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# Performance of Hybrid Coagulation–Adsorption as a Physicochemical Separation Process for Removal of Organic Pollutants and Heavy Metals from Chemical Laboratory Wastewater

**Gang Dong[1], Ermieza Sinin[2], Fahad Abu Mallouh[3]**
[1]College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China
[2]Department of Chemical Engineering, Universiti Malaysia Sabah, Malaysia
Department of Chemical Engineering, Australian University, Australia

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## ABSTRACT

**Purpose of the study:** This study aims to evaluate the performance of a hybrid coagulation and adsorption system as a physicochemical separation process for removing organic pollutants and heavy metals such as iron, manganese, and chromium from chemical laboratory wastewater, as well as to determine optimum operating conditions to improve separation efficiency.

**Methodology:** The study used a batch experimental method consisting of coagulation followed by adsorption. Coagulation was carried out using aluminum sulfate, polyaluminum chloride, and commercial coagulants under controlled conditions of acidity, dosage, and mixing to promote particle destabilization and floc formation. The adsorption process used activated carbon and zeolite with controlled contact time and adsorbent dosage. Parameters analyzed included turbidity, total suspended solids, total dissolved solids, electrical conductivity, chemical oxygen demand, and metal concentrations.

**Main Findings:** The coagulation process significantly improved solid–liquid separation, achieving reductions in turbidity (93.5%), Total Suspended Solids (69.13%), Total Dissolved Solids (46.95%), conductivity (72.33%), and heavy metals, including Fe (85.53%), Mn (55.84%), and Cr (43.07%). However, Chemical Oxygen Demand reduction during coagulation was limited (7.4%), indicating low removal of dissolved organic compounds. The subsequent adsorption stage enhanced Chemical Oxygen Demand removal up to 58.53% using activated carbon and 54.61% using zeolite.

**Novelty/Originality of this study:** This study evaluates a hybrid coagulation and adsorption system as a multi-stage physicochemical separation process for complex laboratory wastewater. The novelty lies in integrating bulk separation and surface-based removal to improve overall performance and reveal process interactions affecting pollutant removal.

***Corresponding Author:***
Gang Dong,
College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China
Email: gdgangong001@gmail.com

## 1. INTRODUCTION

The treatment of chemical laboratory liquid waste is a critical issue in environmental and chemical engineering due to its high content of organic matter and heavy metals, which have the potential to pollute the environment and endanger human health [1], [2]. This waste generally contains complex compounds such as iron, manganese, and chromium, which are toxic and difficult to degrade naturally. Without proper treatment, this waste can cause serious ecosystem damage [3], [4]. Therefore, effective and applicable treatment methods are required to reduce pollutant levels [5], [6]. From a separation science perspective, the treatment of such wastewater involves physicochemical processes to separate suspended, colloidal, and dissolved contaminants from the liquid phase.

Coagulation is a widely used method in wastewater treatment to remove suspended particles and some organic matter [7], [8]. This process works by adding coagulants that destabilize colloidal particles, allowing them to aggregate into larger flocs that can be easily separated. In the context of separation processes, coagulation plays an important role in solid–liquid separation through charge neutralization and particle aggregation mechanisms [9], [10]. These interactions are commonly explained by the Derjaguin–Landau–Verwey–Overbeek theory, where the reduction of electrostatic repulsion enables van der Waals attraction to dominate, resulting in floc formation [11], [12].

However, coagulation alone has limitations in removing dissolved pollutants, particularly low-molecular-weight organic compounds and dissolved metal ions [13], [14]. Therefore, additional treatment methods are required to improve overall separation efficiency [15], [16]. Adsorption is an effective method for removing dissolved contaminants due to its ability to bind pollutants onto the surface of an adsorbent [17], [18]. This process involves surface interaction mechanisms such as pore diffusion and ion exchange, which allow the removal of organic compounds and heavy metals that are not effectively eliminated during coagulation.

