

Evaluation of the effectiveness of wastewater treatment in meeting the effluent quality standard - a case study in Balongan, Indonesia

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Abstract. Wastewater discharged from oil and gas operations contains harmful pollutants, including COD, oil and grease, H₂S, NH₃, and total phenol, which cause environmental risks if not adequately treated. This study evaluates the wastewater treatment at the MGS WTP in Balongan, West Java, Indonesia. This assessment integrates pollutant efficiency, pollutant load reduction, and correlation analysis between water quality parameters. A total of two samples (inlet and outlet) were collected daily from January to December 2024. Wastewater samples were analyzed according to SNI and APHA methods. The results of the study achieved high removal efficiencies for COD (94%), NH₃ (88%), and total phenol (76%). While oil and grease, and H₂S achieved moderate removal efficiencies of 68% and 65%, respectively. Pollutant load analysis showed a substantial reduction in COD (262 kg/day), oil and grease (31.1 kg/day), H₂S (0.06 kg/day), NH₃ (12.2 kg/day), and total phenol (2.36 kg/day). The paired t-test showed statistically significant reductions for all pollutants ($p < 0.001$). The treated wastewater complied with Indonesian Regulation of wastewater quality, resulting in the treatment system effectively reducing pollutant loads and supporting sustainable management of wastewater.

1 Introduction

Indonesia's onshore oilfields account for a significant share of the country's crude oil production. The wide geographic distribution and oilfield maturity resulted in a large volume of produced water or wastewater associated with oil and gas exploitation operations. Produced water is an emulsifier of oil and gas found in underground rock formations. Through exploitation and production in the oilfields, hydrocarbons and gas are streamed to the ground surface, and the produced water is also lifted [1]. A study by Abdelhamid *et al.* (2025) that oil and gas operations generated various types of waste, including sludge, gas, and liquid. Particularly, liquid waste accounted for 80% of the total waste generated [2]. In

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2023, the Indonesian Ministry of Energy and Mineral Resources reported that the produced water volume was 484,800 Barrel Water Per Day (BWPD), with crude oil production at 606,000 Barrel Oil Per Day (BOPD). This data reflects that the Water-Oil-Ratio (WOR) in mature onshore oilfields reaches 80% [3]. In this study, produced waster is called wastewater. The large amount of wastewater is often released into water bodies without sufficient treatment, which can harm aquatic ecosystems and human health. Furthermore, its pollution often leads to a decline in water quality, environmental degradation, reduces biota abundance and health problems [4]. Wastewater contains Chemical Oxygen Demand (COD), oil and grease, dissolved sulfide (H_2S), ammonia (NH_3), total phenol, Potential Hydrogen (pH), and temperature [5]. These parameters constitute pollutant loads that cause environmental negative impacts when their concentrations exceed the wastewater quality standards established by the Minister of Environment Regulation Number 19 of 2010 on wastewater quality for oil, gas, and geothermal industries. Wastewater treatment aligns with environmental sustainability principles, which are in accordance with the Sustainable Development Goals (SDGs). Specifically, SDG 12 focuses on production and consumption through waste management practices. SDG 14 focuses on the preservation and sustainable use of marine ecosystems.

Previous studies on wastewater have advanced considerably in the last two decades. These studies focused on chemical composition, toxicity, and treatment technologies, including physicochemical, biological, adsorption, and membrane processes. However, conventional treatments is insufficient to meet wastewater quality standards for discharge and reuse due to the toxicity of residual contaminants. Integrated treatment systems, which combine physical, chemical, biological, active carbon, and membrane technologies are used to improve the effectiveness of oilfield wastewater treatment. Moreover, recent studies highlight the potential for reusing wastewater as an alternative water source or regenerating injection wells. This practice promotes water conservation and supports a circular economy, particularly in areas with limited water. Simultaneously, it can reduce the volume of wastewater and the negative environmental impacts of oil and gas operations [6]. Most existing studies are limited to laboratory or pilot-scale focus on concentration-based treatment efficiency (mg/L), while pollutant load evaluation (kg/day) is rarely applied. Concentration-based approaches do not adequately represent actual environmental pressures, particularly large wastewater discharges. Environmental assessments based on pollutant loads and correlation analysis between water quality parameters are still very limited, even though both have the potential to provide a more comprehensive understanding of system performance and process mechanisms.

Furthermore, statistical correlations between water quality parameters, including COD, oil and grease, H_2S , NH_3 , total phenol, pH, and temperature, are rarely analyzed. These parameters have the potential to explain pollutant sources, process behavior, and process optimization indicators. The limited integration of removal efficiency, pollutant load, and inter-parameter correlations highlights a methodological gap in existing studies. This gap is particularly significant in developing countries such as Indonesia, where evaluations of the performance of wastewater treatment located near residential and coastal areas are still scarce. Currently, no studies have evaluated the treatment performance in reducing pollutant loads and inter-parameter correlation of onshore oilfield facilities in Balongan, Indonesia.

This study addresses the identified gap by conducting a field-based evaluation of a wastewater treatment from the oil and gas industry. Therefore, this study aims to evaluate the performance of wastewater treatment through an integrated approach that combines removal efficiency, pollutant load reduction, and inter-parameter correlation analysis. The novelty of this study is the evaluation of pollutant load as an indicator of environmental pressure and the integration of inter-parameter correlation analysis into a long-term field-data-based

evaluation. This approach provides a representative evaluation framework compared to concentration-based approaches.

2 Methodology

2.1 Study area

This study was conducted at the Wastewater Treatment Plant (WTP) at the Main Gathering Station (MGS) in Balongan, West Java, Indonesia ($6^{\circ}20'52.7''$ South Latitude and $108^{\circ}22'51.2''$ East Longitude), as illustrated in Fig. 1. The facility was operated in 2023 for integrated wastewater treatment in the West Java region. The facility is located near residential areas, farmlands, and coastal ecosystems. The MGS WTP has a capacity of 40,000 BWPD or $6,359 \text{ m}^3/\text{day}$. The high volume of wastewater is influenced by the age of the mature onshore oil fields [7]. The onshore oil fields in West Java are areas of oil and gas exploitation and production, which have been operating for decades in Indonesia [8, 9].



