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Assessment of the Impact of Palm Oil Mill Effluent (POME) on Water Quality of the Oko-Oko River, Indonesia

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ABSTRACT

Palm oil mill effluent (POME) is one of the primary sources of water pollution in tropical watersheds, especially in areas where waste treatment is not yet optimal. This study aims to evaluate the impact of reducing POME pollutant loads on water quality in the Oko-Oko River in Kolaka District, using parameters such as Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD). The method employed uses the QUAL2Kw water quality model, which has been calibrated and validated. Three pollution load reduction scenarios-baseline/no reduction (Sim1), 30% POME load reduction (Sim2), and 70% POME load reduction (Sim3)-were analyzed to assess changes in DO concentration, BOD, and COD at four monitoring stations. The accuracy of calibration and validation is tested based on the calculation of Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) coefficient functions. Model validation demonstrated excellent agreement between simulation results and observational data, with NSE values of 0.832 (RMSE = 0.584) for BOD, 0.962 (RMSE = 0.655) for DO, and 0.816 (RMSE = 2.548) for COD. Simulation results indicate that a 70% reduction in POME load could increase DO concentration in the downstream section from 6.09 to 6.16 mg.L^{-1}, while BOD and COD would decrease by 7.2% and 5.4%, respectively. These results support the effectiveness of the integrated anaerobic-aerobic filtration system in reducing pollutant loads and ensuring water quality meets Class II national water quality standards.

INTRODUCTION

The palm oil industry, which in 2019 contributed ± 32–35% of the total global vegetable oil production, is an important pillar for food security and the global biocommodity supply chain. Indonesia leads this market, but the surge in plantation expansion has raised a series of ecological issues, ranging from deforestation and biodiversity loss to increased greenhouse gas emissions (Abogunrin-Olafisoye et al. 2024). One of the most significant environmental pressures from the palm oil industry is palm oil mill effluent (POME), which is produced at a rate of 2.5–3.5 tons for every ton of crude palm oil (CPO) processed. All human activities, particularly the palm oil industry, generate waste that contributes to the decline in river water quality (Zulfikar Efendy et al. 2022). Raw POME is known to have a BOD of ± 25,000 mg.L^{-1}, COD of ± 50,000 mg.L^{-1}, TSS of ± 40,500 mg.L^{-1}, and oil and grease of up to 18,000 mg.L^{-1} (Balan et al. 2021). POME poses significant environmental challenges because of its high organic load, which can lead to a decrease in DO levels in water bodies. Inadequate management of POME in tropical producer countries has a direct impact on riverine aquatic ecosystems (Syamriati 2021).

Oil palm plantations in Southeast Sulawesi have expanded to approximately 59,000 ha, making them the third-largest on the island of Sulawesi. The growth of these plantations is expected to increase the volume of POME that needs to be managed sustainably (Central Statistics Agency 2024). The Oko-oko River, located in Kolaka Regency, stretches about 105 km and has an average width of around 13 m. It flows through the plantation area and serves as the main source of drinking water and irrigation for the Tanggetada District. The river faces significant water quality challenges due to the discharge of palm oil mill effluent (POME) from nearby mills. Over the past decade, water quality has shown signs of decline, as indicated in the 2024 Regional Environmental Management Performance Information (IKPLHD) of Kolaka Regency, which notes that the Oko-oko River is slightly polluted. Monitoring downstream reveals high BOD and COD levels that exceed standards. Weak enforcement of existing regulations and the lack of strict rules on POME disposal worsen this situation.

Previous research has been conducted by Hermawan et al. (2024), who modeled the impact of POME on river water quality in Kalimantan, Indonesia, using QUAL2Kw to assess POME pollution. However, the results varied due to hydrological heterogeneity and waste characteristics. Furthermore, the Cigentis River in Karawang Regency, Indonesia, was modeled using QUAL2Kw to determine the distribution of BOD and COD parameters (Yanto et al. 2025). Research has not explicitly been conducted to calibrate and validate QUAL2Kw for mapping the dynamics of BOD, COD, and DO due to POME discharge in the Oko-oko River. This knowledge gap hinders evidence-based policy formulation, especially within the framework of Technical Agreements, as mandated by the Ministry of Environment and Forestry Regulation of the Republic of Indonesia No. 5 of 2021 (Permen LHK No. 5/2021) regarding wastewater quality standards. Therefore, this study aims to evaluate the impact of POME load reduction on the water quality parameters of the Oko-oko River (BOD, COD, and DO) using the QUAL2Kw model. The initial hypothesis is that reducing POME load will lead to improved water quality downstream.

MATERIALS AND METHODS

Location and Field Data

This study uses a quantitative-explanatory method with a field-measurement-supported modeling approach, which is a verification research method combining field measurements and calibrated modeling (Sari et al. 2022). The study was conducted in the Oko-oko River, which is located within the administrative area of Pomalaa Subdistrict, Kolaka Regency, Southeast Sulawesi, Indonesia (Fig. 1).

