J. T. K. L.
JURNAL TEKNIK KIMIA DAN LINGKUNGAN

J. Tek. Kim. Ling. 2025, 9 (1), 1-10
p-ISSN : 2579-8537, e-ISSN : 2579-9746
http://jurnal.polinema.ac.id/index.php/jtkl
DOI: http://dx.doi.org/10.33795/jtkl.v9i1.5156

Redesigning the Coagulation Process for Treating Water Produced from Petroleum Drilling in Water Treatment Injection Plants

Maktum Muharja[1,*], Rizki Fitria Darmayanti[2], Kenji Sonomoto[2]

[1]Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya 60111, Indonesia
[2]Laboratory of Microbial Technology, Division of Systems Bioengineering, Department of Bioscience and Biotechnology, Faculty of Agriculture, Graduate School, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan

ABSTRACT

This study aims to optimize the coagulation process for treating wastewater produced from petroleum drilling. The research includes redesigning the flocculator to enhance the coagulation process. The initial quality of the wastewater, characterized by parameters such as turbidity and Total Suspended Solids (TSS), did not meet the environmental quality standards stipulated by the Indonesian government. Poly Aluminum Chloride (PAC) coagulant and Polyacrylic Acid (PAA) flocculant were utilized at varying doses of 10–150 ppm and 0.25–25 ppm, respectively. The study identified the key challenges in the current coagulation and flocculation processes, including inefficiencies in pollutant removal and high operational costs. Optimal doses of 10 ppm for coagulants and 0.25 ppm for flocculants were determined, resulting in daily operational cost savings of IDR 15,865,030. The economic analysis was conducted to project the potential cost savings based on the optimized dosages, indicating a reduction in chemical costs and operational expenses. Moreover, the optimal injection distance for PAA flocculant was found to be approximately 3.5 meters from the static mixer. A new design for the flocculator was proposed, incorporating these findings to improve the overall treatment efficiency. The redesigned flocculator prototype features a 6-meter-long horizontal tube, 1.5 meters in diameter, with 15 partitions spaced 40 cm apart, and a water level difference between the inlet and outlet of around 0.67 cm. These findings suggest that coagulation redesign and optimization, along with clarifier engineering, can significantly reduce operational costs and enhance water quality for injection into the earth.

Keywords: coagulant, flocculant, oil drilling, produced water, water treatment injection plant.

1. INTRODUCTION

The petroleum processing industry generates significant volumes of waste, notably water extracted during oil well drilling, containing challenging-to-degrade chemicals and organic pollutants [1,2]. This waste comprises a range of hazardous substances, including phenol, colloidal particles, ammonia, sulfide, oil, fat, heavy metals, high COD and BOD, TSS, and hydrocarbons [3–5]. However, the current processes employed in the industry, particularly coagulation and flocculation, often fall short in adequately addressing these pollutants, leading to non-compliance with environmental standards. Due to their complex nature, these contaminants pose a considerable environmental threat, necessitating classification based on settling characteristics and size into dissolved, precipitated solids, and colloidal particles [6].

Colloidal particles in wastewater carry negative charges, causing the attractive force between them to be outweighed by the repulsive force of electric charges, thus keeping them in static suspension due to Brownian motion [7]. These colloids play a detrimental role in water quality, leading to

*Corresponding author:
E-mail: maktum@its.ac.id (Maktum Muharja)

Received : May 6, 2024
Accepted : October 26, 2024

the fouling of membranes, pipes, and equipment, and posing significant challenges to wastewater treatment processes [8–10]. Furthermore, colloidal particles contribute to heightened water color, odor, and turbidity, exerting adverse effects on aquatic ecosystems and clean water availability [11,12]. Typically dispersed, emulsified, or dissolved in wastewater, these pollutants predominantly comprise aromatic and aliphatic compounds, representing the bulk of hydrocarbon contaminants [13,14].

Various conventional technologies have been developed for treating wastewater from oil processing, encompassing physical methods like skim tanks, filtration, and membranes; chemical processes such as coagulation-flocculation, ozonation, and ion exchange; and biological processes like the activated sludge process [15–17]. The current coagulation and flocculation processes utilize a range of coagulants and flocculants; however, the efficacy of these methods is often limited by suboptimal dosing and ineffective mixing conditions, resulting in incomplete pollutant removal and increased sludge production [18]. Among these methods, coagulation-flocculation stands out as highly effective in removing dissolved and precipitated solids as well as water turbidity [11]. Different coagulants, including ferric chloride, ferrous sulfate, aluminum sulfate, alum, and polyaluminum chloride, have demonstrated efficiency in reducing suspended and colloidal pollutants [19,20]. Poly aluminum chloride (PAC) and polyacrylamide (PAA) offer high effectiveness in wastewater treatment, albeit concerns persist regarding environmental impacts such as reduced water alkalinity and increased secondary pollution through sludge discharge [21]. Thus, optimizing the dosage of coagulants and flocculants becomes crucial for cost reduction and mitigating adverse environmental effects.

