Optimizing Laundry Wastewater Treatment: A Hybrid Approach Using Poly-Aluminum Chloride Coagulation and Activated Carbon Adsorption

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***Abstract* - Laundry wastewater contains high levels of Chemical Oxygen Demand (COD) and phosphate (PO_4), contributing to water pollution and eutrophication. This study investigates an integrated treatment approach using poly-aluminum chloride (PAC) coagulation and activated carbon adsorption to improve wastewater treatment efficiency. The research aims to determine the optimal PAC dosage (10% and 15%) and stirring time (0, 5, 15, 30, and 45 minutes) for maximizing COD and PO_4 removal. A batch reactor system was used to conduct the treatment process, and the analysis followed the Indonesian National Standard (SNI) methods. The results demonstrated that the highest removal efficiencies were achieved with a 15% PAC dosage and a stirring time of 45 minutes. Under these conditions, COD levels were reduced from 2189.62 mg/L to 143.47 mg/L, achieving a 93% reduction. Similarly, PO_4 levels decreased from 94.33 mg/L to 5.18 mg/L, corresponding to a 96% removal rate. These findings indicate that the combination of PAC coagulation and activated carbon adsorption is a highly effective treatment method for reducing pollution in laundry wastewater. This hybrid approach meets environmental discharge standards and presents a sustainable solution for large-scale wastewater treatment applications.**

Keywords: Laundry wastewater treatment; Poly-Aluminum Chloride (PAC); Activated carbon adsorption; COD reduction; PO_4 removal.

I. INTRODUCTION

The treatment of laundry wastewater is a critical environmental concern because of the high levels of pollutants such as Chemical Oxygen Demand (COD) and phosphates (PO_4) from detergents and surfactants. Untreated discharge contributes to water pollution, eutrophication, and oxygen depletion in aquatic ecosystems [1], [2], [3], [4]. Conventional treatment methods often struggle to effectively remove these pollutants, necessitating alternative approaches, such as coagulation and adsorption. Coagulation destabilizes and aggregates colloidal particles, whereas adsorption with activated carbon removes dissolved organic and inorganic contaminants [5], [6]. Combining these methods enhances pollutant removal efficiency, making it promising for laundry wastewater treatment. Poly-aluminum Chloride (PAC) is among the most effective coagulants, achieving removal efficiencies of up to 89% for various pollutants by neutralizing surface charges and promoting flocculation [7].

Activated carbon, known for its high adsorption capacity, is widely used to remove COD and PO_4. Research shows that granular activated carbon (GAC) can achieve COD reductions of approximately 63.11%, particularly when combined with other methods such as coagulation [8], [9], [10]. Given these advantages, integrating PAC

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coagulation with activated carbon adsorption is viable for improving laundry wastewater treatment efficiency [11].

Coagulation using PAC has been extensively studied for its efficiency in removing contaminants from various wastewater sources. Studies show that PAC enhances flocculation by neutralizing particle surface charges, promoting the aggregation of suspended solids and pollutants such as PO_4 and surfactants [7], [12], [13]. PAC exhibits superior coagulation performance compared to traditional coagulants, such as alum, particularly in high-strength wastewater applications. Research demonstrates that the removal efficiency of COD and PO_4 using PAC can exceed 80%, depending on the dosage and operating conditions [5]. Optimizing the coagulant dosage and stirring time can improve the PAC performance for laundry wastewater treatment. Adsorption using activated carbon is another widely applied technique for removing organic pollutants and PO_4 from wastewater. Activated carbon, particularly in granular form, has a high surface area and porosity, making it effective for adsorbing dissolved organic matter [9], [12], [14], [15]. Studies indicate that using activated carbon with coagulation can significantly improve COD removal efficiency, achieving up to 63.11% reductions. Activated carbon derived from agricultural waste, such as rice husks, has been explored as a low-cost alternative, demonstrating promising results in PO_4 adsorption [8], [16]. Integrating PAC coagulation with activated carbon adsorption presents a synergistic approach for wastewater treatment. Sequential application of PAC followed by activated carbon improves pollutant removal efficiency while minimizing secondary pollutant formation [17], [18].