The integration of coagulation and adsorption represents a hybrid physicochemical separation system that combines bulk phase separation and surface-based removal mechanisms [19], [20]. In this approach, coagulation reduces the initial pollutant load through floc formation, while adsorption enhances the removal of remaining dissolved contaminants [21], [22]. This multi-stage process has the potential to improve overall separation efficiency and optimize treatment performance for complex wastewater systems [23], [24].

Previous studies have explored hybrid and advanced treatment methods for wastewater; however, important gaps remain in understanding integrated separation performance. The study by Arita et al. [25] focused on the use of Fenton oxidation combined with coagulation and adsorption as a pretreatment process, emphasizing oxidative degradation rather than a detailed evaluation of physicochemical separation mechanisms. Meanwhile, Amr et al. [26] investigated heavy metal removal using natural adsorbents combined with chemical coagulation, but the study primarily emphasized material efficiency without analyzing the interaction between coagulation and adsorption stages in a multi-stage system. In contrast, the present study specifically examines the integration of coagulation and adsorption as a sequential physicochemical separation process, with a focus on both organic pollutants and heavy metals in complex laboratory wastewater. Therefore, this research addresses the gap by evaluating not only removal efficiency but also the interaction between bulk phase separation and surface-based mechanisms that influence overall separation performance.

In addition, the novelty of this study lies in the integration of coagulation and adsorption as a hybrid physicochemical separation system specifically applied to complex chemical laboratory wastewater [27], [28]. Unlike previous studies that tend to evaluate these processes separately, this research emphasizes the interaction between bulk phase separation and surface-based removal mechanisms in a multi-stage system. This approach not only evaluates removal efficiency but also highlights how process interactions influence overall separation performance.

The urgency of this study is driven by the increasing volume and complexity of chemical laboratory wastewater, which contains a mixture of organic compounds and toxic heavy metals that are difficult to treat using conventional single-stage methods. Inadequate treatment may lead to the accumulation of hazardous pollutants in the environment, posing significant risks to ecosystems and human health [29], [30]. Therefore, the development of an effective and integrated separation process is essential to improve wastewater treatment performance and ensure environmental safety. Therefore, this study aims to evaluate the effectiveness of a hybrid coagulation and adsorption system as a multi-stage physicochemical separation process for chemical laboratory wastewater. The study focuses on separation efficiency, process optimization, and the interaction between coagulation and adsorption mechanisms in order to provide a more comprehensive understanding of hybrid separation systems.

## 2. RESEARCH METHOD

The experimental design was conducted using a batch system with controlled variations in pH, coagulant dosage, and adsorbent concentration to determine optimal separation conditions [31], [32]. Each experiment was performed in triplicate, and the results were expressed as mean values. The treatment process consisted of two sequential stages, namely coagulation and adsorption [33], [34]. The coagulation stage was applied as a primary separation process to destabilize colloidal particles and reduce pollutant load, followed by adsorption as a secondary process to remove dissolved contaminants.

### 2.1. Equipment and Chemicals

The equipment used in this study included porcelain crucibles, stirring rods, spatulas, volumetric flasks, Erlenmeyer flasks, droppers, graduated pipettes, volumetric pipettes, beakers, bulbs, analytical balances, dropping burettes, funnels, ring stands, spray bottles, hot plates, ovens, pH meters, mercury thermometers, conductometers, turbidimeters, water baths, and magnetic stirrers. Additionally, a UV-Vis spectrophotometer was used to analyze organic compound levels [35], [36]. Heavy metal concentrations were determined using an Atomic Absorption Spectrophotometer. All analyses were conducted on samples of chemical laboratory liquid waste obtained from the chemistry laboratory facilities of the Department of Chemistry.

The materials used in this study included samples of chemical laboratory liquid waste obtained from several laboratories, namely the affiliated laboratory, physical chemistry laboratory, and inorganic chemistry laboratory. The waste used consisted of a mixture of organic waste such as ethanol, acid waste such as $H_2SO_4$, alkaline waste such as NaOH, and heavy metals collected in one large container over a six-month period. The coagulants used consisted of several types, namely aluminum sulfate ($Al_2(SO_4)_3$/alum), Poly Aluminum Chloride, and commercial coagulants trimer 3626 and trimer 6784 whose chemical composition is not specifically known. The adsorbents used were zeolite and activated carbon obtained from a chemical store. Other chemicals used included distilled water, concentrated $H_2SO_4$, $HgSO_4$, $Ag_2SO_4$, standard solution of Potassium Hydrogen Phthalate, $Na_2C_2O_4$, $KMnO_4$, $AgNO_3$, and boiling stones.

