), PAC, and coal-based activated carbon (CW 130 AR). The constants and correlation coefficients are summarized in Table 2.

For activated carbon, the Langmuir model fitted the data excellently with a coefficient of determination (R^2) of 0.9488, indicating strong monolayer adsorption on a homogeneous surface and suggesting chemisorption. In contrast, the Freundlich fit was poor ($R^2 = 0.0567$), indicating that multilayer adsorption on heterogeneous surfaces was unlikely. This behavior aligns with findings from previous research that reported similar Langmuir dominance in COD removal by activated carbon (Almadani, 2023). In comparison, PAC exhibited moderate Langmuir conformity ($R^2 = 0.6525$) and low Freundlich fit ($R^2 = 0.2635$), indicating a minor role for adsorption in its mechanism. Calcium hypochlorite followed a somewhat opposite trend: the Freundlich fit ($R^2 = 0.6088$) was superior to the Langmuir fit ($R^2 = 0.3491$), suggesting heterogeneous adsorption, likely indicating initial adsorption preceding coagulation. These findings suggest that PAC and calcium hypochlorite primarily act through coagulation/flocculation rather than true surface adsorption, which aligns with the literature reporting aggregate-formation mechanisms over adsorption with similar coagulants (Lakdawala & Lakdawala, 2012; Radhi, 2020).

The isotherm analysis in this study thus provides strong evidence that activated carbon is the optimal choice for targeting dissolved organic pollutants through adsorption, while coagulants are more effective for sedimentation and removal of colloidal particles and larger aggregates. This mechanistic insight supports the design of hybrid or sequential treatment systems that capitalize on both coagulation and adsorption stages for comprehensive water purification.

CONCLUSION

This study compared chemical coagulation and physical adsorption for treating gambier industry wastewater and demonstrated that Poly Aluminium Chloride (PAC) and calcium hypochlorite were effective in reducing COD and color but showed limited performance in decreasing TDS, with increased dissolved solids observed at higher dosages. In contrast, coal-based activated carbon (CW 130 AR) achieved superior removal of dissolved organic compounds and color, producing a clear effluent that met national discharge standards. Adsorption isotherm analysis confirmed that COD removal by activated carbon followed the Langmuir model ($R^2 = 0.9488$), while PAC and calcium hypochlorite exhibited negligible adsorption behavior. Overall, coagulation was more suitable for suspended and colloidal pollutant removal, whereas adsorption was more effective for dissolved organic matter, indicating that an integrated coagulation–adsorption treatment system can optimize pollutant removal efficiency and improve wastewater management in the gambier industry. This work contributes to Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 12 (Responsible Consumption and Production) by reducing industrial pollution loads, enhancing treatment efficiency, and supporting cleaner production and potential water reuse in agro-industrial processes.

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