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Assessment of Reverse Demulsifier Surfactant Performance for Emulsion Separation in Produced Water from Oil and Gas Operations

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Abstract: The increasing volume of produced water from oil and gas production requires effective handling before reinjection or disposal. Produced water contains minerals, oil, and other contaminants, making separation processes at refineries insufficient. This study investigates the use of reverse demulsifiers, specifically surfactants (Alkyl Phenol Ethoxylate – APEOs and Natrium Lignosulfonate – NLS), to separate emulsions in produced water. Surfactants reduce surface tension between oil and water, facilitating contaminant removal. Using a jar test apparatus, experiments varied surfactant dosage, stirring speed, and stirring time to determine optimal conditions for achieving water quality standards. Results indicate differences between APEOs and NLS in removing contaminants. APEOs, at 5 ppm, 130 rpm, and 5 minutes, achieved a COD concentration of 80.33 mg/L, while NLS, at 5 ppm, 220 rpm, and 10 minutes, yielded 77.48 mg/L. Both are well below the quality standard of 200 mg/L, proving the effectiveness of this approach. This study highlights the potential of APEOs and NLS as reverse demulsifiers for produced water treatment. Proper application could enable safe reuse or environmentally sound disposal, providing an effective solution to managing produced water in the oil and gas industry.

Keywords: alkyl phenol ethoxylate; emulsions; natrium lignosulfonat; produced water; reverse demulsfier.

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1. Introduction

Exploration and production of oil and gas (hydrocarbons) would generate waste in the form of solid, gas, and liquid substances, where 80% of the waste is liquid waste [1]. According to the Indonesian Minister of Environment Regulation No. 19/2010, produced water refers to water (brine) that is brought to the surface during oil, gas, or geothermal extraction, which includes formation water, injection water, and any added chemicals. As oil and gas wells age, the volume of produced water increases significantly. This type of water is cllassified as liquid waste [2]. In one oil field, the average amount of produced water collected each month reaches around 49,060 barrels per day, which is about ten times greater than the volume of oil and gas produced [3], [4]. Due to its large volume, produced water can be utilized for various purposes, such as reservoir injection for water flooding, irrigation, and livestock use [5].

Produced water often contains stable water-oil emulsions, formed by natural or added surfactants during production. The key challenge in its treatment lies in effectively breaking these emulsions.This emulsion contains toxic compounds such as hydrocarbons, oil content, polycyclics, and heavy metals [6]. The characteristics of produced water would vary according to the source, field conditions, chemicals used in the oil production process, or the depth of the reservoir. According to [7], the compounds found in produced water are pollutants. If the concentration of these compounds exceeds the established environmental quality standards, the potential for environmental pollution through water bodies would increase significouldtly. Generally, the pollutant content of this produced water is identified through the parameters of Chemical Oxygen Demand (COD), oil and grease, dissolved sulfide (H_2S), ammonia (NH_3), and total phenol. In the process of oil and gas exploitation, the environmental impact that could be generated is quite serious [8]. The process would generate waste that could alter environmental quality, particularly groundwater, therefore the management of produced water needs to be carried out using methods that are economically or environmentally beneficial [9]. State that reinjecting produced water waste into wells provides greater environmental benefits and operational efficiency for companies compared to other produced water disposal technologies, and is the most economical solution. However, the utilization of untreated produced water containing many toxic substances could disrupt the environmental balance.

The handling of produced water emulsions could be carried out through various methods, including physical, chemical, thermal biological, and gravity processes. The chemical method (demulsification) is often considered more efficient for oil and gas industry applications due to its flexibility and ability to handle produced water emulsions [10]. The chemical treatment of produced water involves using agents such as reverse demulsifiers to break oil in water emulsions and separate contaminants. These chemicals adsorb onto oil droplet surfaces, reduce interfacial tension, and promote droplet coalescence. Once larger oil globules form, phase separation occurs naturally due to gravity and density differences [11].