### 2.2. Working Method

Initial characterization of wastewater was conducted by measuring pH, temperature, turbidity, and electrical conductivity using calibrated instruments. Chemical oxygen demand, total suspended solids, total dissolved solids, and permanganate value were analyzed using standard methods, including closed reflux, gravimetric analysis, and titration [37], [38]. Heavy metal concentrations were determined using an Atomic Absorption Spectrophotometer.

The coagulation process was carried out by adding a predetermined dose of coagulant to 100 mL of wastewater under controlled pH conditions. Rapid mixing was conducted at 150 rpm for 2 minutes, followed by slow mixing at 40 rpm for 15 minutes to promote floc formation. The mixture was then allowed to settle for 30 minutes to achieve solid–liquid separation. The supernatant was collected for further analysis.

The adsorption process was performed by adding activated carbon or zeolite to the coagulated wastewater at various concentrations [39], [40]. The mixture was agitated at 120 rpm for 60 minutes to ensure sufficient contact between adsorbent and solution. After adsorption, the samples were filtered, and the filtrate was analyzed for residual organic and metal concentrations. The removal efficiency was calculated using the following equation:

$$Removal\ Efficiency\ (\%) = \frac{C_0 - C_t}{C_0} \text{ x } 100 \ldots (1)$$

where $C_0$is the initial concentration and $C_t$is the final concentration after treatment. The adsorption capacity was determined using:

$$q = \frac{(C_0 - C_t)\,V}{m} \ldots (2)$$

where $q$is the adsorption capacity (mg/g), $V$is the volume of solution (L), and $m$is the mass of adsorbent (g).

Adsorption data were analyzed using Langmuir and Freundlich isotherm models to evaluate surface interaction characteristics [41], [42]. In addition, kinetic models, including pseudo-first-order and pseudo-second-order, were applied to determine the rate-controlling mechanism of the adsorption process.

## 3. RESULTS AND DISCUSSION

### 3.1. Initial Waste Before Coagulation and Adsorption Process

In this study, a preliminary test was conducted to observe the initial state of chemical laboratory waste in terms of pH, temperature, conductivity, Total Suspended Solids, Total Dissolved Solids, TOC, Chemical Oxygen Demand, and heavy metals contained in the waste before waste treatment using coagulation and adsorption methods. Physically, the color of the resulting waste is bluish green, as seen in Figure 1.

Figure 1. Initial Waste Before Coagulation Process

The waste tested came from several chemistry laboratories, including affiliated laboratories, physical chemistry laboratories, and inorganic chemistry laboratories. The waste consisted of organic waste (fat, protein, ethanol, cellulose), acid waste ($H_2SO_4$), base waste (KOH, NaOH), and heavy metals collected over a six-month period. The waste was mixed until homogeneous and collected in large plastic containers until the waste volume was sufficient for processing.

The results of measuring the initial condition of the waste before the waste processing process is carried out are as follows:

- pH : 2.5
- Temperature : 26°C
- Conductivity : 101.2 mS
- Turbidity : 45.64 NTU

### 3.2. Waste Analysis After Treatment with Coagulation and Adsorption Methods

The results of measuring the condition of the waste after the coagulation process are shown in Table 1, as follows:

Table 1. Final Waste Analysis

| pH Total Dissolved Solids (mg/L) | Analysis Method | Initial Concentration | Concentration after (coagulation) | % Adsorption Content of Activated Carbon | % Zeolite Adsorption Content | Wastewater Quality Standard Classification | |
|---|---|---|---|---|---|---|---|
| | | | | | | I | II |
| Total Suspended Solids (mg/L) | pH meter | 2,45 | 4-7 | | | 6-9 | 6-9 |
| Temperature (oC) | Gravimetry | 8997 | 4773 | | | 2000 | 4000 |
| Turbidity (NTU) | Gravimetry | 367 | 113,3 | | | 200 | 400 |
| Chemical Oxygen Demand (mg/L) | Thermometer | 26 | 26 | | | 38 | 40 |
| KMnO4 (mg/L) | Turbidimetry | 45,64 | 2,97 | | | | |
| Fe (mg/L) | Spectrophotometry | 2668,55 | 2470,75 | -58,53 | -54,61 | 100 | 300 |
| Mn (mg/L) | Permanganometry | 23,91 | 12,22 | | | | |
| pH | Atomic Absorption Spectrophotometer | 75,54 | 10,92903 | + 3,95 | +1,22 | 5 | 10 |
| Total Dissolved Solids (mg/L) | Atomic Absorption Spectrophotometer | 1,8799 | 0,8300 | +63,8 | +11,03 | 2 | 5 |
| Cr (mg/L) | Atomic Absorption Spectrophotometer | 3,3681 | 1,9174 | +7,5 % | -38,67 | 0,5 | 1 |

Based on the data results, waste processing by coagulation can reduce Total Suspended Solid = 69.13%, Total Dissolved Solid = 46.95%, electrical conductivity = 72.33%, turbidity = 93.5%, KMnO4 = 48.89%, organic content (Chemical Oxygen Demand) = 7.4%, and heavy metal content Fe = 85.53%, Mn = 55.84%, Cr = 43.07%. Meanwhile, the pH value becomes high and the temperature value remains constant. The adsorption process with activated carbon can reduce organic content (Chemical Oxygen Demand) = 58.53%, but there is an increase in Fe metal content = 3.95%, Mn metal = 63.8%, and Cr metal = 7.5%. Meanwhile, adsorption with zeolite can reduce organic content (Chemical Oxygen Demand) = 54.61% and Cr metal = 38.67%, but there is an increase in Fe metal content = 1.22% and Mn metal = 11.02%. Organic content decreased after the adsorption process, but not too significantly and still far above the liquid waste quality standard.

pH is a parameter that indicates the number of H+ ions in a solution. The pH value of a body of water characterizes the balance between acid and base in the water and is a measure of the hydrogen ion concentration in the solution [43], [44]. pH measurement is important for wastewater, as acidic waste can cause scale formation and corrosion, as well as toxins that are harmful to the environment. In this study, especially in the coagulation process, determining the optimum pH is the right step and influences the formation of large flocs. Based on Table 4.2, the optimum pH obtained is at pH 4-7, with the wastewater being neutral. This is very good and safe for the environment, preventing scale formation or corrosion when the treated wastewater is discharged into the environment. The turbidity level was then tested using a tubidimeter, and the pH range of 4-7 produced lower turbidity values compared to pH 8-12, where the turbidity level increased.

Temperature significantly influences the solubility of a substance, as the higher the temperature, the greater the heat generated [45], [46]. Therefore, it can be concluded that the higher the temperature, the higher the solubility of a substance, and vice versa. The temperature of the chemical laboratory liquid waste samples was measured using a mercury or alcohol thermometer with a temperature range of 0-100°C or greater. In this study, the appropriate temperature for the wastewater conditions was room temperature, where dissolved solids and colloids contained in the wastewater can precipitate or coagulate during the coagulation process [47], [48]. Therefore, the optimal temperature for laboratory liquid waste treatment is room temperature, as it will not interfere with the chemical reactions taking place, and once released into the environment, the processed wastewater will not harm aquatic life.

Electrical conductivity is a measure of the ability of wastewater to conduct an electric current. Conductivity is measured using a conductometer. Its working principle is to measure the ratio of the electric current through a cell to the applied voltage [49], [50]. The capacity or ability of wastewater to generate an electric current is closely related to the total concentration of ionized substances in the water. Solutes, such as strong and weak electrolytes, ionic charge, variations in ionic mobility, ionic strength in solution, and water temperature will affect the specific conductivity of a solution. Inorganic compounds, such as heavy metals that can also conduct electricity and are contained and dissolved in wastewater, are generally found in the form of ions. These ions conduct electricity and move toward electrodes immersed in the solution. Negatively charged ions will migrate toward the positive electrode, and conversely, positively charged ions will migrate toward the negative electrode. This principle is similar to that of an electrolytic cell.