Fig. 1. Map of the MGS WTP Balongan, West Java, Indonesia.

2.2 Characteristics of wastewater, maximum water quality standard, and analysis methods used

This study measured water quality parameters at both the inlet and outlet (at a depth of 50 cm). The parameters analysis encompassed COD, oil and grease, NH_3 , Total Phenol, H_2S , pH, and temperature. A one-liter sample of the wastewater was collected in a sample bottle for analysis at the company's internal laboratory. Water samples were collected daily from January to December 2024 using the grab sampling method, resulting in 365 samples. Because samples were collected at both the inlet and outlet, the dataset consists of 730 water samples. This sampling frequency captures seasonal variability and daily fluctuations of wastewater. Table 1 presents the characteristics of wastewater, maximum water quality, and the analytical methods used. The laboratory analyses were performed in accordance with the Indonesian National Standards (SNI) and the American Public Health Association (APHA)

for the Wastewater Examination, 23rd Edition (2017), to ensure analytical accuracy, precision, and consistency.

Table 1. Characteristics of wastewater, maximum water quality, and analytical methods used

Parameter	Maximum quality standard (mg/L)	Analysis method
COD	200	SNI 06-6989:15-2004 or APHA 5220
Oil and grease	25	SNI 06-6989:10-2004
H ₂ S	0.5	SNI 06-2470-1991 or APHA 4500-S ²
NH ₃	5	SNI 06-6989:30-2005 or APHA 4500-NH ₃
Total phenol	2	SNI 06-6989:21-2005
pH	6 - 9	SNI 06-6989:11-2004
Temperature	40°C	SNI 06-6989.23.2005

Source: Indonesian Regulation under the Minister of Environment Regulation Number 19 of 2010 on Wastewater Quality Standards for Oil, Gas, and Geothermal Businesses at Onshore Facilities.

2.3 Data analysis

The study measured water quality parameters at both the inlet and outlet to determine removal efficiency. The pollutant removal efficiency was calculated in Equation 1 as follows:

$$\text{Removal Efficiency} = \frac{(C_{inlet} - C_{outlet})}{C_{inlet}} \times 100\% \quad (1)$$

Where C_{inlet} and C_{outlet} represent concentrations before and after treatment.

The study applied a paired t-test (inlet vs outlet) to evaluate differences inlet and outlet concentrations, accounting for the paired daily sampling design ($n = 365$) and within-day variability. Statistical significance was evaluated at $\alpha = 0.05$ to ensure a robust evaluation of treatment effectiveness. The paired t-test was calculated in Equation 2 as follows

$$t = \frac{\bar{C}_{inlet} - \bar{C}_{outlet}}{\sqrt{\frac{SD_{in}^2}{n} + \frac{SD_{out}^2}{n}}} \quad (2)$$

Where \bar{C}_{inlet} and \bar{C}_{outlet} represent mean concentrations before and after treatment, SD_{in} and SD_{out} represent the standard deviation of inlet and outlet concentrations, and n represents the number of paired observations ($n = 365$ days).

The p-value is obtained from the t-distribution table using the degrees of freedom. The statistical limits are as follows: $p < 0.05$ indicates a significant decrease in concentration; $p < 0.01$ indicates a very significant decrease; and $p < 0.001$ indicates a highly significant decrease. The 95% Confidence Interval (CI) for removal efficiency was estimated using error propagation to account for variability in both inlet and outlet concentrations. This approach provides a statistical estimate of treatment precision, particularly in large-sample conditions. The 95% CI and Standard Error (SE) were calculated in Equations 3 and 4 as follows :

$$95\% \text{ CI} = \bar{x} \pm 1.96 \times \text{SE} \quad (3)$$

$$\text{SE} = \frac{SD}{\sqrt{n}} \quad (4)$$

Where \bar{x} represents the mean, 1.96 represents the critical value of the standard normal distribution corresponding to a 95% CI, SE represents the standard error of the mean, SD represents the standard deviation, and n represents the sample size (365 days).

The study calculated pollutant loads by multiplying pollutant concentrations by the average daily flow rate and converting units from barrels/day to kg/day. The pollutant load was calculated in Equation 5 as follows:

$$\text{Pollutant Load} \left(\frac{\text{kg}}{\text{day}} \right) = Q \times C \times 0.001 \quad (5)$$

Where Q represent flow rate (m³/hari), and C represent pollutant concentration (mg/L)

To evaluate the relationship between the parameters used Pearson correlation was applied to influent concentration data. Pearson correlation (r) was used to assess the strength and direction of linear relationships between variables. Pearson analysis interprets correlations as follows: strong (r > 0.7), moderate (0.3 < r ≤ 0.7), or weak (r ≤ 0.3). The analysis used a heatmap to visualize correlation matrices and facilitate interpretation of parameter relationships. Pearson correlation is calculated using Equation 6 :

$$r = \frac{\sum(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \times \sum(y_i - \bar{y})^2}} \quad (6)$$

Where x_i represents the first parameter concentration (mg/L), y_i represents the second parameter concentration (mg/L), \bar{x} represents the average value of the first parameter (mg/L), and \bar{y} represents the average value of the second parameter (mg/L).