The process of removing oil from wastewater via coagulation involves both physical and chemical mechanisms: aggregation and flocculation. Initially, a coagulant is introduced to neutralize the negative charge of oil particles, thereby reducing electrostatic repulsion and initiating destabilization. Subsequently, these destabilized particles aggregate and merge into larger clusters. Ultimately, these flocs are separated from the water phase either through precipitation or air flotation [15,22,23]. However, the existing coagulation process, as practiced in many water treatment plants, often results in incomplete floc formation due to inadequate mixing energy and improper dosing of coagulants, leading to increased treatment costs and substandard water quality [21]. Hence, there is a pressing need to develop more efficient, cost-effective, and environmentally friendly pretreatment methods for produced water from petroleum processing [24].

Furthermore, the optimization of the coagulation process relies on the interplay between hydrodynamics and surface chemistry in the produced wastewater, profoundly impacting subsequent treatment stages [25,26]. Particularly in the realm of continuous coagulation-flocculation, the optimization through jar tests becomes crucial, involving considerations of parameters like hydrodynamics and tank geometry to mitigate retroflux phenomena and particle entrapment [22,27]. To best of our knowledge, there has been no explicit research investigation and publication on the optimization of water treatment resulting from oil drilling, subsequently injected back into the earth.

The primary objective of this study is to optimize the dosage of coagulants and flocculants for treating produced water from petroleum drilling. This includes a comprehensive redesign of the flocculator to improve mixing efficiency and reduce operational costs. The study also provides a detailed economic analysis to assess the financial benefits of implementing these optimizations in a large-scale Water Treatment Injection Plant (WTIP).

2. RESEARCH METHODS

2.1. MATERIALS

The produced water for oil well injection comes from PT Pertamina Asset 3 Field Jatibarang, Cirebon, Indonesia. Poly Aluminum Chloride (PAC) flocculant and Polyacrylic Acid (PAA) are sourced from PT. Teknologi Kimia Rakhara. The initial quality of the produced water, including parameters such as turbidity and TSS, was analyzed to establish a baseline for treatment. The results indicated that the water quality did not meet environmental standards, necessitating further treatment. Laboratory-grade water from the PE Laboratory of PT. Pertamina Asset 3 serves as the control and analysis material. All materials are procured from official suppliers and undergo quality verification to ensure accuracy and reliability in the research.

2.2. OPTIMIZATION OF THE COAGULATION PROCESS

The research comprised two stages: determining the optimal dose of coagulant-flocculant and selecting an effective stirring speed using the Jar Test [28,29]. Parameters included the percentage reduction in turbidity and TSS values of the produced water. Analysis of Variance (ANOVA) was used to assess the significance of tested variables using Minitab 16 software (Minitab Inc., ITS Surabaya, Indonesia). Each experiment was performed in triplicate.

2.2.1. DETERMINATION OF OPTIMUM COAGULANT AND FLOCCULANT DOSES

The experiment utilized a jar test equipped with six stirrers, each set at speeds of 50 rpm for slow stirring and 150 rpm for fast stirring, as shown in Figure 1a. PAC coagulant and PAA flocculant were applied at varying doses: 10, 25, 50, 75, 100, and 150 mg/l, and 0.25, 0.5, 1, 10, and 25 mg/l, respectively. The jar test procedure involved initial mixing for 30 seconds, followed by the addition of coagulant and flocculant doses and rapid stirring for 1 minute. Slow stirring then ensued for 15 minutes, after which the produced water samples were allowed to settle for 15 minutes before turbidity and TSS measurements were taken.

2.2.2. SELECTING FLASH AND SLOW MIXING SPEED

The PAC solution was introduced for rapid stirring optimization, with a flash mix conducted at 150-300 rpm for 1 minute, succeeded by slow stirring at 50 rpm for 20 minutes. Subsequently, the flash mix was stirred for 1 minute at the identified optimal speed to ascertain the slow mixing rate, followed by slow stirring at 5-20 rpm for an additional 20 minutes. Water turbidity levels were then analyzed to determine the optimal stirring speed.

2.3. REDESIGNING THE FLOCCULATOR

After determining the optimal stirring speed from the jar test, the speed gradient (G) was computed, which will be utilized to optimize the hydraulic static mixer stirring in the produced water treatment plant [30] (refer to Figure 1b). This G value will determine the ideal mixing length in the static mixer before entering the flocculator (Figure 1c) [31]. In this study, the static mixer in the field measured 5.72 meters in length. Following coagulation, the PAA flocculant injection distance is calculated as the variance between the ideal static mixer length and the actual static mixer length in the field.