Based on previous research, reverse demulsifiers that use surfactants have been the main focus in the related scientific literature. Nevertheless, the use of Alkyl Phenol Ethoxylate (APEOs) and Natrium Lignosulfonate (NLS) surfactants in this context has not been extensively researched. In produced water treatment, the use of reverse demulsifiers plays a key role in facilitating the efficient separation process between the oil and water phases. APEOS is a type of non-ionic surfactant that has a good affinity for oil [12], while NLS is an anionic surfactant that has dispersing properties and could enhance emulsion stability [13]. The use of these surfactants is chosen because of their ability to reduce the interfacial tension between the water and oil phases, and they possess balanced hydrophilic and lipophilic properties, making them effective in breaking emulsions. In addition, both of these surfactants are also considered environmentally friendly and could be produced economically on an industrial scale. APEOs are commercially available in the market, whereas NLS is obtained from the utilization of empty fruit bunches EFB, which during production generates waste in the form of EFB 23%, shells 8%, fibers 12%, and liquid waste 66%. If not properly managed, the increasing accumulation of this waste could pose serious environmental threats.

One of the byproducts from EFB processing is black liquor, which contains a high concentration of lignin, approximately 22% of the EFB dry weight. This lignin is insoluble in water but soluble in alkaline solvents such as dimethylformamide (DMF) and tetrahydrofuran (THF). To improve its solubility and surface-active properties, lignin could be modified through a sulfonation process to produce lignosulfonate. The introduction of sulfonate groups (SO_3^-) increases the polarity of lignin, allowing it to function as a surfactant. When used in reverse demulsification, lignosulfonate-based surfactants must be applied with careful consideration of both operational parameters and dosage to ensure effective emulsion breaking. Improper application of reverse demulsifiers could lead to equipment corrosion, process inefficiency, and reduced surfactant performance in breaking emulsions. Therefore, precise control of operational conditions and dosage is essential.

Adsorption equilibrium plays a key role in understanding the molecular mechanism of emulsion separation in produced water and serves as a crucial tool for evaluating adsorption kinetics and capacity in heterogeneous systems, both under suboptimal and saturated conditions. The quantitative relationship between the amount of adsorbate adsorbed on the adsorbent surface and the equilibrium concentration in the solution, at constant temperature, is represented through adsorption isotherm models. In the context of this research, the Langmuir and Freundlich isotherm models are used to describe the adsorption dynamics of EFB and APEOs-based surfactants on an oil-water emulsion system.

The Langmuir model, which assumes a homogeneous adsorbent surface with uniform adsorption sites, and the Freundlich model, which represents adsorption on a heterogeneous surface, provide a theoretical foundation for studying the complex molecular interactions between surfactants and target molecules [14]. Isotherm modeling not only allows for the prediction of adsorption efficiency based on variations in dosage, stirring speed, and stirring duration also provides insights into the design of more effective separation systems [15]. Therefore, this research aims to evaluate the performance of EFB and APEOs-based surfactants in separating water-oil emulsions and removing COD, validate the adsorption isotherm models using experimental results, and identify the most suitable model for the efficient and sustainable treatment of produced water by optimizing key operational parameters such as surfactant dosage, stirring time, and stirring speed.

2. Methods

2.1. Tools and Materials

This research evaluates the effectiveness of reverse demulsifier surfactants in separating emulsions in produced water in the oil and gas industry [16]. The surfactants used are APEOs and NLS, with a base material of lignin isolated from EFB.The sulfonation process was carried out using N_aHSO3 and N_aOH. The equipment used included a magnetic stirrer, heater, hot plate, separating funnel, and oven. For identification and characterization, spectrophotometry is used. The collection of produced water samples for this study was carried out in November 2023 at the PT SPR (Sarana Pembangunan Rakyat) Langgak field, specifically from the gathering station. Samples, totaling ±80 liters, were explicitly taken from the outlet of the oil-water separation tank within this gathering station, representing the produced water after its initial separation from crude oil. This process is part of a series of separation stages between oil, dissolved gas, and water that are produced using equipment such as Gas Boot, Wash Tank, Shipping Tank and Water Tank.

In the first stage, the dissolved gas produced together with the liquid (oil or water) is separated in the Gas Boot, the gas is then flared while the liquid that has been separated from the gas is channeled to the Wash Tank. In the Wash Tank, further separation processes are carried out to separate oil from water, the oil is channeled to the Shipping Tank while the water is channeled to the Water Tank [17].

