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Research article

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Treatment performance of centralized industrial wastewater using powdered activated carbon and poly-aluminum chloride in combination with the activated sludge process

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ABSTRACT

The present study aimed to evaluate the treatment performance of centralized industrial wastewater using the activated sludge (AS) process combined with powdered activated carbon (PAC) and poly aluminum chloride (PACl). The experiment with PAC was tested at five concentrations of 0.0, 0.5, 1.0, 2.0, and 4.0 g PAC/L_{sludge}, while a PACl was applied at 0, 20, 40, 80, and 160 mg Al/L_{sludge} for 120 minutes. With a C/C_0 ratio of less than 1.0, the addition of PAC and PACl significantly improved the treatment efficiency. Accordingly, the concentrations of COD and NH_4^+-N at the end of the experiment were lower than the initial values in both PAC and PACl experiments. For COD, PACl showed a higher reduction than PAC, with C/C_0 ranging from 0.2 to 0.8, whereas PAC reached only 0.7 to 0.9. Similarly, NH_4^+-N concentrations also decreased after 120 minutes, with C/C_0 ranging from 0.7 to 0.8 in both experiments. Furthermore, the treatment efficiency showed a tendency to increase with increasing dosages of PAC and PACl. The study provides a broader perspective on enhancing the treatment efficiency of industrial wastewater through the combination of adsorption or chemical coagulants processes with the AS process. Data from the investigated PAC and PACl dosages help determine their effective operating ranges in centralized industrial wastewater, thereby supporting the selection of appropriate operational conditions that ensure both technical and economic efficiency while avoiding waste of materials and chemicals.

Key words: Treatment performance, Industrial wastewater, Powder activated carbon, Poly aluminum chloride, Activated sludge process

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INTRODUCTION

In recent years, along with economic development has been the emergence of industries, among which industrial parks, where production activities take place, play a particularly important role in the economy [1]. However, the level and volume of emissions in industrial zones are recorded to be much higher than those of individual industries, making them the main source of industrial pollution [2]. Centralized industrial wastewater refers to wastewater collected from individual manufacturing plants after preliminary treatment, which often contains a large amount of complex and diverse pollutants such as high concentrations of refractory organic matter, inorganic substances, nitrates, phosphates, dyes, and heavy metals, etc [2–4]. According to a study in China, the influent wastewater of 63 centralized industrial wastewater treatment plants contained many non-biodegradable or poorly biodegradable organic pollutants, with average concentrations of COD, BOD, and NH_4^+-N recorded at 323, 145.9, and 30.2 mg/L, respectively, and an average BOD/COD ratio of 0.5 [5].

Worldwide, most wastewater treatment plants (WWTPs) employ biological methods, among which the AS process is one of the most widely used due to its low cost, simple operation, and high efficiency in nutrient removal while maintaining stable biomass [3,6–8]. However, for water sources containing refractory organic compounds, the treatment efficiency of this process decreases due to the insufficient carbon source available for microorganisms, making COD degradation more difficult [9]. In contrast, adsorption and coagulation-flocculation are technologies commonly used to remove high concentrations of organic compounds, synthetic pollutants, heavy metals, and certain anions, and at the same time, the costs of both processes are low [7,10,11]. The simultaneous combination of biodegradation and physical adsorption can reduce the organic content by 20 – 50% [12]. The AS process combining PAC and PACl is considered a promising alternative solution to effectively treat pollutants in industrial wastewater.