2.4. ANALYSIS METHODS AND CALCULATIONS

Turbidity analysis used a turbidity meter (Hach 2100Q turbidimeter, USA). Each sample is analyzed before the produced water is processed to determine the turbidity and TSS values. Total suspended solids (TSS)/total suspended solids are measured using the filtration method [1,19]. The settling time was chosen 15 minutes after the jar test stage. Calculation of TSS and TSS reduction follows Equations 1 and 2. Analysis of Variance (ANOVA) was utilized to assess the significance of all independent variables with a confidence level of 95% ($\rho < 0.05$). All runs were conducted in triplicate.

$$Turbidity\ Reduction/\ TSS\ (\%) = \frac{x_1 - x_2}{x_1} \times 100\% \qquad (1)$$

$$TSS = \frac{(filter + sediment) - empty\ filter}{sample\ volume} \qquad (2)$$

Where x_1 is the Turbidity/TSS value before treatment and x_2 is the Turbidity/TSS value after treatment.

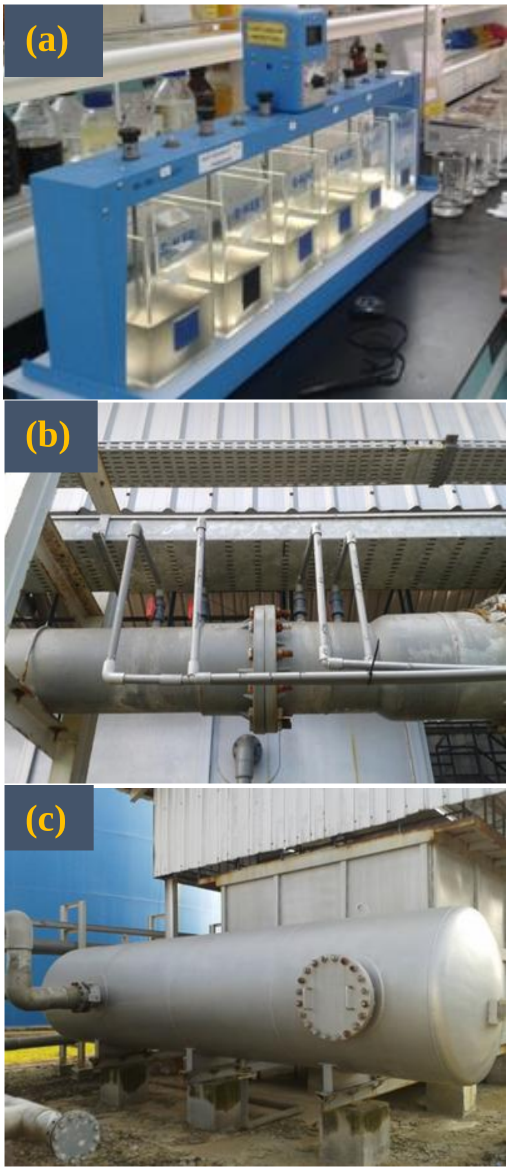

Figure 1. Snapshot of jar test (a), injection of coagulant and flocculant in a static mixer (b), and flocculator (c).

3. RESULTS AND DISCUSSION

3.1. OPTIMIZATION OF COAGULANT DOSAGE

The coagulation process involves three key stages: rapid stirring (1 minute, 150 rpm), slow stirring (20 minutes, 50 rpm), and settling (15 minutes). Rapid stirring facilitates the dispersion of the coagulant in the wastewater, aiding in the agglomeration of small particles present in the water [15]. Conversely, slow stirring, achieved by mixing flocculants, promotes the formation of larger flocs, essential for optimizing the sedimentation process [32]. It is critical to identify the optimal coagulant dosage to prevent the restabilization of particles, which can occur if the dosage is too high. This can lead to increased turbidity and a reduction in the overall effectiveness of the treatment process. The primary focus of the analysis lies in determining the appropriate coagulant dosage, given its significant impact on water turbidity levels. Excessive coagulant doses may lead to restabilization and an increase in turbidity [33].

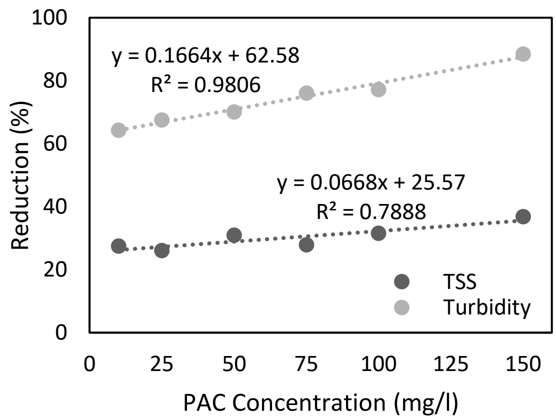

Figure 2. Effect of PAC coagulant concentration on reducing turbidity and TSS.