The river was divided into four segments to determine representative sampling points for the conditions and water quality of the Oko-oko River. The segmentation was based on input from the PT. X wastewater treatment plant outlet and changes in river dimensions. Water sampling was conducted in March, which is the middle of the transition from the rainy season to the dry season, with moderate discharge and pollutant loads, which historically approximates the average annual water quality conditions in rivers in Kolaka (based on 5-year hydrological data). The sampling location descriptions are summarized in Table 1. Surface water sampling at each station used the grab sampling method to measure BOD and COD at specific times, three times from a depth of 0.6

Fig. 1: Map of sampling locations in the Oko-oko River. Scale 1:6,000.

Table 1: Sampling locations.

Sampling Point	Location	Koordinat	Distance from Downstream [km]
ST-1	Upper River	S = 4°16’51.5208” E = 121°36’59.4792”	2.245
ST-2	Outfall	S = 4° 17’0.111” E = 121° 36’42.859”	1.126
ST-3	Middle of the River	S = 4° 17’10.5108” E = 121° 36’34.6968”	0.555
ST-4	Downstream of the River	S = 4° 17’22.47” E = 121° 36’42.93”	0

Source: own study

Table 2: Types of data required.

Data Type	Parameter	Data Source
River water quality	BOD, COD, and DO	Laboratory analysis results
Hydraulic profile of the river	Length, flow velocity, depth, slope, river width, and river discharge	Measurement with a Current meter
River elevation and geographical position	River elevation and Coordinates	Measurement with a Garmin GPS device
Date meteorologists	Air temperature, dew point, wind speed, cloud cover, cover of other objects, and solar irradiation	BMKG Kolaka and www.accuweather.com
Factory effluent data	Palm oil mill wastewater quality analysis results	Laboratory analysis results

m between 9:00 h and 11:00 h. Samples were preserved at a temperature ≤ 4°C under SNI 6989.57:2008 guidelines on surface water sampling methods. River discharge (Q) was calculated using velocity-area integration from three transects per station. Manning’s n was recalculated using the hydraulic radii and slopes from RTK-GNSS elevations.

Modelling with QUAL2Kw

QUAL2Kw is a mathematical model capable of simulating water quality parameters, including BOD, COD, and DO. Primary and secondary data collected from the Oko-oko River were then used to input data into the Software QUAL2Kw version 5.1 worksheet (Table 2). The program was run after the data was entered into the QUAL2Kw program. The QUAL2Kw program automatically generated the output and input files. Tabular output can be viewed in the WQ output worksheet, and graphical output can be viewed in the spatial chart worksheet.

Model calibration is the first step in using the QUAL2Kw program and involves calibrating the data. This was carried out using field data in relation to discharge, depth, and the concentrations of BOD, COD, and DO. After the calibration process, a test was performed to validate the parameters used in the model. Validation was performed by calculating indicators using the RMSE and NSE equations, which are expressed as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi){}^\wedge 2} \qquad \ldots(1)$$

Description:

P_i : Simulated value at time t

O_i : Observed or actual value at time t

n : Number of observations (t = 1,2,….,n)

The NSE equation is as follows (Moriasi et al. 2007):

NSE = 1 - [∑ (*i*=1 to n) (*Y_obs_i* - *Y_sim_i*)^2] /[∑ (*i*=1 to n) (*Y_obs_i* - *Y_mean*)^2] …(2)

Where Yi^{obs} is the *i*th observation for the constituent being evaluated, Yi^{sim} is the *i*th simulated value for the constituent being evaluated, Y^{mean} is the mean of the observed data for the constituent being evaluated, and n is the total number of observations.

Modeling with calibrated QUAL2Kw software was used to simulate river water quality and provide management strategies for improving it (Taherisoudejani et al. 2018). A pollutant load reduction scenario simulation was conducted to evaluate the effectiveness of reducing liquid waste emissions on the recovery of Oko-oko River water quality. There are three scenarios applied to the efficiency of palm oil mill wastewater treatment, namely Simulation 1 (Sim1) – Existing conditions: baseline using actual measurement data of discharge and concentration of palm oil mill effluent at the outlet, Simulation 2 (Sim2) – 30% POME reduction: simulation of improved efficiency in the initial stage of wastewater treatment (anaerobic reactor optimization) and Simulation 3 (Sim3) – 70% POME reduction: simulation of the optimal scenario with an integrated treatment system (anaerobic-aerobic).

The effectiveness of the wastewater management scenarios was assessed by comparing the parameters in the river sections that met quality standards under each scenario. Comparisons between scenarios were conducted using a paired t-test ($\alpha = 0.05$) to identify significant differences in the impact of waste reduction on water quality parameters. The results from the scenario simulations can help develop technical strategies for pollution control, considering the capacity of liquid waste treatment units.