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PAC possesses superior adsorption capacity due to its large surface area and porous structure. The addition of PAC to the AS process not only facilitates the adsorption of slowly, or even poorly biodegradable contaminants but also provides a favorable environment for the growth and accumulation of microorganisms [13] . Not only that, but it also brings several benefits, such as removing color, odor, and ammonia; increasing sludge settling capacity; protecting biomass from toxins; maintaining system stability; and improving the quality of treated water to create a reusable water source [14,15] . According to Gottardo et al. (2023), the removal efficiency of soluble COD in tannery wastewater reached 93 $\pm$ 1% at a dosage of 1.5 g PAC/L_{sludge} [14]. For wastewater from an oil refinery, the AS process combined with 4.5 g PAC/L_{sludge} achieved up to 98% COD removal [15] . The average COD removal efficiency of the PAC–AS system for treating refractory industrial wastewater from a chemical industrial park in Tianjin, China, reached 39% when 10 g PAC was added, whereas the conventional AS process achieved only 20% [9] . Similarly, in recent years, several studies have demonstrated that PAC–AS process can significantly improve the removal of organic matter and nitrogen compounds in wastewater. For example, Wang et al. (2023) compared activated carbon (AC), AS process, and AC–AS configurations and found that the AC–AS process achieved 90% COD removal in a significantly shorter time, saving approximately 30 hours compared to the AS reactor, while also improving NH_4^+-N removal by 24.9% [16] .

For Al-based coagulants, pre-polymerized coagulants such as PACl have gradually been recognized as the most effective coagulants in wastewater treatment facilities, due to their faster coagulation time, lower sludge production, and the formation of more compact flocs compared to alum at equivalent doses [17,18] . PACl contributes to improving the efficiency of removing color, high COD, phosphate, and toxic metals, while reducing the amount of sludge generated during the treatment process, increasing the filtration capacity of the liquid-solid phase, and effectively controlling membrane fouling [19–21] . In the leachate treatment, the addition of PACl significantly improved the removal efficiency of dissolved and colloidal organic matter by up to 36.8%, while reducing color by 91.2% and turbidity by 97.7% [21] . The study by Islam & Mostafa (2020) reported that COD in textile wastewater was effectively removed by 75% to 82% at three different sampling sites when PACl was added [22] .

Although the integration of PAC with the AS process has proven effective in removing organic matter and nitrogen, the application of this method in wastewater treatment was limited to certain specific types of wastewater. Furthermore, while PAC has been studied in biological systems, the use of PACl in combination with AS has not been extensively explored, as current studies on PACl mainly focus on physicochemical stages, such as coagulation-flocculation. It is noteworthy that there have been no reports on the effects of PAC and PACl on the removal efficiency of pollutants by the AS process in centralized industrial wastewater. Therefore, more research is needed to discuss the roles of PAC and PACl in wastewater treatment, particularly in the AS process. From these points of view, this study aims to evaluate the treatment efficiency of organic matter, quantified as COD and NH_4^+-N, using the AS process combined with PAC and PACl at different concentrations over 120 minutes.

MATERIALS AND METHODS

Experiment setup

The setup consisted of five buckets, each corresponding to a different PAC or PACl dosage. Because the test used actual industrial wastewater that fluctuated over time with daily manufacturing activities, it was conducted only once to avoid non-representative results due to such variations. At the beginning, sludge and wastewater were filled into each bucket to get a total volume of each bucket was 5 litres. MLSS concentration of each bucket was maintained at around 2,000 mg/L. Along with that, an air diffuser was installed at the bottom to provide dissolved oxygen for both organic matter and nitrification. Ensure even air blower and throughout the process, uniform control between buckets must be maintained at a DO of approximately 2 mg/L. After setup, PAC was added at concentrations of 0.0, 0.5, 1.0, 2.0, and 4.0 g PAC/L_{Sludge}. Similarly, for PACl, the concentrations were at 0, 20, 40, 80, and 160 mg Al/L_{Sludge}. Finally, stir thoroughly and take samples at intervals of 0, 30, 60, 90, and 120 minutes, respectively.

All batch reactors are operated simultaneously in the same laboratory environment, using identical activated sludge and wastewater sources, ensuring that environmental factors such as pH and temperature remain relatively stable throughout the experiment, minimizing their impact on the comparison results.

Components of wastewater

The wastewater used in this study was taken after the first physicochemical sedimentation tank of a centralized WWTP in Ho Chi Minh City, Vietnam. The wastewater contains the following components: COD was 421 – 658 mg/L; NH_4^+-N was 10 – 17 mg/L.