In this study, there was a decrease in the electrical conductivity value, at the optimum pH obtained ranging from pH 4-7 where the waste condition is in an acidic state towards neutral. The electrical conductivity value (DHL) can be high due to the addition of NaOH to obtain the optimum condition of the coagulant, where the high Na conductivity value is 50 ohm-1.cm2 so that it affects the increase in the electrical conductivity value obtained at pH 4-7. The initial waste conductivity value is 101.2 mS at pH 2.5. The conductivity value obtained after the coagulation process for each type of coagulant used in this study is shown in Table 2 with the optimum pH condition at pH 6 as follows:

Table 2. Conductivity Values of Each Type of Coagulant in Optimum Conditions with Conductometry

| Parameter | Coagulant Type | Initial Analysis | Final Analysis (pH 6) |
|---|---|---|---|
| Electrical Conductivity (mS) | Alum | 101,9 | 29,2 |
| | Polyaluminum Chloride | 100,2 | 29,0 |
| | Trimer 3626 | 101,5 | 28,8 |
| | Trimer 6784 | 101,2 | 28,0 |

Table 2 shows that the lowest electrical conductivity value was obtained from wastewater treated with trimer 6784 coagulant, which is suitable for the chemical laboratory wastewater used in this study. The value obtained was 28.0 mS at pH 6, resulting in a reduction percentage of 72.33%. Therefore, the chemical laboratory wastewater sample after coagulation is safe for release into the environment, as the electrical conductivity, a measure of the wastewater's ability to conduct electrical current, is reduced.

Total Dissolved Solids is an analysis of dissolved solids content, typically similar to Total Suspended Solids, as the water sample solution being analyzed contains a certain amount of solids, such as samples from river water. In this study, the initial Total Dissolved Solids value was 8997 mg/L, but decreased after coagulation to 4773 mg/L, a reduction percentage of 46.95%. In the process, an empty beaker is oven-dried until it reaches a constant mass. A 100 mL sample of laboratory liquid waste is then placed into the beaker and evaporated on a hot plate to determine the total mass of dissolved solids in a solution that is not filtered by the filter paper in the Total Suspended Solids process. The evaporation product is then oven-dried until it reaches a constant mass, allowing the Total Dissolved Solids value to be obtained by subtracting the mass of the final beaker from the mass of the empty beaker.

Total Suspended Solids is a measurement of the number of mg/L of insoluble or suspended solids and is typically found as sandy or muddy solids. Dissolved solids in the Total Suspended Solids process consist of suspended solids and colloids contained in the wastewater [51], [52]. Therefore, a wastewater filtration process is carried out. The process involves weighing the initial mass of the empty filter paper, which is then oven-dried until it reaches a constant mass. Next, the 100 mL sample is filtered using Whatmann filter paper with a diameter of 47 mm, then oven-dried and weighed until its mass is constant. The purpose of heating to obtain a constant mass is to ensure that no water content affects the results of the filtered suspended dissolved solids. In this study, the initial Total Suspended Solid value obtained was 367 mg/L and decreased after the coagulation processing process to 113.3 mg/L with a reduction percentage of 69.13%.

Turbidity analysis is a method of analyzing the transparency of a sample, specifically related to the presence of particles in the sample. Turbidity parameters are measured using a turbidimeter. In research, various factors influence errors or disturbances. These include a dirty cuvette, the presence of air bubbles in the cuvette, vibrations that cause water movement in the cuvette, and the presence of coarse sediment that easily settles during the reading process.