3 Results

3.1 Wastewater treatment

The MGS plant produces crude oil that will be transferred and processed at the refinery. The plant produces a wastewater by-product, namely produced water. The wastewater is sent to the WTP, which is part of the upstream oil and gas production facility. The MGS WTP functions to process wastewater in an integrated in the West Java region, illustrated in Fig. 2. The first treatment stage is an oil catcher that uses gravity to separate residual oil from wastewater. The separation process is based on density differences, with lower-density oil floating to the water surface, with a retention time of 4.5 hours. The oil layer is removed daily and returned to the MGS plant. Meanwhile, solids and sludge that settle at the bottom of the basin are cleaned by operators according to the maintenance schedule.

Air stripping is a process of mixing wastewater with an aeration system to remove volatile gases such as H₂S, NH₃, and light hydrocarbons, take about 45 minutes. After this, wastewater will transfer to the biological process, where aerobic bacteria decompose hydrocarbons, with oxygen provided by aeration for 2.9 hours. Subsequently, the chemical process uses coagulation and flocculation to remove hard-to-settle and organic matters, which takes about 2.9 hours. The resulting sludge is removed and delivered to the dewatering system, while treated water returns to the oil catcher.

The filtration process removes suspended particles from the coagulated wastewater. Specifically, solid particles are allowed to settle, while the filtration unit removes particles that remain after sedimentation. Wastewater is flowed to the absorption process with coconut

shell media as activated carbon, followed by an adsorption process to remove residual organic material that has escaped the previous separation process. The filtration and absorption process works based on superficial velocity, which means water flows naturally at a rate of 5 gpm/ft². After treatment, the wastewater is collected in a treated water pond for reuse as production regeneration for injection wells and released into water bodies. Therefore, the company needs to comply with regulations governing the use and disposal of wastewater.

3.2 Sludge handling

Sludge is a significant by-product of wastewater treatment, which is generated from the oil catcher pond, air stripping pond, and chemical treatment pond, with a total production of about 3,700 kg/day. This sludge has a moisture content of 80%, meaning that most of its mass is water. The WTP applies a dewatering system to reduce sludge weight by 30–50%, depending on sludge characteristics and operating conditions. These aim to minimize transport costs and improve sludge handling efficiency.

The dewatering system uses a belt-press mechanism in which sludge passes between two belts under increasing pressure, expelling water from the sludge and separating it into the pressurized zone. The result is solid sludge as waste and water transferred to the oil catcher pond for retreatment. Solid sludge contains organic and inorganic compounds, which cause environmental pollution and human health problems. Effective sludge treatment requires consideration of several factors: sludge characteristics, sludge source, industry type, sludge treatment method, and chemicals used. In this study, the MGS WTP generates 650 kg/day of solid sludge. The sludge is managed and transported by PT WASTEC, a company that handles Hazardous and Toxic Waste (LB3).

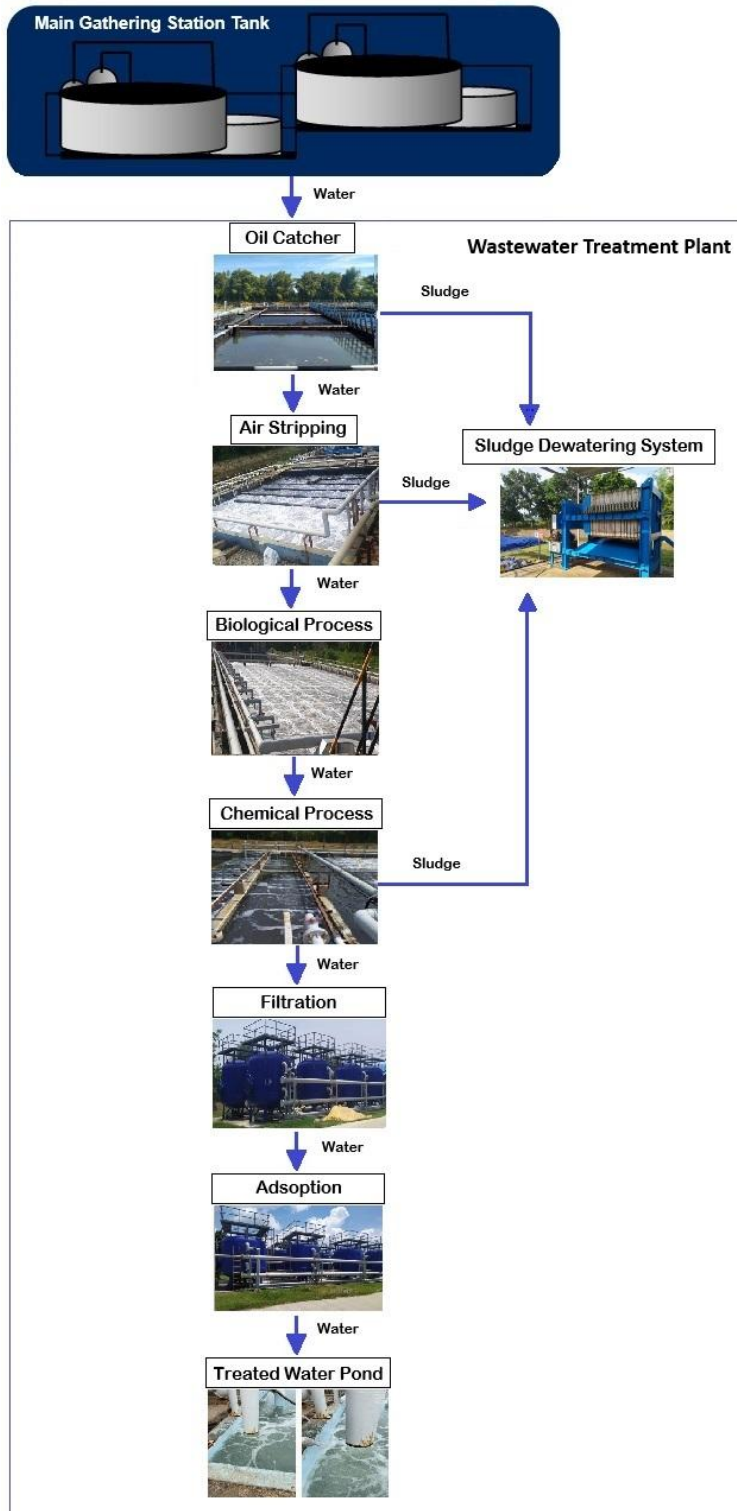


Fig. 2. Process flow diagram of the wastewater treatment system at the Balongan facility.