Seed sludge

The activated sludge for this research was collected from the aeration tank of the same centralized WWTP. Before starting the experiment, the sludge was brought to the laboratory and maintained with a DO concentration of 2 mg/L to be consistent with the experimental setup.

Chemicals

In this study, PAC was supplied by Xilong Scientific Co., Ltd. (China). According to the manufacturer, PAC has a pH range of 5.0 – 7.0, with methylene blue adsorption capacity meeting standard requirements, ethanol-soluble substances ($\leq 0.2\%$), volatile matter ($\leq 2\%$), and low heavy metal content.

The PACl used in the experiment was purchased under the trade name PAC VIKRAM, imported from India. This PACl is a white powder with high purity and is known for its Al_2O_3 (31%), alkalinity (60 – 90%), and low containment of toxic substances such as As, Pb, Cd, and Cr^{6+}. These chemicals were stored in a dry place and weighed before the experiment began.

Analytical methods

COD, NH_4^+-N follow the analytical methods in Standard Methods for the Examination of Water and Wastewater [23] . COD concentration was determined using the closed reflux and titrimetric method No. 5220C with a ZRD-A7140 device. NH_4^+-N was determined according to the Kjeldahl distillation method No. 4500-NH_3 B using a UDK 129 – VELP F30200125. COD and NH_4^+-N were assessed in each experiment in two replicates to evaluate repeatability.

RESULTS AND DISCUSSION

Removal efficiency associated with PAC addition

Organic removal

Figure 1 presents the COD removal plots expressed as C/C_0 (with error bars) over five different PAC dosages for 120 min. In general, an increasing trend in COD removal was observed with higher PAC doses. For AS without PAC addition (0 g PAC/L), the C/C_0 value remained close to 1.0 throughout the entire period, reflecting no significant COD reduction. At a concentration of 0.5 g PAC/L, the COD concentration decreased slightly in the initial period (30 minutes and 60 minutes) with a C/C_0 ratio of 0.9. However, the concentration decreased sharply with a C/C_0 ratio recorded at 0.6-0.7 in the following period. A slight decrease in COD concentration was also observed at 1 g PAC/L, with C/C_0 ranging from 0.8 to 1.0; however, this downward trend was not stable throughout the operation. At high PAC doses (2 g PAC/L and 4 g PAC/L), a significant and stable decrease in COD concentration was observed, with the C/C_0 ratio maintained from 0.6 to 0.8. The PAC dosage is inversely correlated with the C/C_0 ratio. Accordingly, as PAC increases, the C/C_0 ratio decreases. These results show that adding PAC to the AS process significantly increases COD treatment efficiency compared to the conventional AS process. The increase in removal efficiency is not due to adsorption but rather to the addition of PAC, which improves the biological degradation process (9). The presence of PAC increases the contact time between the adsorbed organic compounds and the microorganisms in the activated sludge, thereby promoting the continued biodegradation of organic matter and contributing to the improvement of organic removal efficiency. However, the study combining PAC with a membrane bioreactor (MBR) for swine wastewater treatment also showed that, within the total COD removal efficiency of 81%, adsorption by activated carbon accounted for the highest proportion at 46.5%. The activity of activated sludge contributed 30.1%, of which 9.3% resulted from the enhancement of microbial activity, 20.8% from the adsorption process of activated sludge, and the remaining 4.4% was attributed to membrane filtration [24] .

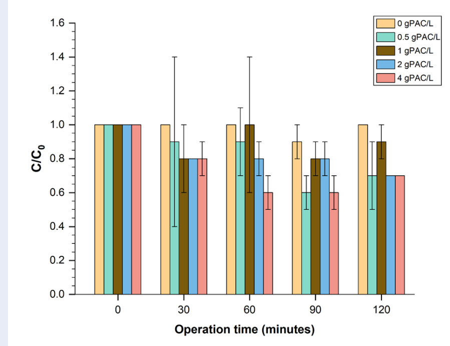

Figure 1: Effect of different PAC dosages on organic removal

Ammonia removal

In batch experiments, consisting of industrial wastewater and AS with various PAC concentrations (0.0; 0.5; 1.0; 2.0; 4.0 g PAC/L) were conducted, the results are shown in **Figure 2**. Overall, the amount of NH_4^+-N removed tended to increase with the operating time. At 0 g PAC/L, NH_4^+-N concentration