Produced water separated from oil and gas is treated in the WTP, with quality parameters analyzed based on Indonesian National Standards (SNI) and APHA methods. COD is measured using SNI 6989.2:2009 (closed reflux spectrophotometry), oil and grease by gravimetric method (SNI-6989-10-2011), H_2S by iodometric titration (APHA 4500 S^{2-} F-05), NH_3 by phenate method (SNI 06-6989.30-2005), total phenol via spectrometry (SNI 06-6989.21-2004), temperature by direct thermometer (SNI 06-6989.1.23-2005), pH by potentiometry (SNI 06-6989-11-2004), and TDS by gravimetry (SNI 06-6989.27-2005).

2.2. Experimental Procedure and Reagent Preparation

APEOs used in this study are liquid with a density of 1.05 g/cm³, enabling effective interaction with oil particles to enhance separation. Approximately 1 L was used to ensure consistency throughout the experiments. NLS was synthesized by sulfonating 5 g of lignin in 150 mL water (1:30 w/w), using $NaHSO_3$ and adjusting pH to 7 with N_aOH at 90°C. The product was filtered, distilled, purified with methanol, and evaporated at 60°C, then dried in a vacuum oven (50–60°C) until constant weight to yield pure NLS.

2.3. Optimization of Testing Dose Variations, Speed, and Mixing Time

This study focuses on optimizing dosage, mixing speed, and time for emulsion separation in produced water using APEOs and NLS surfactants. Produced water was collected in sterile containers, and surfactant doses of 5-30 ppm were tested, reflecting industrially relevant concentrations. Stirring speeds ranged from 130-300 rpm, with durations of 5 and 10 minutes, to simulate common industrial mixing conditions. For each jar test experiment, a sample volume of 500 mL of produced water was used. Experiments were conducted using a jar test apparatus following SNI 19-6449-2000. In total, 132 individual jar test experiments were performed, comprising 11 variations for stirring speed and time, each tested with 6 different surfactant dosages, for both APEOs and NLS surfactants (**Table 1**). This approach enables analysis of how dosage, speed, and time affect separation efficiency, providing practical insights for oil and gas operations.

Table 1. Experimental Variation

Variation	Strirring Speed (rpm)	Stirring Time (minutes)
1	200	10
2	220	10
3	230	10
4	250	10
5	300	10
6	130	5
7	150	5
8	160	5
9	170	5
10	200	5
11	250	5

2.4. Linear Regression Approach on Adsorption Isotherm

The stage of adsorption isotherm modeling in this study involves in-depth analysis and selection of the most representative isotherm models, namely Langmuir and Freundlich, to identify the optimal adsorption capacity parameters in the water-oil emulsion system [18]. This process is carried out through a linear regression approach that explores the mathematical relationship between the adsorbate concentration at equilibrium as the independent variable and the adsorption capacity on the adsorbent surface as the dependent variable. This approach is designed to produce isotherm parameters that not only represent the adsorption mechanism with high accuracy but also predict the residual COD concentration in the effluent with optimal precision [19]. This analysis is crucial in supporting the validity of the isotherm model for the design and optimization of surfactant-based reverse demulsifier produced water treatment systems. The adsorption isotherm analysis method uses the linear Equation of the Langmuir model in Equation (1) and the Equation (2).

$$\frac{1}{q_\mathrm{e}} = \left[\frac{1}{K_\mathrm{L}\, q_m}\right] \frac{1}{C_\mathrm{e}} + \frac{1}{q_m} \tag{1}$$

q_m is the theoretical maximum capacity (mg/g), C_e and q_e are the adsorption capacity (mg/g) and concentration (mg/L). K_L indicates the Langmuir isotherm constant. The K_L are used to evaluate the suitability of the adsorption process as indicated by the dimensionless variable q_e.

$$R_L = \frac{1}{1 + K_\mathrm{L}\, C_0} \tag{2}$$

The determination of the calculation results is based on linear regression analysis using a graph of the

$$\log q_\mathrm{e} = \log K_\mathrm{F} + \frac{1}{n} \log C_\mathrm{e} \tag{3}$$

relationship between $1/q_e$ and $1/C_e$. The Freundlich isotherm model is shown in the Eq (3).