This hybrid treatment method meets environmental discharge standards and contributes to sustainable wastewater management practices by reducing chemical consumption and optimizing resource utilization. The combination of these technologies aligns with emerging trends in wastewater treatment, emphasizing efficiency and environmental sustainability [5], [14].

Several studies have demonstrated the effectiveness of coagulation and adsorption in wastewater treatment. Research on PAC as a coagulant has shown high removal efficiencies for COD and PO_4, with up to 89% reduction in textile and laundry effluents [7]. Similarly, GAC and zeolite as adsorbents have been widely used to remove organic pollutants from wastewater, achieving PO_4 reductions exceeding 57.14% [9]. These findings suggest that combining these methods can optimize laundry wastewater treatment. Although many studies have explored coagulation and adsorption separately, limited research has focused on combining PAC and activated carbon for laundry wastewater. Most studies on activated carbon adsorption have examined its performance with alternative coagulants, such as alum and ferric chloride [8]. Furthermore, while previous research has highlighted the importance of coagulant dosage, there is a lack of studies on optimizing PAC dosage and stirring time to maximize COD and PO_4 removal. Additionally, the potential interactions between PAC and activated carbon in batch treatment systems remain largely unexplored. The existing literature highlights the need for further investigation into the combined use of PAC and activated carbon in treating laundry wastewater, particularly optimizing operational parameters such as coagulant dosage and stirring time. Addressing these research gaps is essential for developing an efficient and practical treatment approach that aligns with environmental regulations and sustainability goals [16], [19].

This study focuses on integrating PAC coagulation and activated carbon adsorption, an approach that has not been extensively explored in laundry wastewater treatment. Unlike previous studies that have examined these methods separately, this research seeks to optimize their combined performance, providing a more efficient and sustainable solution. Additionally, this study investigates the impact of varying PAC dosages (10% and 15%) and stirring times (0, 5, 15, 30, and 45 minutes), filling a critical gap in the existing literature on operational parameter optimization. This study aims to optimize the treatment of laundry wastewater by investigating the effectiveness of PAC coagulation and activated carbon adsorption in reducing COD and PO_4 levels. The specific objectives of this research are as follows: (1) to determine the optimal dosage of PAC for reducing COD and PO_4 levels in laundry wastewater, and (2) To identify the effective stirring time for reducing COD and PO_4 levels in laundry wastewater.

II. METHOD

Materials

This study utilized several tools, including batch reactors, mixer stirrers, activated carbon from coconut shells, and other supporting materials, such as PVC pipes and faucets. Using these materials and tools reflects the method's practicality, which can be adapted for a larger scale in sewage treatment.

Sample source and initial characteristic

This study used laundry effluent samples from the Tambak Sawah area in Waru, Sidoarjo, to ensure the analysis results are relevant to real conditions. Before and after treatment, these samples were used to evaluate the main parameters, namely

COD and PO_4 levels. These two parameters were chosen because of their consistently high pollution values. During this study, the initial characteristics for COD contaminants were 4919.7 mg/L and PO_4 of 114.34 mg/L. The results of previous studies for the initial values of COD and PO_4 pollutants varied greatly, ranging from 265.7 - 727.1 mg/L for COD and 9.5 - 14.2 mg/L for PO_4 [2], [3], [4].

Coagulation and Adsorption method

The study used a batch reactor system with 3 liters per unit capacity. The batch system facilitates the control of experimental parameters, such as coagulant dosage and stirring time. This allowed targeted testing to understand the relationship between treatment variations and the results obtained. Sample treatment was carried out in two main stages: coagulation with PAC and adsorption using activated carbon. Two variations of PAC dosage were used, namely 10% and 15%. The dosage of activated carbon is 0.02 g, which is added to all samples that have been processed with the coagulation system. The coagulation process was carried out with different stirring times: 0 min, 5 min, 15 min, 30 min, and 45 min. The coagulation stage aims to agglomerate suspended particles, while the adsorption stage uses activated carbon to adsorb the remaining organic and inorganic substances. This combination allows for the effective treatment of wastewater. Thus, this study aimed to identify PAC coagulant agitation's optimal concentration and duration in reducing COD and phosphate parameters. These variations were designed to measure the efficiency under different conditions.