Figure 2 illustrates the impact of coagulant concentration on reducing turbidity and TSS values. It can be observed that although higher concentrations of coagulant generally result in greater reductions in turbidity and TSS, there is a point where further increasing the coagulant dose leads to diminishing returns or even adverse effects. For instance, while a PAC concentration of 10 ppm achieves a TSS reduction of 27.5%, increasing the dose to 25 ppm does not yield a proportionate improvement and may actually cause the TSS reduction to decrease due to restabilization effects [34]. The hydrolysis of PAC generates three moles of H^+ and typically occurs within a pH range of 5.8-7.5, where colloids are eliminated through adsorption onto the formed metal hydroxide hydrolysis products [35]. It is important to note that the use of inorganic coagulants may elevate the concentration of Total Dissolved Solids (TDS) in treated water [36].

3.2. OPTIMIZATION OF FLOCCULANT DOSAGE

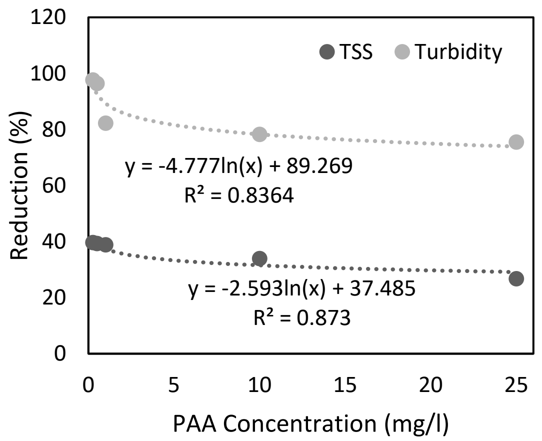

Figure 3. Effect of PAA flocculant concentration on reducing turbidity and TSS.

Figure 3 illustrates the impact of flocculant concentration on reducing turbidity and TSS values. As seen, an optimal dose exists, beyond which further increases in flocculant concentration can negatively impact the coagulation process. For instance, a PAA dose of 0.25 ppm was found to be more effective, resulting in a 39.64% reduction in TSS and 97.64% reduction in turbidity, compared to a 25 ppm dose, which only achieved a 26.79% reduction in TSS and a 75.5% reduction in turbidity. This inverse relationship may be due to the excessive addition of flocculant leading to the formation of overly dense flocs that are difficult to settle [37].

3.3. OPTIMIZATION OF MIXING SPEED

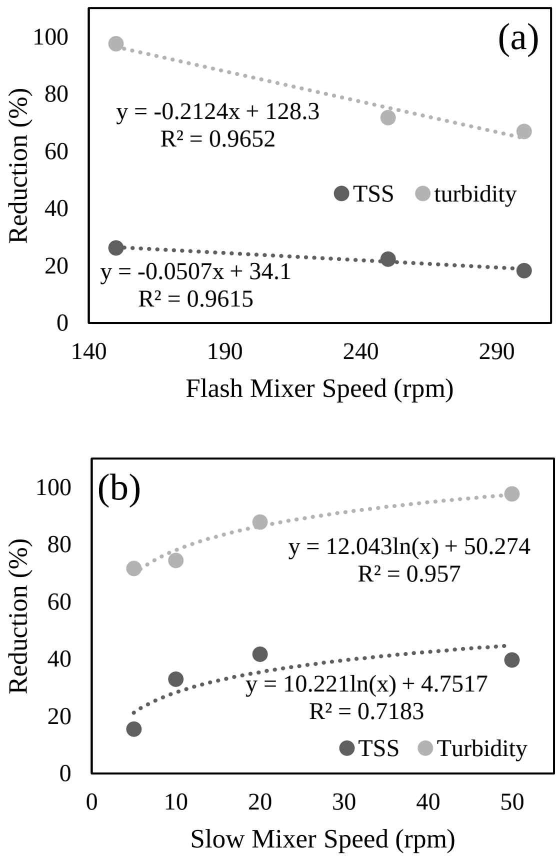

Figure 4. Effect of (a) flash and (b) slow stirring speed on decreasing turbidity and TSS.