3.3 Wastewater samples analysis

3.3.1 Chemical Oxygen Demand (COD)

COD was measured using the colorimetric method, following the procedures in SNI 06-6989:15-2004 and APHA 5220. A 10 mL filtered sample was prepared. Then, 0.5 mL of filtrate was added to the COD reagent vials, along with 1.5 mL of deionized water. A reagent blank was prepared by adding 2 mL of deionized water. The sample and blank vials were digested in a COD reactor at 150°C for two hours. After cooling, COD was measured using a Hach DR-900 colorimeter, according to the COD HR method (Program 435). After the instrument was calibrated using the blank sample measurement, the COD was recorded, calculated using the specified dilution factor, and reported in mg/L.

3.3.2 Oil and Grease (O&G)

O&G concentration was determined using the gravimetric solvent extraction method, following SNI 06-6989:10-2004. An empty porcelain dish was pre-weighed (O&G₁). Then, 100 mL of the sample was acidified (pH 2) with concentrated HCl to enhance phase separation. The sample was transferred to a separatory funnel and extracted using 30 mL N-hexane by shaking for roughly 5 minutes. After the separation, the water layer was removed. Then, the organic extract was passed through a column of sodium sulfate to remove moisture. The organic extract was dried, transferred to a pre-weighed porcelain dish, and heated at 100°C to completely evaporate the solvent. After cooling in a desiccator, the dish was reweighed (O&G₂). The O&G concentration as recorded and calculated by weighing the difference in mass, and the result was reported as mg/L.

3.3.3 Dissolved Sulfide (H₂S)

H₂S concentration was assessed through iodometric titration, following in SNI 06-2470-1991 and APHA 4500-S². A 25 mL water sample was treated with Zn-acetate, which prompted the precipitation of sulfide as zinc sulfide, which is subsequently separated by filtration and rinsed with deionized water. The resulting precipitate was transferred into an acidic iodine solution (0.1 N I₂ in 4 N HCl), thereby allowing for the quantitative reduction of iodine by the sulfide. The remaining iodine was titrated using a standardized 0.1 N sodium thiosulfate (Na₂S₂O₃), until the solution turned colourless. A reagent blank was analyzed following the same analysis for iodine. H₂S concentration was calculated stoichiometrically from the difference between iodine added and sodium thiosulfate consumed and reported as mg/L.

3.3.4 Ammonia (NH₃)

NH₃ concentration was determined using the alkaline distillation–titrimetric method, following SNI 06-6989:30-2005 and APHA 4500-NH₃. A water sample (500 mL) was transferred into a one-liter distillation flask. Then, 1 N NaOH was added to the sample (pH 9.5). This change caused the ammonium ions to become ammonia gas. Then, 25 mL of borax buffer was added. The NH₃ released was distilled and absorbed in 2% boric acid (H₃BO₃), and 300 mL of the distillate was collected at a condenser temperature below 29°C. The distillate was diluted to a fixed volume, and 5 mL was titrated with 0.02 N sulfuric acid (H₂SO₄) using a mixed indicator. The endpoint was indicated by a lavender colour. A reagent blank was analyzed simultaneously to account for acidity. NH₃ concentration was calculated stoichiometrically and reported as mg/L.

3.3.5 Total Phenol

Total phenol concentration was determined by the colorimetric method, according to SNI 06-6989:21-2005. A filtered sample (10 mL) was transferred to a vial and reacted with the HI 3864A-0 and HI 3864B-0 reagents, then thoroughly mixed. A reagent blank was prepared by adding 10 mL of deionized water and treating it identically to the sample. The sample and the blank vial were allowed to react for 10 minutes to achieve complete colour. Instrument calibration was performed using reagent blanks prepared with deionized water. Phenol concentration was measured using the user-defined Program 1002 (Phenol) on the spectrophotometer, resulting value was displayed and reported in mg/L.

3.3.6 Potential of Hydrogen (pH)

The pH was determined using a pH meter in accordance with SNI 06-6989:11-2004. The sample was placed in a beaker and measured directly with a pH meter that had a glass electrode. Before measuring, the electrode was calibrated to ensure accuracy. The electrode was immersed in the sample until a stable pH reading was obtained and recorded. To prevent contamination between samples, the electrode was rinsed with deionized water.

3.3.7 Temperature

Water temperature was measured using a thermometer in accordance with SNI 06-6989:23-2005. The sample is transferred to a beaker, and immediate analysis to mitigate heat exchange with the ambient surroundings. The temperature was determined by submerging a calibrated thermometer directly within the sample until a consistent reading was achieved. The temperature was recorded in degrees Celsius (°C). After measures, the thermometer was rinsed to prevent any cross-contamination between the samples.

3.4 Treatment efficiency analysis

The study evaluated the effectiveness of the wastewater treatment using water quality parameters, including COD, oil and grease, H₂S, NH₃, and total phenol. Water samples were collected daily from January to December 2024 using the grab sampling method, resulting in 365 sampling events at each monitoring point. The study collected samples from the inlet (n = 365) and the outlet (n = 365), resulting a total dataset of 730 samples. The frequency of repeated sampling increases temporal and operational variability. All parameters were analyzed based on the analytical methods listed in Indonesian Regulation Number 19 of 2010.