Processing and data analysis

The parameters analyzed included COD and PO_4 levels. The analysis method used is the Indonesian national standard (SNI). For COD, titrimetry concerning SNI 6989.73: 2009 used the closed reflux method. In contrast, PO_4 uses spectrophotometry with an ascorbic acid method by SNI 06-6989.31:2005. These standards ensure that the results of parameter analysis are by nationally recognized procedures so that the data obtained have high credibility. After that, the data was processed based on laboratory tests of samples after coagulation and adsorption treatments. The data were presented in graphical form and analyzed descriptively. Presentation of results is done to facilitate interpretation of the method's efficiency. The data were processed to show the decrease in COD and PO_4 values as well as the efficiency comparison of various dose variations and stirring times.

III. RESULTS AND DISCUSSION

Alleviation of COD by coagulation and adsorption process

The removal of COD from laundry wastewater through coagulation processes has garnered significant attention due to the increasing environmental concerns associated with untreated wastewater discharge. Coagulation is a widely utilized method for wastewater treatment, effectively destabilizing colloidal particles and facilitating their removal through sedimentation or flotation. Figure 1 compares COD values before and after the coagulation process using PAC with variations in PAC concentrations of 10% and 15% and various operating times (0, 5, 15, 30, and 45 minutes). Various studies have demonstrated the efficacy of different coagulants and processes in reducing COD levels in laundry wastewater.

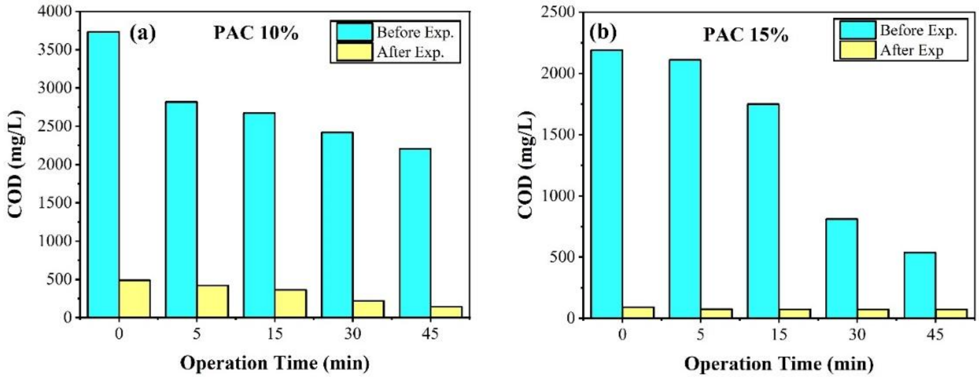

Figure 1. The reduction of COD before and after coagulation by using PAC. (a) for PAC 10% and (b) for PAC 15%

At 10% PAC concentration (Figure 1a), COD before the experiment started from about 3731.54 mg/L and gradually decreased as the operation time increased until it reached 2268.71. After the experiment, the COD decreased significantly, especially at an operating time of 45 minutes (486.2 - 143.475 mg/L), where the COD value reached a very low level. This indicates that 10% PAC can reduce COD efficiently within a certain time. Meanwhile, at 15% PAC concentration (Figure 1b), the COD before the experiment started from around 2189.62 mg/L and showed a significant decrease with increasing operation time until it reached 537.22 mg/L. After the experiment, the COD decreased drastically even at the initial operating time of 0 and 5 min, and the result was lower than that of 10% PAC at the same duration, reaching a final value of 143.475 mg/L. Higher PAC concentrations make COD reduction efficiency faster and more effective. In conclusion, increasing the PAC concentration accelerates the COD reduction process, and sufficient operating time provides optimal results. This indicates that proper selection of PAC dosage and duration of operation is critical to achieve efficient wastewater treatment.

Coagulation processes, especially those using metal salts such as aluminum sulfate and PAC, have shown promising results in COD reduction. Chemical coagulation using PAC can achieve COD reduction efficiencies between 40% and 60% at a dose of 100 mg/L [20]. Similarly, electrocoagulation methods can reduce COD levels in laundry wastewater by up to 62% [21]. The effectiveness of these processes is often influenced by factors such as pH, coagulant dosage, and the specific characteristics of the treated wastewater. For example, optimal pH conditions enhanced the coagulation process, where neutral pH resulted in better COD reduction [22]. In addition, integrating coagulation with other treatment methods, such as advanced oxidation processes, has been explored to improve COD reduction efficiency. Combining coagulation with the Fenton process can significantly reduce COD, with efficiency levels of up to 92.4% [23]. This combined approach improves the overall treatment efficiency and reduces the chemical load required for the next treatment stage.