The results of the Jar test analysis show that increasing the flash mixer speed has a negative impact on reducing TSS and turbidity. The higher the stirring speed, the smaller the decrease in TSS and turbidity [38], as seen in Figure 4a. Fast stirring at 150 rpm produced the most significant reduction, namely 26% for TSS and 97.65% for turbidity, compared with 22.27% TSS and 71% turbidity at 250 rpm and 18% TSS and 66.93% turbidity at 300 rpm. From an economic perspective, fast mixing at 150 rpm costs less than other speeds and is considered optimal for flash mixing.
The results from the jar test analysis for slow stirring revealed a notable trend in the influence of flash mixer speed on the percentage reduction in TSS and turbidity

(refer to Figure 4b). During slow stirring, it was observed that higher stirring speeds corresponded to smaller percentage reductions in TSS and turbidity [39]. Specifically, slow stirring at 20 rpm yielded the most significant reductions, namely 41.6% for TSS and 97.65% for turbidity, compared to speeds of 5 rpm and 10 rpm, which experienced decreases in TSS of 15.5% and 32.92%, and decreases in turbidity of 71.6% and 74.4%, respectively. Although a speed of 50 rpm resulted in a relatively modest decrease in TSS (39.6%), it exhibited a higher reduction in turbidity (97.6%) compared to the 20 rpm speed. Consequently, a stirring speed of 20 rpm is deemed optimal due to its lower operational costs compared to the 50 rpm speed.

3.4. REDESIGNING OF FLOCCULATOR

Based on the jar test results, the optimal speed for the flash mix was determined to be 150 rpm. This corresponds to a speed gradient (G) value of 359.23/s, with a Champ number (GTd) of 21554.11. These values align with literature, which suggests that the optimal speed gradient for slow stirring falls within the range of 300 to 1000/s, with an optimal detention time ranging from 20 to 60 seconds [26].

Based on the jar test results, the optimal stirring conditions were determined to be at a stirring speed of 20 rpm with a detention time of 15 minutes. Under these conditions, the velocity gradient (G) and Champ number (GTd) were calculated to be 17.5/s and 15740.89, respectively. Notably, these values align with references indicating that the ideal velocity gradient for slow stirring falls within the range of 10 to 50/s, while the Champ number (GTd) typically ranges between 10,000 and 100,000 [40]. Furthermore, the analysis revealed that the optimal distance for PAA flocculant injection is 3.5 meters after stirring with a static mixer. These findings offer practical recommendations consistent with established scientific standards, providing valuable guidance for optimizing stirring in the injector before entering the flocculator.

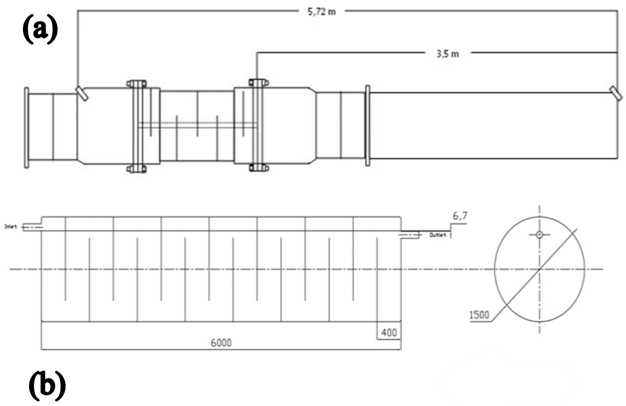

Figure 5. Design of (a) ideal flocculant injection, and (b) flocculator prototype from the results of jar test.

Based on the calculations, an ideal design for the flocculator prototype can be proposed, as illustrated in Figure 5. The flocculator prototype was designed with a horizontal tube 6 meters in length and 1.5 meters in diameter, containing 15 partitions spaced 40 cm apart. This configuration was selected to ensure effective mixing and floc formation, leading to improved sedimentation and pollutant removal. The water level difference between the inlet and outlet was maintained at approximately 0.67 cm, which is critical for maintaining optimal flow and mixing conditions within the flocculator.

The prototype was further validated by comparing its performance with the existing system, showing significant improvements in both TSS and turbidity reduction. The optimal injection distance for the PAA flocculant was calculated to be 3.5 meters from the static mixer, ensuring that the flocculant is effectively mixed before entering the flocculator. This design change is expected to enhance the overall efficiency of the water treatment process, particularly in large-scale operations like those in WTIP.

3.5. ECONOMIC ANALYSIS

The economic analysis revealed significant potential cost savings through the optimized use of coagulants and flocculants [41]. The study compared the current WTIP Jatibarang protocol, which uses a coagulant dose of 50 ppm and a flocculant dose of 16 ppm, with the optimized doses of 10 ppm PAC and 0.25 ppm PAA. The optimized doses not only improved TSS and turbidity reduction (by 41.6% and 87.8%, respectively) but also led to daily operational cost savings of IDR 15,865,000. This analysis included a detailed breakdown of chemical costs, energy consumption, and potential savings from reduced sludge disposal.