Removal efficiency (%) was determined for each parameter by comparing inlet and outlet concentrations using a mass balance approach. The 95% confidence interval was analyzed using uncertainty propagation, which accounted for the variability in inlet and outlet concentrations. The Standard Error (SE) of the removal efficiency was calculated using error propagation. This calculation assumed that the measurements taken from the inlet and outlet, as well as the variability samples, followed a normal distribution. This combined framework allowed a comprehensive assessment of the WTP performance.

Table 2 shows the results of the removal efficiency analysis, 95% CI, and paired t-tests for each wastewater parameter. The results showed high removal efficiency for COD, NH₃, and total phenol. COD concentrations decreased from 893.85 ± 226.52 mg/L (95% CI: 870.60–917.10) at the inlet to 54.16 ± 9.61 mg/L (95% CI: 53.17–55.15) at the outlet, with a removal efficiency percentage of 94% (95% CI: 91–97). This result suggests that the treatment effectively degraded organic compounds. Then, the NH₃ concentration decreased from 21.16 ± 4.13 mg/L to 2.53 ± 0.64 mg/L, resulting in 88% reduction (95% CI: 86–90),

indicating effective nitrogen transformation, due to adequate aeration and the nitrification process. Total phenol decreased by 76%, from 2.02 ± 0.18 mg/L to 0.49 ± 0.10 mg/L, with a narrow confidence interval (75–77), indicating stable performance in oxidative and adsorption treatment.

Table 2. The result of the removal efficiency analysis

Parameters	Values (mg/L)		Percentage reduction (%) (95% CI)	p-value	Paired t-test
	Inlet (mg/L) (Mean ± SD)	Outlet (mg/L) (Mean ± SD)			
COD	893.85 ± 226.52 (CI: 870.60 - 917.10)	54.16 ± 9.61 (CI: 53.17 - 55.15)	94% (CI: 91 - 97)	< 0.001	74.5
Oil and grease	19.75 ± 2.80 (CI: 19.46 - 20.04)	6.41 ± 2.07 (CI: 6.20 - 6.62)	68% (CI: 67 - 69)	< 0.001	91.3
H ₂ S	0.04 ± 0.01 (CI: 0.039 - 0.041)	0.01 ± 0.0 (CI: 0.010 - 0.010)	65% (CI: 62 - 68)	< 0.001	60.2
NH ₃	21.16 ± 4.13 (CI: 20.74 - 21.58)	2.53 ± 0.64 (CI: 2.46 - 2.60)	88% (CI: 86 - 90)	< 0.001	95.6
Total Phenol	2.02 ± 0.18 (CI: 2.00 - 2.04)	0.49 ± 0.10 (CI: 0.48 - 0.50)	76% (CI: 75 - 77)	< 0.001	153.4
pH	7.55 ± 0.46 (CI: 7.50 - 7.60)	6.99 ± 0.75 (CI: 6.91 - 7.07)	-	-	-
Temperature	28.60 ± 4.06 (CI: 28.18 - 29.02)	25.13 ± 4.35 (CI: 24.68 - 25.58)	-	-	-

Source: Authors analysis (2024)

Conversely, oil and grease and H₂S showed relatively lower removal efficiencies of 65% and 68%, respectively. Oil and grease decreased from 19.75 ± 2.80 mg/L to 6.41 ± 2.07 mg/L, while H₂S decreased from 0.04 ± 0.01 mg/L to 0.01 ± 0.00 mg/L. These decreased due to limitations in sulfide removal and hydrocarbon separation, caused by fluctuating pollutant loads, inadequate retention time, and incomplete separation in the flotation and sedimentation units. The paired t-test showed a significant reduction in COD, oil and grease, H₂S, NH₃, and total phenol ($p < 0.001$), with t-test ranging from 60.2 to 153.4. However, the moderate removal efficiency for H₂S, oil and grease indicates operational optimization is necessary. The operational optimization includes separation efficiency, hydraulic retention time, chemical oxidation, volatile compounds treatment, and emulsification of hydrocarbons.

Pollutant load reduction from wastewater is due to the effectiveness of the treatment, which is influenced by pH and temperature within stable operational limits. Therefore, the WTP demonstrates effective treatment capability in reducing pollutant loads, mitigating negative environmental impacts, and consistently complying with water quality standards. High removal efficiencies for all parameters indicate that the treatment operates reliably under operational conditions.

3.5 Pollutant load analysis

The pollutant load (kg/day)-based approach is the main contribution of this study. The conventional approach focuses on pollutant concentration, whereas pollutant load analysis reflects environmental pressures, particularly the treatment of large waste discharges such as the MGS WTP. Pollutant load was calculated by multiplying the concentration (mg/L) by the daily flow rate (m³/day). This calculation assumes that the concentration and flow rate accurately averaged for each sampling day. Meanwhile, flow rate variability was accounted

for using daily flow rates to ensure that operational fluctuations were considered in the load calculation. This calculation assumes flow meter precision and outlet sample accurately represents daily discharge conditions. The uncertainty in pollutant load estimation was calculated by taking into account the variability in measured concentrations (SD) and sample size ($n = 365$) in the calculation of SE and 95% CI. Although uncertainty arises from flow measurements, analytical errors, and large sample sizes. This method strengthen pollutand load-based performance assessments.