In this study, the initial turbidity value was 45.64 NTU, and after coagulation, the turbidity decreased to 2.97 NTU, a 93.5% reduction. This reduction was achieved under optimal coagulation conditions, with the addition of 19.2 mg/100 mL of coagulant, and Trimer 6784, which yielded the lowest turbidity value of 2.97 NTU. The low turbidity value indicates that the wastewater produced after the coagulation process is clear and not cloudy, making it environmentally friendly due to the reduction in colloids and other suspended solids.

In this study, the permanganate (KMnO4) content decreased from 23.91 mg/L to 12.22 mg/L using the titration method, a percentage reduction of 48.89%. This permanganate value indicates a decrease in the organic content of the chemical laboratory wastewater. The principle of the permanganate value is the amount of permanganate used to oxidize organic compounds in the wastewater sample. Excess permanganate is reduced by oxalic acid using the titration method. The excess oxalate is then titrated back with potassium permanganate solution. The permanganate reaction used to oxidize organic compounds in the wastewater sample is as follows:

$$C_xH_yO_z + KMnO_4 \rightarrow CO_2 + H_2O$$

Excess potassium permanganate is reduced by oxalic acid, the reaction that occurs is as follows:

$$2KMnO_4 + 5\,H_2C_2O_4 + 3\,H_2SO_4 \rightarrow 2\,MnSO_4 + K_2SO_4 + 10\,CO_2 + 8\,H_2O$$

Thus, the permanganate used successfully oxidized organic compounds in the tested chemical laboratory liquid wastewater samples.

The results of the determination of Chemical Oxygen Demand are widely used to measure the pollution load of wastewater or waste. The results of the determination of Chemical Oxygen Demand indicate the total oxygen requirement to oxidize organic materials in water samples into CO2 and H2O. After going through the adsorption process, the organic content (Chemical Oxygen Demand) in the waste was measured using the UV-Vis spectrophotometry method. The Chemical Oxygen Demand value obtained after the addition of 25 grams of activated carbon adsorbent produced 1024.5 mg/L with a percentage reduction of 58.53%. In addition, color changes also occurred in liquid waste samples where the silica element contained in activated carbon is a hard and insoluble material content in water, functioning as a cleaner of particles contained in cloudy water to obtain clear water. In addition, the structure of activated carbon is amorphous and has certain crystalline properties, is porous, and has a large surface area. Activated carbon can adsorb organic compounds in chemical laboratory liquid waste samples through porous holes on the surface of the activated carbon, trapping these pollutants, particularly organic compounds, and entering the pores on the surface of the activated carbon [53], [54]. Consequently, the color, odor, and organic content of chemical laboratory liquid waste samples are absorbed. Meanwhile, for adsorption with zeolite adsorbents, the color of the test waste samples remained yellow.

However, as the adsorbent content increased, the waste color became clearer (clear yellow), and the percentage reduction in Chemical Oxygen Demand with zeolite adsorbents was 54.61%. This is because the zeolite's adsorbent capacity increases with increasing zeolite weight, and the rate of cation exchange in zeolite is influenced by the size of the zeolite grains. Zeolite, which has a hollow structure that is usually filled with water and cations, can exchange with negatively charged colloids [55], [56]. Furthermore, unsaturated or polar molecules more easily pass through, so organic compounds are not completely adsorbed by the zeolite adsorbent. The results obtained indicate that the adsorption process with activated carbon and zeolite can reduce organic content along with the increasing addition of activated carbon adsorbent. However, the organic content obtained is still above the wastewater quality standard limit. Some of these parameters, after the coagulation process, decreased to within the wastewater quality standard, namely Total Dissolved Solid, Total Suspended Solid, turbidity, KMnO4, and heavy metals Fe, Mn, Cr. However, for the Chemical Oxygen Demand parameter, after the coagulation and adsorption processes, the Chemical Oxygen Demand level is still high and does not meet the wastewater quality standard. Therefore, further processing is needed, such as the addition of adsorbents and the presence of activation treatment and biological treatment to reduce organic content.