Coagulant selection plays an important role in the effectiveness of the coagulation process. Studies have shown that different coagulant types can give different COD reduction results. Poly ferric sulfate (PFS) was more effective than traditional aluminum sulfate in treating paper industry wastewater, with a COD reduction efficiency of 95.2% under optimal conditions [24]. This shows the importance of selecting the appropriate coagulant according to the specific wastewater characteristics to maximize treatment efficiency. In addition to chemical coagulants, natural coagulants have been investigated as a sustainable alternative for wastewater treatment. In addition, the chemical coagulation (CC) process successfully achieved a COD reduction efficiency of 54.02% in textile wastewater in Tunisia with optimal conditions, including pH 8.57, coagulant concentration of 204.75 mg/L, and slow stirring time of 28.41 min [25].

In addition, PAC has also been proven effective in reducing COD up to 58.97% at an optimum concentration of 300 mg/L in the treatment of laundry wastewater [26]. In another context, magnetic coagulants derived from modified fly ash can reduce COD by surface adsorption and precipitation mechanisms, which is relevant for laundry wastewater [27]. The peroxy-coagulation (PC) process using iron anode and carbon-polytetrafluoroethylene cathode also showed high efficiency in reducing COD significantly [28]. Research shows that coagulation methods can be optimized by selecting operational parameters, including coagulant dosage, pH, and operating time. This approach allows significant pollutant reduction before wastewater is discharged into the environment. Combining coagulation with other methods, such as advanced oxidation and membrane separation, further strengthens the ability to treat wastewater sustainably [29], [30].

Alleviation of PO_4 by coagulation and adsorption process

The alleviation of PO_4 from laundry wastewater through coagulation systems is a critical area of research, given the environmental implications of PO_4 discharge into aquatic ecosystems. Coagulation processes have effectively reduced PO_4 concentrations in various wastewater types, including laundry effluents, by destabilizing colloidal particles and facilitating their removal. Figure 2a. shows the efficiency of the coagulation process using PAC with 10% and 15% concentrations in reducing PO_4 levels in laundry wastewater. At 10% PAC, the initial PO_4 concentration before treatment was about 100.74 mg/L, gradually decreasing with operating time. A significant decrease was seen at 45 min, indicating that the 10% PAC required a longer operating time to achieve optimal efficiency (97.68 mg/L). In contrast, at 15% PAC, PO_4 reduction occurs faster, with significant results even at the initial operating time, reaching a much lower PO_4 value after 45 minutes (94.33 - 28.61 mg/L). In Figure 2b, in the coagulation process with 15% PAC, the PO_4 concentration after treatment appears much lower than before. This result demonstrates the effectiveness of 15% PAC in significantly reducing PO_4 levels at various operating times. A faster and more consistent decrease was observed even at the initial operating time from 0 to 30 minutes, with a reduction reaching 8.28 - 5.85 mg/L, where the phosphate concentration after treatment was drastically reduced compared to the initial value. After 45 minutes, the PO_4 concentration reached a very low value of 5.18 mg/L. This confirms that increasing the PAC concentration increases the phosphate removal efficiency.