The results clearly indicate that adopting the optimized doses can significantly reduce the operational costs associated with produced water treatment, making the process more cost-effective and sustainable in the long term. Furthermore, the optimized process minimizes the environmental impact by reducing the amount of chemicals used and the volume of sludge generated, thereby aligning with environmental regulations and sustainability goals. Therefore, the study suggests adopting the optimized doses to enhance efficiency and cost-effectiveness in the produced water treatment process.

4. CONCLUSION

Based on the findings of this study, it can be concluded that the optimal doses of PAC coagulant and PAA flocculant for treating produced water are 10 ppm and 0.25 ppm, respectively. Implementing these doses could lead to daily operational cost savings of approximately IDR 15,865,000. The redesigned flocculator prototype, with a horizontal tube measuring 6 meters in length and 1.5 meters in diameter, 15 partitions spaced 40 cm apart, and a water level difference of 0.67 cm between the inlet and outlet, has demonstrated significant improvements in the efficiency of the water treatment process. Additionally, the recommended placement for optimal flocculant injection is approximately 3.5 meters from the static mixer. These findings promise enhanced efficiency in treating produced water for petroleum well injection, facilitating more cost-effective and sustainable operations.

ACKNOWLEDGMENT

The author would like to thank the Indonesian Ministry of Education, Culture, Research and Technology and PT. Pertamina Asset 3 Field Jatibarang, Cirebon, Indonesia.

REFERENCES

[1] N. N. Ayhan, A. Aldemir, A. Özgüven, Treatment of petroleum refinery wastewater by chemical coagulation method: determination of optimum removal conditions using experimental design, *Brazilian J. Chem. Eng.*, vol. 41, no. 1, pp. 121–137, 2024.

[2] M. Muharja, S. Hasanah, D. A. D. Sari, M. Khoirunnafiuddin, S. N. Fadilah, R. F. Darmayanti, D. Satrio, M. Ismayati, Enhanced oil removal by graphene oxide/N,N′-methylene bisacrylamide modified magnetite-cellulose aerogel derived from ramie stem waste: Adsorption performance, kinetics, and economical analysis, *Bioresour. Technol. Reports*, vol. 24, pp. 101645, 2023.

[3] O. Dkhissi, A. El Hakmaoui, M. Chatoui, R. Bouyakhsass, H. Bakraouy, T. A. Kurniawan, A. Anouzla, A. Jada, S. Souabi, Vegetable Oil Refinery Wastewater Treatment by Using the Cactus as a Bio-flocculant in the Coagulation-Flocculation Process, *Water. Air. Soil Pollut.*, vol. 234, no. 5, pp. 1–15, 2023.

[4] E. S. Agudosi, E. C. Abdullah, N. M. Mubarak, M. Khalid, M. Y. Pudza, N. P. Agudosi, E. D. Abutu, Pilot study of in-line continuous flocculation water treatment plant, *J. Environ. Chem. Eng.*, vol. 6, no. 6, pp. 7185–7191, 2018.

[5] M. Muharja, S. N. Fadilah, I. M. Arimbawa, S. Hasanah, R. F. Darmayanti, M. F. Rois, M. Asrofi, Low-cost, sustainable, and high-capacity magnetite–cellulose adsorbent from Ramie stem (*Boehmeria nivea L.*) as oil spill solution, *Chem. Pap.*, vol. 76, no. 12,

pp. 7429–7440, 2022.

[6] M. S. S. Abujazar, S. U. Karaağaç, S. S. A. Amr, M. Y. D. Alazaiza, M. JK. Bashir, Recent advancement in the application of hybrid coagulants in coagulation-flocculation of wastewater : A review, *J. Clean. Prod.*, vol. 345, pp. 131133, 2022.

[7] B. Singh, P. Kumar, Pre-treatment of petroleum refinery wastewater by coagulation and flocculation using mixed coagulant: Optimization of process parameters using response surface methodology (RSM), *J. Water Process Eng.*, vol. 36, pp. 101317, 2020.

[8] Y. Sun, Y. Liu, J. Chen, Y. Huang, H. Lu, W. Yuan, Q. Yang, J. Hu, B. Yu, D. Wang, W. Xu, H. Wang, Physical pretreatment of petroleum refinery wastewater instead of chemicals addition for collaborative removal of oil and suspended solids, *J. Clean. Prod.*, vol. 278, pp. 123821, 2021.

[9] Z. Mumtazah, R. E. Nugraha, A. Priyangga, M. Muharja, R. F. Darmayanti, D. K. Y. Putri, H. Khotimah, Evaluating the impact of Fe_2O_3-Zeolite on enhancing hydrophilicity and porosity of PVDF membranes for fouling mitigation using humic acid in membrane bioreactors, *Case Stud. Chem. Environ. Eng.*, vol. 10, pp. 100956, 2024.