The coagulation process showed significant effectiveness in improving solid–liquid separation, as indicated by the substantial reduction in turbidity and total suspended solids [57], [58]. This result confirms that coagulation successfully destabilizes colloidal particles through charge neutralization and promotes floc formation. The aggregation of particles into larger flocs facilitates their removal through sedimentation. In addition, the reduction in total dissolved solids and conductivity suggests partial removal of dissolved ionic species [59], [60]. However, the relatively low reduction in organic content indicates that coagulation alone is insufficient for removing dissolved organic pollutants.

The adsorption process further improved the removal of organic contaminants through surface interaction mechanisms. Activated carbon demonstrated higher removal efficiency compared to zeolite, which can be attributed to its larger surface area and porous structure [61], [62]. These characteristics enhance the adsorption of organic molecules through pore diffusion and surface binding. Zeolite, on the other hand, relies more on ion exchange mechanisms, which are more effective for specific ions rather than complex organic compounds. As a result, adsorption complements coagulation by targeting dissolved pollutants that are not removed in the initial stage.

The increase in certain metal concentrations after the adsorption process indicates the presence of complex interactions within the system. This phenomenon may be attributed to desorption, where previously bound metal ions are released back into the solution. In addition, competition between ions for active sites on the adsorbent surface may reduce adsorption efficiency [63], [64]. Another possible explanation is the release of impurities from the adsorbent material into the solution. These findings highlight that adsorption performance is influenced not only by adsorbent properties but also by solution chemistry [65], [66]. Therefore, careful selection and pre-treatment of adsorbents are important to minimize such effects.

Despite the improvement in several parameters, the final chemical oxygen demand value remained above the wastewater quality standard [67], [68]. This indicates that the hybrid coagulation and adsorption system is more effective in removing particulate and partially dissolved contaminants than refractory organic compounds [69], [70]. The limited removal of these compounds suggests that additional treatment methods are required. Advanced processes such as biological treatment or membrane separation may enhance the overall treatment efficiency [71], [72]. Therefore, the hybrid system can be considered as a pre-treatment step in a multi-stage wastewater treatment process.

The results of this study demonstrate that the hybrid coagulation and adsorption system has a significant impact as an effective physicochemical separation approach for reducing suspended solids, turbidity, and heavy metals in chemical laboratory wastewater. The integration of bulk phase separation and surface-based removal mechanisms enhances overall treatment performance and provides a practical alternative for small-scale laboratory wastewater management. In addition, this approach offers operational simplicity and flexibility, making it suitable as a preliminary treatment stage before advanced processes. However, this study has several limitations, particularly in the limited removal of dissolved organic compounds as indicated by the high residual chemical oxygen demand values. Furthermore, the observed increase in certain metal concentrations after adsorption suggests the need for further investigation into adsorbent stability, process optimization, and the potential integration with advanced treatment methods to achieve complete pollutant removal.

## 4. CONCLUSION

This study demonstrates that a hybrid coagulation–adsorption system is capable of reducing various pollutant parameters in chemical laboratory wastewater, including organic materials and heavy metals such as Fe, Mn, and Cr. Coagulation proved effective as an initial step, with Trimer 6784 coagulant providing optimum conditions at a concentration of 19.2 mg/100 mL, pH 4–7, and room temperature. The adsorption step using activated carbon and zeolite was able to improve the visual quality of the wastewater and reduce organic materials, although an increase in certain metals was still found. Overall, this system does not fully meet wastewater quality standards, so optimization of operating conditions and development of further methods are needed to increase separation efficiency. Future research is recommended to optimize operating conditions such as pH, coagulant dosage, and adsorbent concentration to further improve separation efficiency. In addition, the use of modified or activated adsorbents with higher stability and selectivity should be investigated to minimize desorption and enhance pollutant removal performance.

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## AUTHOR CONTRIBUTIONS

Conceptualization, G.D. and E.S.; Methodology, G.D.; Software, G.D.; Validation, G.D., E.S. and F.A.M.; Formal Analysis, G.D.; Investigation, G.D.; Resources, E.S.; Data Curation, G.D.; Writing – Original Draft Preparation, G.D.; Writing – Review & Editing, E.S. and F.A.M.; Visualization, G.D.; Supervision, E.S.; Project Administration, E.S.; Funding Acquisition, F.A.M.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies

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