K_F is the adsorption capacity (L/mg), 1/n is the adsorption intensity and indicates the relative energy distribution and heterogeneity. The determination of the calculation results is based on regression analysis using the graph of the relationship between log q_e and log C_e.

3. Results and Discussion

3.1. Analysis of Produced Water Characteristics

The results of the analysis of the characteristics of produced water with the parameters COD, oil content, H_2S, NH_3, total phenol, temperature, pH, TDS are 327.75 mg/L, 0.06 mg/L, 0.01 mg/L, 0.10 mg/L, 0.02 mg/L, 30°C, 7.12, and 987 mg/L, respectively (**Tabel 2**). The data is used as a basis to evaluate compliance with the quality standards for produced water set by the Regulation of the Minister of State for the Environment of the Republic of Indonesia Number 19 of 2010 concerning Quality Standards for Wastewater for Oil and Gas and Geothermal Business and/or Activities. From the analysis conducted, the COD characteristic exceeds the quality standard tolerance limit of 327.75 mg/L with a standard of 200 mg/L. Produced water in the oil and gas industry often has a high COD content. This is caused by several factors involving the oil and gas production process as well as the natural characteristics of the subterranean fluids being extracted.

One of the main factors is the contamination by complex hydrocarbon compounds, which often originate from underground reservoirs containing crude oil. The process of extracting oil and gas from geological formations causes the water trapped within them to be brought to the surface along with the oil and gas. This water then becomes produced water containing complex organic compounds, such as aliphatic and aromatic hydrocarbons, as well as other compounds like alkanols and phenols. In addition, the process of separating oil, gas, and water could also lead to the formation of emulsions, where oil and water form a stable mixture.

This emulsion tends to have a high COD content because the organic compounds in the oil are not fully soluble in water, requiring additional oxygen for degradation. The use of additional chemicals in the production process, such as corrosion inhibitors and solvents, could also increase the COD value in the produced water. Therefore, produced water in the oil and gas industry generally has a high COD content due to the complexity of the organic compounds contained within it and the production process that involves the use of additional chemicals. As a result, further treatment is carried out using the reverse demulsifier method (APEOs and NLS surfactants), followed by testing using a jar test before being disposed of into the environment.

Table 2. Characteristic of Produced Water

Parameter	Unit	Standard*	Concentration
COD	mg/L	200	327.75
Oil Content	mg/L	25	0.06
Sulfida (H_2S)	mg/L	0.5	0.01
Amonia (NH_3)	mg/L	5	0.10
Phenol Total	mg/L	2	0.02
Temperatur	°C	40	30
pH	-	6-9	7.12
TDS	mg/L	4000	987

*Regulation of the Minister of State for the Environment of the Republic of Indonesia Nomor 19 of 2010 concerning the Standard Quality of Wastewater for Oil and Gas and Geothermal Business and/or Activities

3.2. Level of APEOs Usage

The testing of APEOs surfactants was conducted 66 times continuously to achieve a low COD concentration. Low COD concentration is important for maintaining water quality, supporting ecosystem balance, complying with environmental regulations, and optimizing water management costs. From the analysis of COD concentration at stirring speeds ranging from 130 to 300 rpm with a stirring duration of 5 minutes, the results show that at a dose of 5 ppm, the COD concentration at stirring speeds of 130 rpm, 150 rpm, 160 rpm, 170 rpm, 200 rpm, and 250 rpm for a stirring time of 5 minutes is relatively low, with results of 80.33 mg/L, 148.58 mg/L, 103.08 mg/L, 105.92 mg/L, 114.45 mg/L, and 86.01 mg/L, all below the established quality standard limit of 200 mg/L. In experiments with a stirring time of 10 minutes, doses of 5 ppm and 10 ppm, and the same stirring speeds as in the 5-minute stirring time, the results were below the quality standard tolerance limit, with values of 154.27 mg/L, 108.76 mg/L, 91.70 mg/L, 83.17 mg/L, 88.86 mg/L, and 131.52 mg/L, 188.39 mg/L, 100.23 mg/L, 168.49 mg/L, 174.17 mg/L, respectively (**Figure 1**).