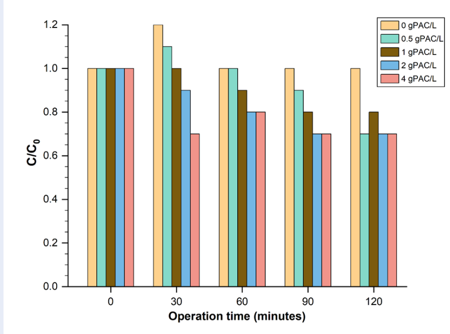

Figure 2: Effect of different PAC dosages on ammonia nitrogen removal

witnessed a slight increase during the first 30 minutes, with C/C_0 rising from 1.0 to 1.2. However, it was reduced to the initial concentration and remained unchanged after 120 minutes. At 0.5 g PAC/L, the dosage was relatively low, which explains the reason why ammonia reduction rate was not enough to make a significant impact on the system. Even though the decreasing trend was still noticeable. Dosage 1.0 g PAC/L showed no significant difference compared to 0.5 g PAC/L, yet it was clearly more effective than 0 g PAC/L, indicating PAC addition can potentially have a positive impact improvement on ammonia removal. At 2.0 g PAC/L, the ammonia removal became more pronounced and consistent. At 4.0 g PAC/L, despite a doubling increase in PAC dosage, the removal efficiency did not witness a doubling in removal efficiency compared to 2.0 g PAC/L. This symptom points out the threshold of the technology, which means the increase in PAC dosage will not continue to have a positive effect on the removal efficiency but rather a needless expense. Showed a linear relation between PAC addition dosage and NH_4^+-N removal efficiency, suggesting that PAC did play a significant role in enhancing efficiency by adsorbing both ammonia and compounds inhibitory to Nitrosomonas and Nitrobacter, which furthermore increases the nitrification process [25] . Previous studies have shown that the addition of activated carbon to the AS process is capable of adsorbing toxic organic compounds such as aniline, nitrobenzene, phenol, cyanide, and thiocyanate at high concentrations, as well as heavy metals including Cu^{2+}, Zn^{2+}, Ni^{2+}, Cd^{2+}, Pb^{2+}, and Cr^{6+} via ion exchange [26–28] . These substances can deactivate enzymes in nitrogen-transforming bacteria such as Nitrosomonas and Nitrobacter, thereby negatively affecting the nitrification process. The adsorption process helps reduce the toxicity of wastewater and enhances the protection of microorganisms from the inhibitory effects of pollutants, resulting in higher ammonia removal efficiency and shorter treatment time [16] .

With these results, the addition of PAC to the AS process significantly improves pollutant removal efficiency without requiring changes to the reactor configuration. The high adsorption capacity of PAC enhances the removal of non-biodegradable organic compounds and reduces the toxic effects of industrial wastewater on microorganisms, thereby promoting stable biological activity. This indicates that PAC is particularly suitable for industries with fluctuating organic loads or complex organic compositions, such as centralized industrial wastewater. However, future studies should perform detailed techno-economic assessments when applying PAC due to its relatively high cost and daily supplementation requirements, which may limit its large-scale application; strategies for PAC regeneration or reuse should also be considered.