[10] R. A. Rachman, N. Widiastuti, A. S. Purnomo, A. Widjaja, Z. Mumtazah, R. F. Darmayanti, M. Muharja, Permeate flux recovery and removal foulant performances of hollow fiber polyvinylidene fluoride membrane bioreactor with peroxodisulfate activated iron (II) sulfate as a chemical cleaning agent, *South African J. Chem. Eng.*, vol. 48, pp. 436–450, 2024.

[11] P. E. Ovuoraye, V. I. Ugonabo, M. A. Tahir, P. A. Balogun, Kinetics-driven coagulation treatment of petroleum refinery effluent using land snail shells: An empirical approach to Environmental sustainability, *Clean. Chem. Eng.*, vol. 4, pp. 100084, 2022.

[12] M. Muharja, R. A. Rachman, A. Widjaja, R. F. Darmayanti, C. Wijaya, D. Satrio, Harnessing Microalgae Photobioreactors to Address Rising Sludge and Fouling Challenges in Membrane Bioreactors, *ASEAN J. Chem. Eng.*, vol. 24, no. 2, pp. 229–241, 2024.

[13] C. E. Santo, V. J. P. Vilar, C. M. S. Botelho, A. Bhatnagar, E. Kumar, R. A. R. Boaventura, Optimization of coagulation-flocculation and flotation parameters for the treatment of a petroleum refinery effluent from a Portuguese plant, *Chem. Eng. J.*, vol. 183, pp. 117–123, 2012.

[14] R. F. Darmayanti, M. Muharja, A. Widjaja, N. Widiastuti, R. A. Rachman, A. R. Widyanto, A. Halim, D. Satrio, B. Piluharto, Performance of modified hollow fiber membrane silver nanoparticles-zeolites Na–Y/PVDF composite used in membrane bioreactor for industrial wastewater treatment, *Heliyon*, vol. 9, no. 11, pp. e21350, 2023.

[15] N. P. Sibiya, S. Rathilal, E. K. Tetteh, Coagulation treatment of wastewater: Kinetics and natural coagulant evaluation, *Molecules*, vol. 26, no. 3, pp.698, 2021.

[16] B. Wang, Y. Shui, H. Ren, M. He, Research of combined adsorption-coagulation process in treating petroleum refinery effluent, *Environ. Technol. (United Kingdom)*, vol. 38, no. 4, pp. 456–466, 2017.

[17] Z. Mumtazah, R. E. Nugraha, A. Priyangga, M. Muharja, R. Fitria Darmayanti, D. K. Y. Putri, Change of Pvdf Ultrafiltration Membranes For Humus Acid Removal Applications In Water By Adding Fe2o3/Zeolite Additives, *E3S Web Conf.*, vol. 473, pp. 03007, 2024.

[18] B. N. Thorat, R. K. Sonwani, Current technologies and future perspectives for the treatment of complex

petroleum refinery wastewater: A review, *Bioresour. Technol.*, vol. 355, pp. 127263, 2022.

[19] H. Ye, L. Chen, Y. Kou, Z. T. How, P. Chelme-Ayala, Q. Wang, Z. An, S. Guo, C. Chen, M. G. El-Din, Influences of coagulation pretreatment on the characteristics of crude oil electric desalting wastewaters, *Chemosphere*, vol. 264, pp. 128531, 2021.

[20] A. K. Badawi, R. S. Salama, M. M. M. Mostafa, Natural-based coagulants/ flocculants as sustainable market-valued products for industrial wastewater treatment: a review of recent developments, *RSC Adv.*, vol. 13, no. 28, pp. 19335–19355, 2023.

[21] F. K. Katrivesis, A. D. Karela, V. G. Papadakis, C. A. Paraskeva, Revisiting of coagulation-flocculation processes in the production of potable water, *J. Water Process Eng.*, vol. 27, pp. 193–204, 2019.

[22] P. Bruno, R. Campo, M. G. Giustra, M. De Marchis, G. Di Bella, Bench scale continuous coagulation-flocculation of saline industrial wastewater contaminated by hydrocarbons, *J. Water Process Eng.*, vol. 34, pp. 101156, 2020.

[23] C. Zhao, J. Zhou, Y. Yan, L. Yang, G. Xing, H. Li, P. Wu, M. Wang, H. Zheng, Application of coagulation/ flocculation in oily wastewater treatment: A review, *Sci. Total Environ.*, vol. 765, pp. 142795, 2021.

[24] I. Khouni, G. Louhichi, A. Ghrabi, P. Moulin, Efficiency of a coagulation/ flocculation–membrane filtration hybrid process for the treatment of vegetable oil refinery wastewater for safe reuse and recovery, *Process Saf. Environ. Prot.*, vol. 135, pp. 323–341, 2020.