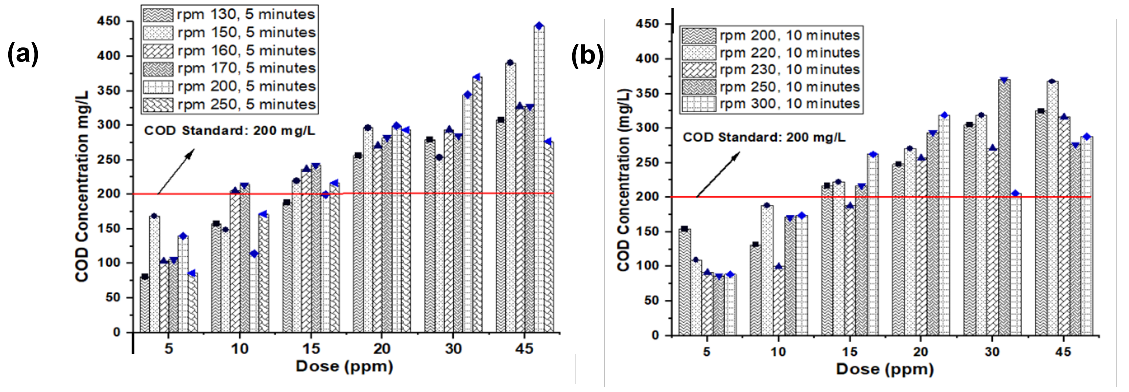

Figure 1. The final concentration of COD surfactant APEOs by stirring time: (a) 5 minutes, (b)10 minutes

Based on the test results, the lowest COD concentration was obtained at a dose of 5 ppm, 130 rpm, and a stirring time of 5 minutes, amounting to 80.32 mg/L. Dose of 45 ppm, almost all COD concentrations exceeded the standard quality tolerance limit, especially at higher stirring speeds. Variations in stirring speed also result in significouldt variations in COD concentration, where higher speeds tend to show greater increases in COD concentration. Stirring at higher speeds and doses tends to result in higher concentrations due to increased interactions between surfactants and the phases involved in the emulsion system. The stirring speed is increased, surfactant particles have more opportunities to interact with the oil and water phases, facilitating the formation or increase in the size of oil droplets. This could lead to an increase in COD concentration due to the higher amount of organic material dispersed in the water phase. Higher doses could increase the amount of surfactant present in the solution, thereby enhancing the emulsification effect and consequently increasing the COD concentration. Thus, the combination of higher speed and dose amplifies the surfactant's influence in emulsion separation, as reflected in the observed increase in COD concentrationin the system.

3.3. Level of NLS Usage

The relationship between COD concentration and surfactant dosage (ppm) with stirring speeds between 130 to 300 rpm for 5 minutes at a dosage of 5 ppm shows that COD concentration remains low and below the quality standard limit. The effect of surfactant on the increase of COD in produced water is still minimal with stirring speeds of 130 rpm, 150 rpm, 160 rpm, 170 rpm, 200 rpm, and 250 rpm over a stirring time of 5 minutes, yielding results of 114.45 mg/L, 125.83 mg/L, 131.52 mg/L, 111.61 mg/L, 103.08 mg/L, and 94.46 mg/L respectively, with the quality standard tolerance set at 200 mg/L. As the surfactant dosage increases, a clear pattern of COD concentration increase is observed. At a dose of 45 ppm, the COD concentration almost always exceeds the quality standard limit, especially at higher stirring speeds 250 rpm. The increase COD indicates that higher surfactant doses introduce more organic materials that could be oxidized.