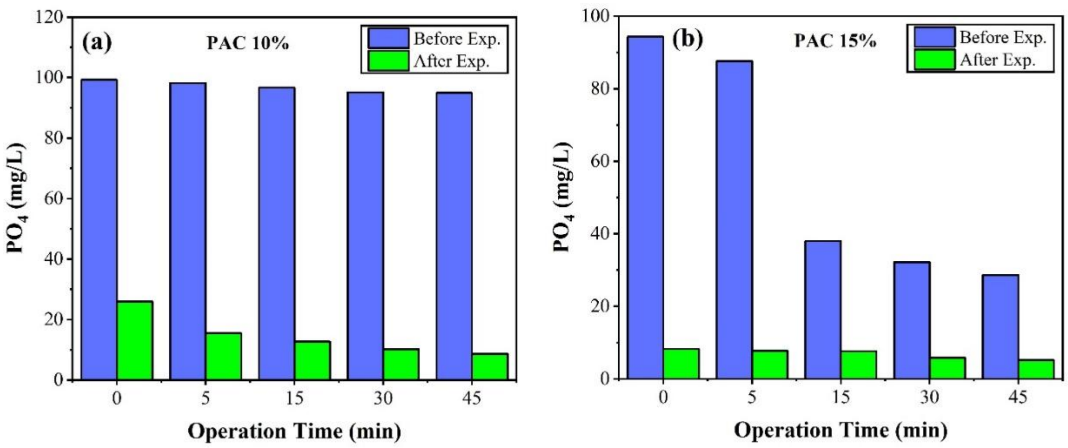

Figure 2. The reduction of PO_4 before and after coagulation by using PAC. (a) for PAC 10% and (b) for PAC 15%

The effectiveness of the coagulation process in reducing PO_4 levels has been documented in various studies. An electrocoagulation model using Faraday's law and Langmuir's adsorption model showed high efficiency in removing PO_4 from laundry wastewater, highlighting the importance of parameters such as current density and initial PO_4 concentration [31]. In addition, the proxy-coagulation (PC) process using iron anode and carbon-polytetrafluoroethylene cathode at optimal conditions, such as pH 7 and current density 45 mA/cm², was able to achieve total PO_4 removal [28]. These findings align with the results showing that optimal conditions increase removal efficiency. The coagulation process also plays an important role in PO_4 removal from domestic wastewater, as Vishali et al. [32] reported that coagulation collects suspended particles and contaminants, including PO_4, for easier removal. Furthermore, combining electrocoagulation and dual coagulation methods can significantly improve PO_4 removal efficiency, especially from detergent residues in laundry wastewater [33].

Natural coagulants have also shown great potential in sustainably removing PO4. Chitosan-magnetite nanocomposites were reported to be superior to traditional chemical coagulants, such as alum, in PO_4 removal from palm oil mill effluent, which can be applied to laundry wastewater [34]. Moringa seed powder also effectively reduced suspended and total dissolved solids, demonstrating its potential to remove PO_4 from laundry wastewater [35]. The coagulant dosage greatly influences the effectiveness of PO4 removal through coagulation. Research shows that increasing PAC dosage increases PO_4 removal efficiency [20]. However, a dose that is too high can reduce efficiency due to the charge reversal of suspended particles, as noted by Sibiya et al. [36]. In addition to chemical coagulation, using natural coagulants such as Hibiscus sabdariffa has shown promising results in reducing PO_4 levels with optimal performance at specific pH conditions [14]. This study showed that 15% PAC was more effective than 10% PAC in removing PO_4 from laundry wastewater, supporting previous reports on the efficiency of PAC as a coagulant in wastewater treatment. These findings confirm the importance of coagulant dose selection, optimization of operating parameters, and the potential use of natural coagulants to improve the sustainability of laundry wastewater treatment.

COD Removal

PAC as a coagulant for COD removal from laundry wastewater has been studied, and it has shown effectiveness in reducing COD levels. PAC is favored for its ability to operate over a wide pH range and its efficiency in forming flocs that enhance the sedimentation process. Figure 3 shows the COD removal efficiency as a function of operating time for two PAC concentrations, 10% and 15%. At 10% PAC, the initial COD efficiency started from about 90.12%, increasing gradually to about 97.08% after 45 minutes. This trend indicates that 10% PAC requires a longer operating time to achieve high COD removal efficiency. In contrast, the 15% PAC showed a higher initial efficiency, around 98.15%, and remained stable at the same efficiency level for the entire operating time. This stability indicates that the 15% PAC can achieve maximum efficiency in a shorter operating time than the 10% PAC.