RESULTS AND DISCUSSION

Water Quality Data for the Oko-Oko River

The hydraulic conditions of the Oko-oko River were measured on March 15, 2025. Table 3 presents the field observation data for the Oko-oko River at the four sampling points. The source of pollution in this study is the palm oil factory PT.X, which discharges its liquid waste 1.07 km upstream at a total discharge rate of 0.0094 m^3.s^{-1}.

Table 4 presents the analysis of river water quality at four monitoring points, as well as the quality of palm oil mill wastewater. In summary, DO concentrations ranged from 6.44 mg.L^{-1} (ST 2) to 7.05 mg.L^{-1} (ST 4), while COD showed a much wider range, from 3.70 mg.L^{-1} (ST 1) to 15.65 mg.L^{-1} (ST 4). This reflects the accumulation of nonbiodegradable organic matter and oxidized chemical compounds along the river flow. Although there was a further increase, these values remained within safe limits according to the water quality standards of Class II under Indonesian Government Regulation No. 22 of 2021.

The highest BOD concentration was observed in the upstream segment, indicating pollution from the source. Conversely, the lowest concentration appeared in the downstream segment. Although this value remains within safe limits, caution is necessary due to the increasing pollutants from human activities nearby. These BOD levels show a reduction in organic matter from upstream to downstream, aligning with the natural self-purification process.

Model Calibration and Validation

Table 5 presents the kinetic parameters required by Qual2Kw for calibration. These parameters are recommended from several literature sources, including. Pelletier and Chapra (2008), which was also applied by Hossain et al. (2014) and Kannel et al. (2007).

Model calibration is adjusting the input parameter values and initial or boundary conditions within a reasonable range, until the simulation results closely match the observed variables (Moriasi et al. 2015). Fig. 2 shows that the model was close to the input data (black dots). Fig. 2. An indicates that the highest discharge occurs at the 0.00 km point because

Table 3: Hydraulic data of Oko-oko River.

Sampling Code	Hydraulic characteristics							
	mean velocity [m.s^{-1}]	water depth [m]	width [m]	discharge [m^3·s^{-1}]	Elevasi [m]	Cross-sectional area [m^2]	Slope	Manning
ST 1	0.76	0.44	20.75	6.96	58	9.20	0.002	0.03
ST 2	1.02	0.67	10.20	6.97	51	6.80	0.002	0.03
ST 3	0.95	0.35	21.80	7.14	48	7.56	0.006	0.04
ST 4	1.15	0.80	10.12	9.33	40	8.10	0.006	0.04

Source: Own study

Table 4: Water quality analysis results of the Oko-oko River and PT. X's wastewater effluent.

Parameter	Measurement unit	Values of Oko-oko River Water				PT. X wastewater
		ST 1	ST 2	ST 3	ST 4	
Temperatur	°C	27	26.8	26.5	27	26.80
pH	-	7.78	7.16	8.17	7.94	8.26
DO	mg.L^{-1}	6.64	6.44	6.8	7.05	-
BOD	mg. L^{-1}	3.67	2.99	2.95	2.81	310
COD	mg.L^{-1}	3.703	3.878	3.98	15.65	963
TSS	mg.L^{-1}	134	99	133	196	132
Nitrogen Total as N	mg. L^{-1}	-	-	-	-	613
oil & grease	mg. L^{-1}	0.15	0.36	0.38	0.6	3.8

Source: own study

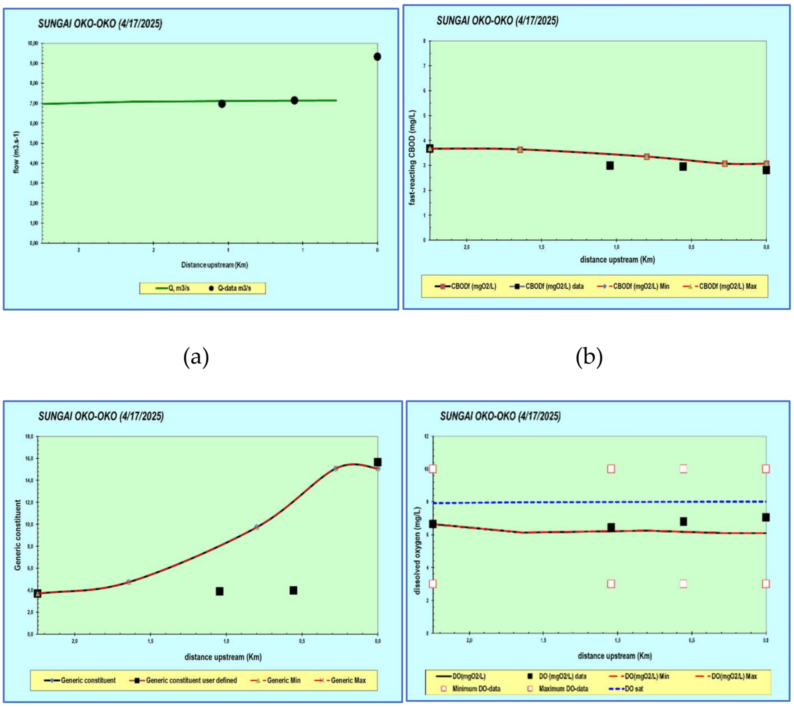
Table 5: Calibrated system parameters in the Oko-oko River.