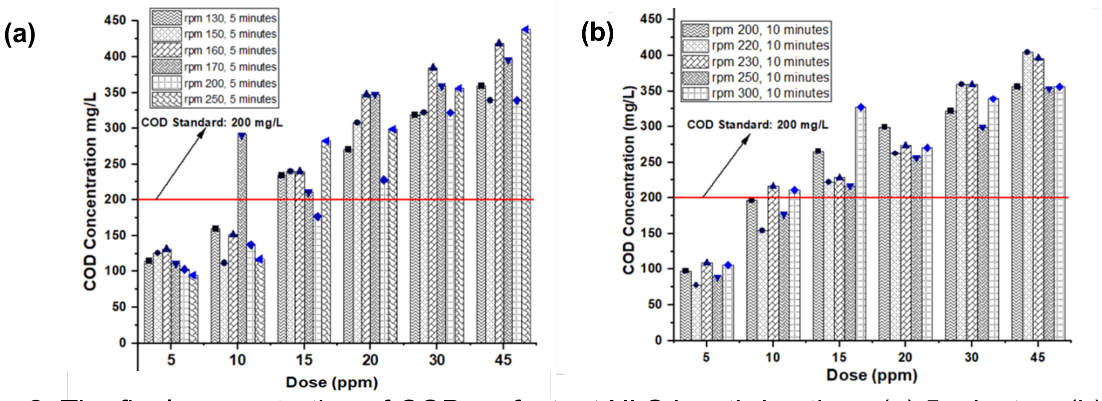

Figure 2. The final concentration of COD surfactant NLS by stirring time: (a) 5 minutes, (b) 10 minutes

A similar analysis at stirring speeds between 130 to 300 rpm and a stirring duration of 10 minutes shows that the COD concentration at a 5 ppm dose remains below the quality standard limit for the same stirring speed with a 5-minute stirring time, with values of 97.39 mg/L, 77.48 mg/L, 108.76 mg/L, 88.86 mg/L, and 105.92 mg/L, respectively. These results confirm that at low doses, the surfactant's influence on COD is minimal (Fig. 2). However, increasing the dosage significouldtly raises the COD concentration, especially at dosages of 30 ppm and 45 ppm. At these dosages, many measurements show COD concentrations exceeding the quality standard limits, particularly at higher stirring speeds (300 rpm).

3.4. Analysis of Surfactant Adsorption Isotherm Model for COD Parameter Efficiency

The results of the Langmuir model analysis with APEOs surfactant show that the maximum q_m varies from 416.67 mg/g to 769.23 mg/g, with Langmuir adsorption coefficients ranging from 0.03 mg/L to 0.05 mg/L (**Table 3**). The R_L value, which indicates the suitability of the adsorption process, ranges from 0.05 to 0.09, indicating that the adsorption process in coagulation with APEOs is effective in reducing COD, in accordance with the criteria $0 < R_L < 1$.The results of the Langmuir model analysis with NLS surfactant show that the q_m varies between 111.11 mg/g and 714.28 mg/g at variations 1 to 11. The obtained

Langmuir adsorption coefficients range from 0.03 L/mg to 0.06 L/mg. The resulting R_L values indicate that the adsorption process occurs well, with values ranging from 0.048 to 0.11. Based on these results, coagulation using NLS is effective in supporting the adsorption process to reduce COD concentration in produced water.

The variable estimation analysis in the Freundlich model is similar to the Langmuir model, where the variable n indicates the type of adsorption process: $n = 1$ for linear adsorption, $n < 1$ for chemical adsorption, and $n > 1$ for physical adsorption. In variations 1 to 11, the n values range from 0.54 to 0.80, indicating that the adsorption process occurs chemically. K_f variations range from 30.57 L/mg to 63.59 L/mg, with the sixth variation showing the best performance (K_f = 63.59 L/mg (**Table 3**)), indicating the significouldt capacity of APEOs to adsorb organic substances and reduce COD [20]. The analysis results of the Freundlich model with NLS surfactant show that the adsorption process occurs chemically, with n values in variations 1 to 11 ranging from 0.56 to 0.78.