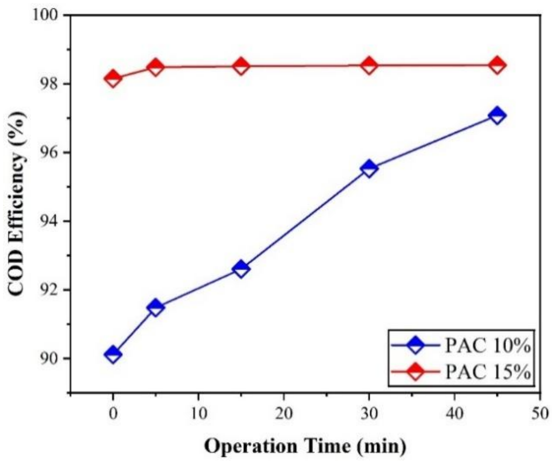

Figure 3. COD removal efficiency after using PAC as a coagulant

Research supports this finding, where optimal PAC concentrations often range from 300 to 500 mg/L depending on the characteristics of the wastewater. For example, research by Audria et al. [26] showed that a PAC dosage of 300 mg/L reduced COD levels in laundry wastewater to an average of 58.97%. However, further treatment was required to meet discharge standards. Another study by Islam and Mostafa [37] found that the same dosage of PAC can achieve COD removal efficiency of up to 82.05% in textile effluent, where stirring speed and temperature also play an important role. Using electrocoagulation/electroflotation technology to reduce COD from laundry wastewater can achieve maximum removal of up to 62% [6]. The effectiveness of PAC in various wastewater treatment applications has been widely confirmed. COD removal efficiency was up to 85% with a PAC dosage of 500 mg/L in wastewater with high initial COD values, such as 4800 mg/L. This study confirms that higher doses and optimal operational conditions, including neutral or slightly alkaline pH, can increase removal efficiency [12]. Further support was provided by Metin and Çifçi [38], who reported a maximum efficiency of 84% at pH 8 with the same PAC dosage.

In addition, the integration of PAC in multi-stage treatment systems has been shown to increase the overall COD removal efficiency. Combining coagulation-flocculation with additional methods can result in an efficiency of up to 88% [39]. Meanwhile, the COD removal efficiency was 75% with a PAC dosage of 1000 mg/L in an effluent with an initial COD level of about 3000 mg/L [40]. However, although PAC is highly effective, combining additional treatment methods can further improve COD removal efficiency. For example, using PAC alone gives an efficiency of about 40%, but the combination with electrocoagulation at 60 V voltage increases the efficiency to 93.1%. This shows that while PAC can significantly reduce COD, additional treatment, such as electrocoagulation, can significantly improve the effectiveness of laundry wastewater treatment [41]. In addition, the use of PAC in non-laundry applications also showed similar effectiveness. Yang [42] and Verma [43] showed that PAC effectively reduced Linear Alkylbenzene Sulfonate (LAS) and chroma in wastewater, although COD removal efficiency was not specifically reported.

PO_4 removal

PO_4 removal from laundry wastewater is a critical environmental concern, particularly due to the detrimental effects of PO_4 on aquatic ecosystems, which can lead to eutrophication [44]. A significant volume of wastewater containing PO_4 is released into water bodies, promoting excessive algal growth, reducing dissolved oxygen levels, and ultimately degrading water quality [45], [46]. Coagulation processes, particularly using various coagulants, have been extensively studied for their effectiveness in removing PO_4 and other contaminants from wastewater. Figure 4 shows the relationship between PO_4 removal efficiency in percentage (%) and operating time (min) at two PAC concentrations of 10% and 15%. At 10% PAC concentration, the initial efficiency was around 77.35% and increased sharply during the first 15 minutes to around 88.95%. After that, the increase slowed until it reached 91.71% at an operating time of 45 min. In contrast, at a PAC concentration of 15%, the initial efficiency was already at a higher level, around 92.76%, and continued to increase gradually until it was close to 96% at the 45^{th} minute. From this data, it can be seen that higher PAC concentrations resulted in higher PO_4 removal efficiencies at each operating time. At 15% PAC concentration, the efficiency increase was more stable compared to 10% PAC, which showed a significant increase at the beginning of the operation time. This indicates that higher PAC concentration accelerates the coagulation and flocculation process, increasing the PO_4 removal efficiency. Based on the trend, operating time also plays an important role in

PO_4 removal efficiency, especially at lower PAC concentrations. At 10% PAC, the increase in efficiency was significant in the initial phase, while at 15% PAC, the increase tended to be consistent throughout the operation time. Thus, both variables - PAC concentration and operating time - have significantly influenced the efficiency of the PO_4 removal process.