Table 3. The result of pollutant load analysis

Parameters	Pollutant load values (Kg/day)		Maximum pollutant load (Kg/day)*	p-value	Paired t-test
	Inlet (Mean ± SD)	Outlet (Mean ± SD)			
COD	4,329.8 ± 1,097.3 (CI: 4,217.2 – 4,442.4)	262.3 ± 46.6 (CI: 257.5 - 267.1)	968.80	< 0.001	70.8
Oil and grease	95.6 ± 13.5 (CI: 94.2 - 97.0)	31.1 ± 10.1 (CI: 30.1 - 32.1)	121	< 0.001	72.5
H ₂ S	0.17 ± 0.03 (CI: 0.16 – 0.17)	0.06 ± 0.02 (CI: 0.05 – 0.06)	24	< 0.001	58.9
NH ₃	102.5 ± 20.1 (CI: 100.4 - 104.6)	12.2 ± 3.1 (CI: 11.8 - 21.5)	2.4	< 0.001	84.3
Total Phenol	9.8 ± 0.9 (CI: 9.7 - 9.9)	2.36 ± 0.5 (CI: 2.3 - 2.4)	10	< 0.001	142.8
pH	7.6 ± 0.5 (CI: 7.50 - 7.60)	7.0 ± 0.7 (CI: 6.91 - 7.07)	6 - 9	-	-
Temperature	28.6 ± 4.1 (CI: 28.18 - 29.02)	25.1 ± 4.4 (CI: 24.68 - 25.58)	40°C	-	-

Source: Authors analysis (2024)

*Indonesian Regulation under the Minister of Environment Regulation Number 19 of 2010 on Wastewater Quality Standards.

Table 3 presents the results of pollutant load analysis at the inlet and outlet, 95% CI, regulatory maximum limits, and paired t-test. The results showed that all indicator parameters showed significant differences between the inlet and outlet loads ($p < 0.001$). The COD load decreased from $4,329.8 \pm 1,097.3$ kg/day to 262.3 ± 46.6 kg/day ($t = 70.8$; $p < 0.001$), showing a decrease below the maximum limit of 968.8 kg/day. The oil and grease loads decreased from 95.6 ± 13.5 kg/day to 31.1 ± 10.1 kg/day ($t = 72.5$; $p < 0.001$), remaining below the limit of 121 kg/day. Similarly, the H₂S load decreased from 0.17 ± 0.03 kg/day to 0.06 ± 0.02 kg/day ($t = 58.9$; $p < 0.001$), below the allowed threshold of 24 kg/day. The NH₃ load decreased from 102.5 ± 20.1 kg/day to 12.2 ± 3.1 kg/day ($t = 84.3$; $p < 0.001$), below the allowed threshold of 2.4 kg/day. It is indicated that high nitrogen removal efficiency is achieved despite the high influent load. In addition, the total phenol load decreased from 9.8 ± 0.9 kg/day to 2.36 ± 0.5 kg/day ($t = 142.8$; $p < 0.001$), within the maximum allowed limit of 10 kg/day. The relatively narrow 95% CI for outlet loads indicates a stable, consistent treatment under daily operational conditions. The large t-test value (58.9–142.8) indicated that the pollutant load reduction was not affected by random variability, and reflected the systematic and robust effectiveness of the treatment. These results showed that the effluent concentration meets quality standards and a significant reduction in pollutant load (e.g., COD from 4,330 kg/day to 262 kg/day) has implications for reducing cumulative pressure on aquatic ecosystems. Therefore, this approach provides a more relevant evaluation framework for environmental sustainability.

3.6 Parameter correlation analysis

The Pearson correlation (r) was chosen to measure the strength and direction of the linear relationship between variables. The linear relationships were evaluated by scatter plots to verify the presence of a linear trend (Fig. 3). All parameters showed relatively stable trends during the observation period, with daily operational fluctuations. The large sample sizes ($n = 365$) enhance statistical analysis, reduce standard error for moderate correlation, and increase coefficient stability.

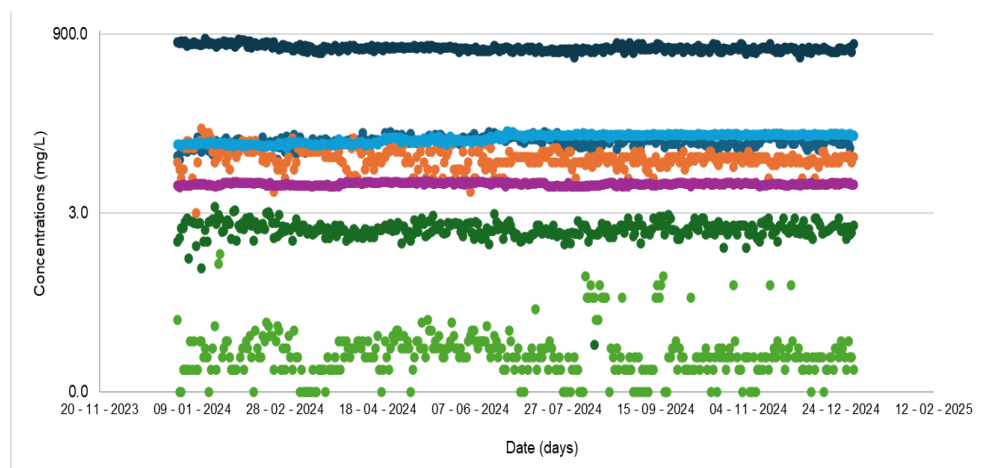


Fig. 3. The time series scatter plot (January 2024–December 2024) illustrates fluctuations in water quality parameters, including NH_3 (blue), oil and grease (orange), phenol (dark green), temperature (light blue), pH (purple), H_2S (light green), and COD (dark blue). The observed fluctuations reflect routine daily operational fluctuations. The pattern shows that these parameters are stable during the monitoring period, with no extreme long-term increase or decrease.

As shown in Fig. 3, COD concentrations show the highest values with temporal variations that reflect a relatively consistent organic load in wastewater treatment. NH_3 concentrations showed a stable trend with moderate fluctuations and no significant extreme fluctuations. Oil and grease concentrations showed greater variation than NH_3 and COD. Although the concentrations remained within the controlled range, this indicated effective removal. Meanwhile, phenol and H_2S concentrations were relatively low and zero during the observation period, indicating effective control despite small fluctuations. Temperature stability was limited by seasonal and operational factors. In addition, pH values remained stable within the normal range, indicating the effectiveness of the chemical treatment process.