K_f variations ranges from 25.29 L/mg to 59.26 L/mg, with the second variation showing the best adsorption performance with a K_f of 59.26 L/mg. This high K_f value indicates that NLS based on EFB has a significouldt ability to adsorb organic substances, contributing to the reduction of COD in produced water. Table 3 shows a comparison of the Langmuir and Freundlich adsorption isotherm parameters for APEOs and NLS surfactants in reducing COD concentration in produced water [21]. Based on the Langmuir model, APEOs surfactant has a q_m of 796.23 mg/g, with a K_L of 0.04 L/mg and a coefficient of determination (R^2) value of 0.98. This indicates that the Langmuir model fits the experimental data for APEOs very well, with an R_L value that indicates the adsorption process is effective. Meanwhile, the NLS surfactant has a q_m of 714.28 mg/g, a Langmuir constant (K_L) of 0.05 L/mg, and an R^2 value of 0.99. These results indicate that NLS, although having a slightly lower maximum adsorption capacity, remains highly efficient in the adsorption process and is very well-suited to the Langmuir model [22].

Freundlich model for the APEOs surfactant shows a K_f value of 63.59 L/mg, with an exponent n value of 0.80, indicating the chemical nature of the adsorption process. The R^2 value of 0.93 indicates that the Freundlich model is also relevant for explaining the experimental data, although its fit is slightly lower compared to the Langmuir model. For the NLS surfactant, the Freundlich constant K_f value reaches 59.26 L/mg, with an exponent n value of 0.78, also indicating a chemical adsorption mechanism. The R^2 value of 0.97 indicates that the Freundlich model is very suitable for describing the adsorption process using this surfactant [23].

Table 3. The isotherm adsorption kinetic variables of APEOs and NLS surfactant

Langmuir			**Freundlich**			**Susfactant dose (ppm)**	**Strirring Speed (rpm)**	**Strirring Time (minutes)**	**Standard (mg/L)**	**COD Concentration (mg/L)**
K_L (L/mg)	q_m	R^2	K_f (L/mg)	n	R^2					
APEOs 0.0431	796.23	0.98	0.80	63.59	0.93	5	130	5	200	80.33
NLS 0.0524	714.28	0.99	0.78	59.26	0.97	5	220	10	200	77.48

Efficiency of the treatment process based on operational conditions also shows significouldt results. At a surfactant dose of 5 ppm, an agitation speed of 130 rpm for 5 minutes for APEOs resulted in a final COD concentration of 80.33 mg/L, which meets the quality standard of 200 mg/L. Meanwhile, at the same dose and quality standard, but with an agitation speed of 220 rpm for 10 minutes, the NLS surfactant produced a lower COD concentration of 77.48 mg/L. This value indicates that NLS has slightly higher efficiency compared to APEOs in the tested parameters. Overall, these results show that both APEOs and NLS surfactants are effective in reducing the COD concentration in produced water. Strong adsorption performance, as indicated by the isotherm parameter values and the alignment of experimental data with the mathematical model, confirms the validity of the approach used. Additionally, EFB based NLS surfactants offer the added advantage of being an environmentally friendly alternative that is potentially more economical [24].

4. Conclusion

Based on the analysis of the characteristics of the produced water, the parameter that exceeds the quality standard is COD at 327.75 mg/L with a quality standard of 200 mg/L. Testing of APEOs and NLS surfactants could be concluded that the dosage and stirring speed affect the concentration of COD in produced water, especially at a dosage of 45 ppm, where almost all COD concentrations exceed the standard quality tolerance limit. Variations in stirring speed also result in significouldt variations in COD concentration, with higher speeds tending to show greater increases in COD concentration. Stirring with higher doses and speeds produces higher COD concentrations due to more intense interactions between the surfactant and the phases involved in the emulsion system.

Effective concentration was obtained with the surfactant type NLS at a dose of 5 ppm, a speed of 220 ppm, and a stirring time of 10 minutes. The COD concentration obtained was 77.48 mg/L from the COD quality standard of 200 mg/L established by the Regulation of the Minister of State for the Environment of the Republic of Indonesia Number 19 of 2010 concerning the Quality Standard for Wastewater for Oil and Gas Business and/or Activities. The Langmuir model indicates the maximum adsorption capacity of the surfactant. At low doses, the model predictions align with the decrease in COD because adsorption is effective. However, when the dosage is increased, the model and experimental data show adsorption saturation, where the addition of surfactant no longer improves separation efficiency and instead worsens the COD condition.

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