Removal efficiency associated with PACl addition

Organic removal

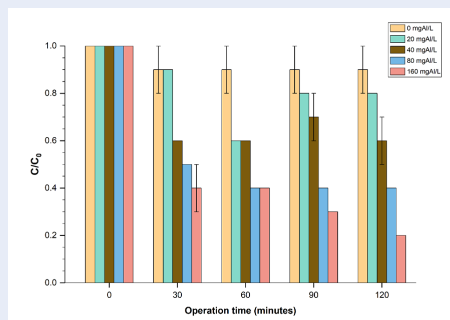

Figure 3: Effect of different PACl dosages on organic removal

Figure 3 illustrates the effect of PACl at different dosages on the variation of COD concentration, which is expressed as the C/C_0 ratio, with error bars. On the whole, the COD concentration tended to decrease with the addition of PACl over 120 minutes, with this trend varying among the dosages. COD concentration showed almost no significant change at the dose of 0 mg Al/L, with C/C_0 values ranging from 0.9 to 1. However, a slight decrease was observed from 20 mg Al/L, and this trend was unstable across different time intervals. Accordingly, the concentration reached its lowest value at 60 minutes, with

C/C_0 dropping to 0.6, but subsequently rose again toward the end of the experiment, reaching 0.8. At 40 mg Al/L, the concentration showed a sharp decrease within the first 30 minutes. However, this decrease was maintained until the end of the experiment with little change, with C/C_0 ranging from 0.6 to 0.7. The improvement in COD concentration was observed at 80 mg Al/L and 160 mg Al/L. In the first 30 minutes, the concentration at both doses decreased significantly, with C/C_0 reaching 0.5 and 0.4, respectively. From 60 minutes onward, the trends of the two doses differed. At 80 mg Al/L, the concentration decreased slightly at this time and was maintained until the end of the experiment, whereas the concentration continued to decrease at 160 mg Al/L with C/C_0 of 0.2. The results indicate that the improvement in COD concentration is directly proportional to the aluminum dosage. PACl is a pre-polymerized coagulant that undergoes hydrolysis in water to form various aluminum species. Among these, colloidal or precipitated forms (Al_c) play a crucial role in removing dissolved organic matter through surface adsorption mechanisms[29]. As the PACl dosage increases, a greater amount of precipitate is formed, thereby enhancing the adsorption capacity for dissolved organic compounds. Consequently, the efficiency of dissolved COD removal tends to increase with increasing PACl dosage.

Ammonia removal

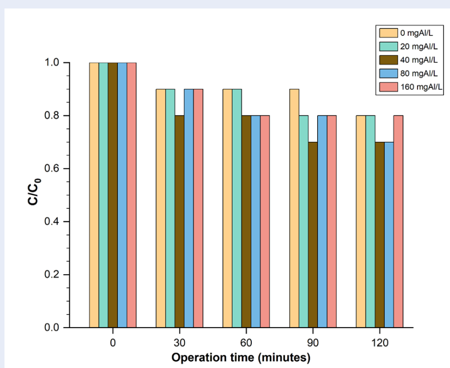

Figure 4: Effect of different PACl dosages on ammonia nitrogen removal

Ammonia removal rate demonstrated no decent increase in the removal efficiency by the addition of PACl depicted in Figure 4. At 0 mg Al/L, C/C_0 ratio indicated only a slight portion of NH_4^+-N was removed by bio-chemical activities (20%), which was without PACl addition. At dosage 20 mg Al/L showed only minor changes in NH_4^+-N removal, likely due to the minute amount of PACl added. It only witnessed a slight improvement in removal rate at 90 minutes compared with 0 mg Al/L. This suggests that the PACl dosage was insufficient to produce a substantial positive effect. On the other hand, 40 mg Al/L demonstrated a noticeable removal efficiency enhancement of 30% at the end compared with 0 mg Al/L and 20 mg Al/L. It showed that the addition of PACl can probably enhance the removal process. The improvement in the removal efficiency is mainly because PACl is attributed to better floc formation and a reduction in suspended solids, which facilitates oxygen transfer and decreases competition for space and nutrients[30]. On the other hand, doubling the PACl concentration to 80 mg Al/L compared to 40 mg Al/L showed slight symptoms in bacteria inhibition, and a slower ammonia removal rate was witnessed among the whole experiment supported that statement. The bacterial inhibitory evidence was more severe at 160 mg Al/L. They indicated that aluminum could disrupt enzyme activity and damage cell membranes, while the hydrolysis of PACl lowers pH, further suppressing microbial function[31]. Even when oxygen is sufficient, nitrification may fail due to biological inhibition, resulting in a significant decrease in ammonia removal efficiency. This may be due to the overdosing, which leads to the adsorption surface becoming saturated or flocculated simultaneously, limiting the contact between ammonia and microorganisms, resulting in ammonia removal being less rapid. In addition, it is possible that high PACl concentrations may create unfavorable conditions for biological activity due to pH reduction by PACl realeasing H^+ion, which disrupts and inhibits nitrifying bacteria. Cell membrane damage caused by Al^{3+} disrupting proton exchange and reducing enzyme activity may lead to reduced ammonia conversion. Thus, PACl addition can change the hydrophobicity of the sludge, which reduces the ammonia diffusion into the sludge's surface. This symptom can reduce the reduction in ammonia concentration as well. This means that the lower hydrophobicity of the sludge is better for ammonia removal, but the higher the PACl addition can increase the hydrophobic characteristic of the activated sludge itself[32]. Overall, the inhibitory effect observed at higher PACl concentrations in this study is consistent with previously reported findings, emphasizing that excessive aluminum-based flocculants may inhibit bacterial activity by lowering pH and disrupting enzyme function.