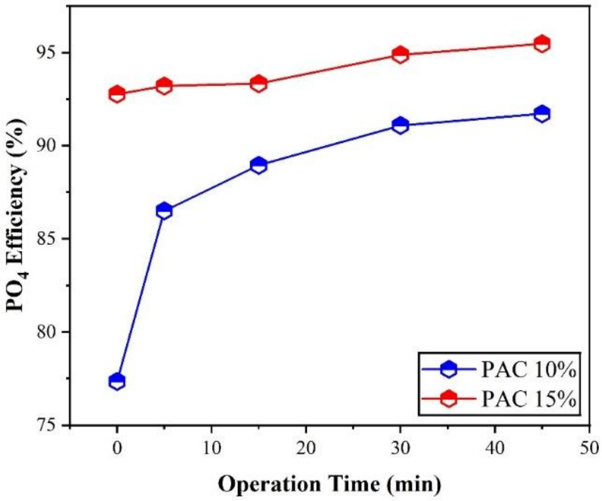

Figure 4. PO_4 removal efficiency after using PAC as a coagulant

Previous research by Adesoye et al. [47] showed that phosphate removal using alum and ferrous sulfate at two sites in Lagos State, Nigeria, only achieved efficiencies of 26.0% and 30.0%, respectively. These results were much lower than PACs in this study, indicating that PAC has a superior ability to remove phosphate from laundry wastewater. In addition, alum and ferrous sulfate resulted in phosphate levels that remained above the limits set by the Federal Environmental Protection Agency, indicating a potential environmental hazard if the wastewater is discharged without further treatment. Furthermore, Nayir et al. [28] reported that the peroxy-coagulation (PC) process at optimal conditions (pH 7, current density 45 mA/cm², and temperature 25°C) was able to remove total phosphorus (TP) completely. In terms of overall contaminant removal efficiency, PAC provided superior results compared to other coagulants, such as ferric chloride and alum, with 82.5% removal of linear alkylbenzene sulfonate (LAS) and 87.8% removal of chroma from laundry wastewater [42]. These results align with our study's high efficiency of PAC, especially in phosphate removal. This indicates that PAC improves the coagulation process and increases contaminant removal efficiency.

In addition to using PACs, other studies, such as the one by Ali and Jaeel [48], have explored the potential of combining natural and chemical coagulants. This study showed that plant-based coagulants can significantly reduce turbidity and total suspended solids (TSS) in textile wastewater. Integrating natural coagulants with PAC may improve phosphate removal efficiency while reducing the environmental impact of entirely using chemical coagulants. Optimization of coagulation conditions is also an important factor in improving efficiency. Adjusting pH and coagulant dosage parameters is key to achieving optimal results [49], [50]. Research also shows that combining coagulation methods with other treatment technologies, such as flotation and ozonation, can improve efficiency. The combination of the coagulation-ozonation-flotation process achieved a COD removal efficiency of 87% in hydraulic loom wastewater. Applying such a multi-barrier approach could improve the removal efficiency of phosphate and other contaminants in laundry wastewater [51].

IV. CONCLUSION

This study aimed to optimize laundry wastewater treatment by integrating PAC coagulation and activated carbon adsorption to effectively reduce COD and PO_4 levels. The research examined the impact of varying PAC dosages (10% and 15%) and different stirring times (0, 5, 15, 30, and 45 minutes) to determine the optimal conditions for pollutant removal. The results showed that the highest removal efficiency was achieved using a 15% PAC dosage with a stirring time of 45 minutes. Under these optimal conditions, COD was reduced from 2189.62 mg/L to 143.47 mg/L, achieving a 93% reduction. Similarly, PO_4 levels decreased from 94.33 mg/L to 5.18 mg/L, corresponding to a 96% removal rate. The study confirms that increasing PAC dosage and optimizing stirring time significantly enhance pollutant removal efficiency. This hybrid treatment method effectively meets environmental discharge standards and presents a sustainable approach to laundry wastewater treatment. Integrating coagulation and adsorption reduces secondary pollutants and offers a practical solution for large-scale wastewater treatment applications. Future research should explore the economic feasibility, scalability, and potential use of natural coagulants to improve the sustainability of this treatment system further.

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