[25] E. K. Tetteh, S. Rathilal, Evaluation of different polymeric coagulants for the treatment of oil refinery wastewater, *Cogent Eng.*, vol. 7, no. 1, pp. 1785756, 2020.

[26] Y. S. Vadasarukkai, G. A. Gagnon, Influence of the Mixing Energy Consumption Affecting Coagulation and Floc Aggregation, *Environ. Sci. Technol.*, vol. 51, no. 6, pp. 3480–3489, 2017.

[27] S. Verma, B. Prasad, I. M. Mishra, Pretreatment of petrochemical wastewater by coagulation and flocculation and the sludge characteristics, *J. Hazard. Mater.*, vol. 178, no. 1–3, pp. 1055–1064, 2010.

[28] J. Ribera-Pi, M. Badia-Fabregat, D. Arias, V. Gómez, E. Taberna, J. Sanz, X. Martínez-Lladó, I. Jubany, Coagulation-flocculation and moving bed biofilm reactor as pre-treatment for water recycling in the petrochemical industry, *Sci. Total Environ.*, vol. 715, pp. 136800, 2020.

[29] G. Louhıchı, L. Bousselmı, A. Ghrabı, I. Khounı, Process optimization via response surface methodology in the physico-chemical treatment of vegetable oil refinery wastewater, *Environ. Sci. Pollut. Res.*, vol. 26, no. 19, pp. 18993–19011, 2019.

[30] A. Ghanem, T. Lemenand, D. Della Valle, H. Peerhossaini, Static mixers: Mechanisms, applications, and characterization methods – A review, *Chem. Eng. Res. Des.*, vol. 92, no. 2, pp. 205–228, 2014.

[31] J. P. Valdés, L. Kahouadji, O. K. Matar, Current advances in liquid–liquid mixing in static mixers: A review, *Chem. Eng. Res. Des.*, vol. 177, pp. 694–731, 2022.

[32] W. He, Z. Zhao, J. Nan, Z. Xie, W. Lu, The role of mixing hydrodynamics on floc growth in unbaffled square stirred-tank reactors for flocculation, *J. Environ. Chem. Eng.*, vol. 6, no. 2, pp. 3041–3053, 2018.

[33] K. Saxena, U. Brighu, A. Choudhary, Parameters affecting enhanced coagulation: a review, *Environ. Technol. Rev.*, vol. 7, no. 1, pp. 156–176, 2018.

[34] G. Rytwo, A. Rettig, Y. Gonen,

Organo-sepiolite particles for efficient pretreatment of organic wastewater: Application to winery effluents, *Appl. Clay Sci.*, vol. 51, no. 3, pp. 390–394, 2011.

[35] Y. Chen, Y. Matsui, T. Sato, N. Shirasaki, T. Matsushita, Overlooked effect of ordinary inorganic ions on polyaluminum-chloride coagulation treatment, *Water Res.*, vol. 235, pp. 119909, 2023.

[36] S. Sharif, Q. uz Zaman, F. Hassan, S. Javaid, K. Arif, M. Z. Mansha, N. Ehsan, S. Nazir, R. Gul, M. Iqbal, A. Nazir, Coagulation of Metallic Pollutants from Wastewater Using a Variety of Coagulants Based on Metal Binding Interaction Studies, *Zeitschrift für Physikalische Chemie*, vol. 235, no. 4, pp. 467–481, 2021.

[37] M. Ehteshami, S. Maghsoodi, E. Yaghoobnia, Optimum turbidity removal by coagulation/flocculation methods from wastewaters of natural stone processing, *Desalin. Water Treat.*, vol. 57, no. 44, pp. 20749–20757, 2016.

[38] S. BinAhmed, G. Ayoub, M. Al-Hindi, F. Azizi, The effect of fast mixing conditions on the coagulation–flocculation process of highly turbid suspensions using liquid bittern coagulant, *Desalin. Water Treat.*, vol. 53, no. 12, pp. 3388–3396, 2015.

[39] G. M. Ayoub, S. W. BinAhmed, M. Al-Hindi, F. Azizi, Coagulation of highly turbid suspensions using magnesium hydroxide: effects of slow mixing conditions., *Environ. Sci. Pollut. Res. Int.*, vol. 21, no. 17, pp. 10502–10513, 2014.

[40] T. J. Mohammed, E. Shakir, Effect of settling time, velocity gradient, and camp number on turbidity removal for oilfield produced water, *Egypt. J. Pet.*, vol. 27, no. 1, pp. 31–36, 2018.

[41] E. K. Tetteh, S. Rathilal, K. Robinson, Treatment of industrial mineral oil wastewater – effects of coagulant type and dosage, *Water Pract. Technol.*, vol. 12, no. 1, pp. 139–145, 2017.