In the treatment process, PACl is primarily used as a flocculant, promoting the sedimentation of suspended solids and colloidal organic matter in wastewater before it enters the biological treatment unit. Based on the above results, when integrated into the activated sludge process, PACl enhances floc formation, thereby improving pollutant removal efficiency; however, this is highly dependent on dosage and wastewater characteristics. Excess PACl can inhibit microbial activity by altering pH. Therefore, future studies should focus on optimizing operating conditions, such as pH, temperature, and on evaluating microbial bioassays to gain more detailed information about the effects of PACl before large-scale application.

Comparison of COD and ammonia removal efficiency between PAC and PACl

During the same 120-minute experiment, the addition of PACl resulted in a more significant reduction in COD concentration than PAC, as indicated by the C/C_0 ratio. At the end of the process, the C/C_0 ratio for PACl ranged from approximately 0.2 to 0.8, while that for PAC varied between 0.7 and 0.9. However, the addition of both PAC and PACl to the AS process each provided higher COD removal efficiency compared to the conventional AS process. In addition, at higher dosages of PAC and PACl, the COD concentration decreased more significantly than at lower dosages. This pronounced reduction was observed for PACl, where the removal efficiency increased as the PACl dosage rose from 0 mgAl/L to 160 mgAl/L. Although both reduced COD concentration, the removal mechanisms of PAC and PACl are entirely different. In the PAC–AS process, COD removal occurs simultaneously through physical–chemical adsorption and enhanced biodegradation [16] . In contrast, COD in the PACl–AS process is removed through a surface adsorption mechanism associated with the formation of precipitates generated during the hydrolysis of PACl [29] . Unlike COD, the decrease in NH_4^+–N concentration between PAC and PACl combined with AS processes showed almost no significant difference, with C/C_0 ratios ranging from 0.7 to 0.8. Nevertheless, the addition of PAC and PACl exhibited positive effects on NH_4^+–N removal efficiency. The addition of PAC to the AS process not only helps adsorb NH_4^+–N onto its surface but also adsorbs toxic organic compounds and heavy metals in wastewater [26–28] . These compounds are considered inhibitors of nitrogen-transforming bacteria, thereby supporting nitrifying microorganisms to operate more effectively. For PACl, NH_4^+–N removal via floc entrapment, which traps the organic–nitrogen compounds, and sometimes ammonium ions bound to particulates, resulting in a reduction in ammonia concentration [10] . However, the addition of PACl at high doses should be carefully considered, as bacterial inhibition and changes in sludge characteristics may occur, leading to decreased removal efficiency [32] .

Although the COD removal efficiency of PACl is higher than that of PAC, the current results are not sufficient to provide recommendations for practical application. The selection of which compound to use in operation should be based on the operational objectives of the system. In particular, the economic aspect between the addition of PAC and PACl should be carefully evaluated.