The study results show a correlation between physicochemical parameters in wastewater treatment. A strong correlation ($r > 0.7$) indicates that fluctuations in organic load concentrations occur simultaneously between these parameters. A moderate correlation ($0.3 < r \leq 0.7$) indicates a partial process relationship between the parameters. A weak correlation ($r \leq 0.3$) indicates limited interaction or independent behavior between the parameters. These correlations provide insight into pollutant sources, treatment methods, and alternative parameter optimization. A heatmap visualization is presented in Table 4, which illustrates the parameter clustering and mechanistic interpretations of the treatment system.

Correlation analysis in this study was used not only as a statistical approach, but also to interpret the interaction processes within a complex treatment system. The correlations were dominated by weak to moderate relationships, indicating that pollutant removal is not controlled by a single dominant process, but rather by a combination of complementary

physical, chemical, biological and adsorption processes. This confirms that the effectiveness of a wastewater treatment system is highly dependent on the integration of multiprocess treatment.

A moderate negative correlation was identified between COD and temperature ($r = -0.50$, $t = -10.98$, and $p\text{-value} < 0.001$). These results indicate that higher temperatures are associated with lower COD concentrations. In the context of wastewater treatment, this trend indicates that higher temperatures accelerate the degradation of organic matter. Increasing temperature can increase the metabolic activity of microorganisms in biological processes and accelerate physicochemical reactions, thereby reducing the concentration of oxidizable organic compounds.

Table 4 The results of parameter correlation in heatmap

Parameters	pH	Temp	COD	O&G	H ₂ S	NH ₃	Phenol
pH	1.00	-0.06	0.04	0.04	-0.11	0.26	0.03
Temp	-0.06	1.00	-0.50	-0.27	0.05	0.21	-0.06
COD	0.04	-0.50	1.00	0.21	0.11	-0.21	0.27
O&G	0.04	-0.27	0.21	1.00	-0.02	-0.10	-0.03
H₂S	-0.11	0.05	0.11	-0.02	1.00	-0.07	0.17
NH₃	0.26	0.21	-0.21	-0.10	-0.07	1.00	-0.03
Phenol	0.03	-0.06	0.27	-0.03	0.17	-0.03	1.00

Source: Authors analysis (2024)

A weak positive correlation was identified between COD and phenol ($r = 0.27$, $t = 5.43$, $p\text{-value} < 0.001$), between COD and oil grease ($r = 0.21$, $t = 4.20$, $p\text{-value} < 0.001$). This finding is consistent with the composition of wastewater, in which phenol and hydrocarbon compounds are dispersed in the organic load. The moderate correlation between COD and phenol indicates that hydrocarbons are measured from oxidizable organic matter, although the r -value is relatively low. The weak negative correlation between COD and NH₃ ($r = -0.21$, $t = -4.14$, $p < 0.001$) indicates different removal mechanisms during the treatment process. COD reduction occurs through oxidation and biodegradation of organic carbon in biological treatment. Meanwhile, ammonia removal is influenced by nitrification, aeration systems, and chemical processes.

The absence of a strong positive correlation indicates that organic carbon degradation and ammonia transformation occur through independent mechanisms within the system. The positive correlation between pH and NH₃ ($r = 0.26$, $t = 5.06$, $p\text{-value} < 0.001$) is consistent with ammonia balance shifts (equilibrium). High pH conditions shift the equilibrium toward un-ionized NH₃, thereby increasing its concentration. This relationship is relevant in the wastewater treatment, where pH stability is influenced by nitrogen removal efficiency and the volatilization of organic compounds. The results of parameter correlation studies are dominated by weak correlations ($r < 0.30$), indicating that pollutants in wastewater are influenced by an integration of physical, chemical, and biological processes. The complexity of this treatment reflects the heterogeneous composition of parameters in wastewater, as well as the technology used.

4 Discussion

This study evaluated the pollutant removal efficiency of wastewater treatment using concentration-based and pollutant load-based approaches as a key indicator of environmental pressure. The study results showed that the MGS WTP was highly effective in reducing pollutant concentrations and loads. The removal efficiency values of COD (94%), NH₃ (88%), and total phenol (76%) concentrations were within the range of efficiency values in previous studies for treatment systems in the oil and gas industry, namely 70–95% for COD and 65–90% for NH₃, indicating stable and efficient operational conditions [5]. The high COD removal efficiency indicates effective biodegradation of dissolved hydrocarbons and organic matter, influenced by an adequate aeration system and sufficient retention time in the treatment. The NH₃ removal efficiency indicates that the nitrification process is effectively controlled by pH and dissolved oxygen, thereby helping to minimize the risk of eutrophication in receiving water bodies [10]. The phenol removal efficiency of 76% align with the reported range of 60–80% for a combined biological and activated carbon treatment. The removal efficiency values indicate that the MGS WTP complies with Regulatory Number 19 of 2010 on wastewater quality for the oil and gas industries and operates effectively under real conditions.

The MGS WTP indicates high efficiency due to its multiprocess treatment. The treatment process begins with an oil separation process followed by the removal of volatile compounds using air stripping. This is followed by aerobic biological degradation, coagulation-flocculation, filtration, and activated carbon treatment. The integration of these processes allows for the removal of pollutant load entering each subsequent unit. Moreover, an adequate distribution of hydraulic retention time across each process contributes to process stability and enhances biological and physicochemical reactions. A multiprocess treatment system enhances resistance to load fluctuations and increases overall efficiency, compared to conventional systems.