CONCLUSION

The study was conducted by adding PAC and PACl to the activated sludge process to evaluate their effects on the treatment efficiency of centralized industrial wastewater. Compared with the conventional activated sludge process, the addition of PAC and PACl can significantly reduce COD and NH_4^+-N concentrations. For PAC, the highest reductions in COD and NH_4^+-N concentrations were recorded at a dose of 4 g/L, with C/C_0 reaching 0.6 and 0.7, respectively. However, the concentrations remained relatively high. In contrast, the application of PACl at a dosage of 160 mg Al/L showed the greatest reduction in COD concentration, with C/C_0 reaching 0.2. Overall, increasing the dosages of both PAC and PACl resulted in a corresponding decrease in COD concentration.

AUTHORS' CONTRIBUTIONS:

Thi-Thanh-Thuy Phan: Experiments, data management and analysis, manuscript writing.

Anh-Toan Pham: Experiments, methodology, manuscript writing.

Cao-Hung To: Experiments, manuscript writing.

Phuong-Thao Nguyen: Manuscript review & editing, original draft preparation.

Viet Huu Nguyen: Manuscript review & suggestions.

Thi-Hien To: Manuscript review & suggestions.

Le My Du: Manuscript review & suggestions.

Xuan-Thanh Bui: Funding, Supervision, Manuscript review & editing the final.

CONFLICT OF INTERESTS

There are no conflicts to declare.

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Bài báo nghiên cứu

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Hiệu suất xử lý nước thải công nghiệp tập trung sử dụng than hoạt tính dạng bột và poly-aluminum chloride kết hợp với quá trình bùn hoạt tính

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TÓM TẮT

Nghiên cứu này nhằm đánh giá hiệu suất xử lý nước thải công nghiệp tập trung bằng quá trình bùn hoạt tính (AS) kết hợp với than hoạt tính dạng bột (PAC) và poly-aluminum chloride (PACl). Thí nghiệm với PAC được thực hiện ở năm liều lượng gồm 0,0; 0,5; 1,0; 2,0 và 4,0 g PAC/$L_{bùn}$, trong khi PACl được khảo sát ở các liều lượng 0,0; 20; 40; 80 và 160 mg Al/$L_{bùn}$ trong thời gian 120 phút. Với tỷ lệ C/C0 nhỏ hơn 1,0, việc bổ sung PAC và PACl đã cải thiện đáng kể hiệu suất xử lý. Theo đó, nồng độ COD và NH_4^+-N ở cuối thí nghiệm đều thấp hơn giá trị ban đầu trong cả hai thí nghiệm PAC và PACl. Đối với COD, PACl cho thấy mức giảm cao hơn PAC, với tỷ lệ C/C0 dao động từ 0,2 đến 0,8, trong khi PAC chỉ đạt từ 0,7 đến 0,9. Tương tự, nồng độ NH_4^+-N cũng giảm sau 120 phút, với tỷ lệ C/C0 dao động từ 0,7 đến 0,8 ở cả hai thí nghiệm. Hơn nữa, hiệu suất xử lý có xu hướng tăng khi tăng liều lượng PAC và PACl. Nghiên cứu cung cấp góc nhìn rộng hơn về việc nâng cao hiệu suất xử lý nước thải công nghiệp thông qua việc kết hợp các quá trình hấp phụ hoặc keo tụ hóa học với quá trình bùn hoạt tính. Dữ liệu từ các liều lượng PAC và PACl được khảo sát giúp xác định phạm vi vận hành hiệu quả trong xử lý nước thải công nghiệp tập trung, từ đó hỗ trợ lựa chọn các điều kiện vận hành phù hợp, vừa đảm bảo hiệu quả kỹ thuật và kinh tế, đồng thời tránh lãng phí vật liệu và hóa chất.

Từ khoá: Hiệu suất xử lý, Nước thải công nghiệp, Than hoạt tính dạng bột, Poly-aluminum chloride, Quá trình bùn hoạt tính

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