In addition to multiprocess design factors, the stability of influent characteristics, as demonstrated in the time-series analysis (Fig. 3), is crucial for improving treatment system monitoring. Stable parameter variations allow microorganisms to adapt to substrate conditions, thereby increasing the biodegradation efficiency of organic compounds. These results align with previous study showing that influent load stability is a key factor in sustaining the effectiveness of the biological systems in wastewater treatment [6]. Therefore, high removal efficiency is influenced by the technology used and the compatibility between wastewater characteristics and operating system conditions, particularly activated carbon adsorption for effective phenol removal. The phenol removal efficiency of 76% demonstrates a significant contribution from the activated carbon adsorption unit as a final stage. The use of coconut shell-based activated carbon can increase the adsorption capacity for phenols, which is difficult to remove through biological processes. This indicates that selecting an adsorption material suited to pollutant characteristics is a critical factor in improving system performance, particularly for persistent organic compounds. In contrast, the removal efficiencies for oil and grease (68%) and H₂S (65%) were relatively low compared to other parameters. This indicates limitations in the initial separation process and removal of volatile compounds. The presence of stable hydrocarbon emulsions in wastewater can inhibit gravity-based separation in the oil catcher when oil droplets are small and stabilized by natural surfactants.

Furthermore, H₂S removal efficiency is strongly influenced by the duration of air-water interaction in the aeration system, particularly in unstable conditions. Recent studies have shown that improving efficiency for this parameter requires integrating technologies includes Dissolved Air Flotation (DAF) or chemical oxidation [2]. Therefore, these results indicate that the multi-stage system are effective treatment. However, limitations in removing certain

contaminants, including H₂S and COD, require further optimization to improve overall treatment efficiency, particularly by identifying specific conditions or technologies that enhance their removal rates.

Parameter correlation analysis provides insight into the relationship mechanisms between parameters in the treatment system. A moderate negative correlation between temperature and COD ($r = -0.50$) indicates that higher temperature accelerates biodegradation by increasing microbial activity. However, weak correlation indicates that dissolved oxygen availability and substrate composition influence the COD removal. A weak positive correlation between COD and phenol ($r = 0.27$) and oil and grease ($r = 0.21$) indicates that these two parameters contribute a small amount of the total organic load. Because the COD in wastewater is dominated by a complex of other dissolved organic compounds [5, 11]. A weak negative correlation between COD and NH₃ ($r = -0.21$) indicates that the removal processes for these two parameters operate independently through different biological pathways. COD reduction is associated with heterotrophic biodegradation of organic matter, while NH₃ removal occurs through nitrification by autotrophic organisms [5, 12]. These results demonstrate the importance of multi-stage processes to address the complexity of compound components present in wastewater.

The pollutant load (kg/day)-based approach used in this study provides an important contribution in evaluating the effectiveness of operational treatment. Pollutant load analysis provides a more comprehensive assessment of environmental pressure than concentration-based methods, particularly high-flow-rate treatment, such as the MGS WTP. The study results show effluent concentrations meet quality standards, and a substantial reduction in pollutant load (e.g., COD from 4,330 kg/day to 262 kg/day; t -test = 70.8 and p -value < 0.001) have important implications for reducing cumulative pressure on coastal ecosystems [13]. Therefore, this method provides a framework for evaluating the sustainability of wastewater treatment in the oil and gas industry [13].

This study has several limitations that need to be considered. First, the grab sampling method limits the representation of temporal variation compared to composite sampling, particularly fluctuating flow rates. Second, the analysis of wastewater samples in the company's internal laboratory based on SNI and APHA methods, introduces measurement uncertainty and potentially affects pollutant load estimates. Third, the study did not include analysis of toxicity parameters or micropollutants, which provide a more comprehensive view of environmental risks. Therefore, the results of this study are interpreted with these potential uncertainties. Future study is recommended to integrate toxicology-based approaches, process modelling techniques, and real-time monitoring systems to improve the accuracy of performance evaluations. The results of this study indicate that the MGS WTP performance is determined by the interaction between process design, operational conditions, and wastewater characteristics. These findings emphasize that wastewater optimization requires an integrated systems approach and operational stability under actual conditions.

5 Conclusion

This study evaluates the efficiency of concentration-based treatment and the pollutant load-based approach as a key indicator of environmental pressure. This study provides a more comprehensive perspective on assessing wastewater treatment systems under operational conditions. The study results show that the MGS WTP is able to operate effectively and stably in reducing pollutant concentrations and loads under operational conditions. High removal efficiencies for COD ($94\% \pm 1\%$), NH₃ ($88\% \pm 2\%$), and total phenol ($76\% \pm 4\%$) indicate that the integration of physical, chemical, and biological processes is able to optimally process organic compounds and nitrogen in a multistage treatment system.

The pollutant load-based approach shows a decrease in pollutant load, particularly COD, from approximately 4,330 kg/day to 262 kg/day (t-test = 70.8 and $p < 0.001$), indicating a significant contribution to reducing environmental pressure on receiving water bodies. This finding confirms that the evaluation of wastewater treatment not only considers effluent concentration, but also pollutant load as a more representative indicator of cumulative environmental impacts, especially large waste discharges. Thus, this study provides a methodological contribution through the integration of pollutant removal efficiency analysis, pollutant load, and correlation between parameters in a comprehensive evaluation framework.

Correlation analysis shows that the relationship between parameters is dominated by weak to moderate correlations, indicating that the pollutant removal mechanism in this system occurs through complex and complementary processes. This demonstrates the importance of a multiprocess approach in the treatment of wastewater with heterogeneous waste characteristics. However, the lower removal efficiency of oil and grease, and H₂S indicates limitations in the separation unit and the volatile compound removal process. Therefore, increasing efficiency by separating hydrocarbon emulsions and increasing the contact time of the aeration system is important for operational performance.

Methodologically, this study contributes by integrating analysis of pollutant removal efficiency, pollutant load, and correlations between parameters into a field-data-driven evaluation framework. This approach expands performance evaluation methods previously dominated by concentration-based analysis and provides a more comprehensive understanding of the relationship between process performance and environmental impacts. These findings have important implications for industry and policymakers, particularly in encouraging the use of pollutant load indicators and the application of a systems-based approach to sustainable wastewater treatment.

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The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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