Parameter	Value	Units	Auto-calibration	Min value	Max value
Stoichiometry:					
Carbon	40	gC	No	30	50
Nitrogen	7,2	gN	No	3	9
Phosphorus	1	gP	No	0,4	2
Dry weight	100	gD	No	100	100
Chlorophyll	1	gA	No	0,4	2
ISS settling velocity	0,06128	$m.d^{-1}$	Yes	0	2
Oxygen inhib parameter CBOD oxidation	0,60	$LmgO_2^{-1}$	No	0,60	0,60
Oxygen inhib parameter nitrification	0,60	$LmgO_2^{-1}$	No	0,60	0,60
Oxygen-enhanced parameter denitrification	0,60	$LmgO_2^{-1}$	No	0,60	0,60
Oxygen inhib parameter phyto resp	0,60	$LmgO_2^{-1}$	No	0,60	0,60
Oxygen enhance parameter bot alg resp	0,60	$LmgO_2^{-1}$	No	0,60	0,60
Slow CBOD Hydrolysis rate	1,93545	/d	Yes	0	5
Slow CBOD Oxidation rate	1,18385	/d	Yes	0	0,5
Fast CBOD Oxidation rate	0,5447	/d	Yes	0	5
Organic N Hydrolysis	0,8365	/d	Yes	0	5
Organic N Settling velocity	0,24964	$m.d^{-1}$	Yes	0	2
Ammonium Nitrification	2,1554	/d	Yes	0	10
Nitrate Denitrification	1,02986	/d	Yes	0	2
Sed denitrification transfer coefficient	0,05126	$m.d^{-1}$	Yes	0	1
Organic P Hydrolysis	3,4361	/d	Yes	0	5
Organic P Settling velocity	0,62926	$m.d^{-1}$	Yes	0	2
Inorganic P Settling velocity	0,01384	$m.d^{-1}$	Yes	0	2
Sed P oxygen attenuation half sat constant	1,69154	$mgO_2.L^{-1}$	Yes	0	2
Max Growth rate	49,3845	$gD.m^{-2}.d^{-1}$ or /d	Yes	0	100
First-order model carrying capacity	100	$gD.m^{-2}$	No	50	200
Basal respiration rate	0,48434	/d	No	0	0,3
Excretion rate	0,46367	/d	Yes	0	0,5
Death rate	0,40579	/d	Yes	0	0,5
External nitrogen half sat constant	163,368	$ugN.L^{-1}$	Yes	0	300
External phosphorus half sat constant	47,556	$ugP.L^{-1}$	Yes	0	100
Inorganic carbon half-saturation constant	1,05E-05	$moles.L^{-1}$	Yes	1,30E-06	1,30E-04
Light constant	2,09098	$langleys.d^{-1}$	Yes	1	100
Ammonia preference	1,48807	$ugN.L^{-1}$	Yes	1	100
Subsistence quota for nitrogen	29,95736472	$mgN.gD^{-1}$	Yes	0,072	72
Subsistence quota for phosphorus	0,3928168	$mgP.gD^{-1}$	Yes	0,01	10
Maximum uptake rate for nitrogen	446,5885	$mgN.g^{-1}D.d^{-1}$	Yes	350	1500
Maximum uptake rate for phosphorus	114,4235	$mgP.gD^{-1}.d^{-1}$	Yes	50	200
COD Decay rate	0,8	/d	No	0,8	0,8
COD Settling velocity	1	$m.d^{-1}$	No	1	1

Source: own study

this segment is unaffected by bends, and the river width also narrows.

The calibration and validation results generally demonstrate strong agreement between model simulations



(a) (b)

(c) (d)

Source: own study.

Fig. 2: Calibration of measurement and simulation data results with QUAL2Kw for the River. (a) River discharge (b) BOD (c) COD (d) DO.

and field measurements (NSE > 0.80), particularly for the river water quality variables BOD, COD, and DO, as reported in Tables 6, 7, and 8. Validating with available data confirms that the model accurately captures water quality dynamics.

Table 6: RMSE and NSE values for the BOD parameter.

Sampling point	Observation Results [X]	Qual2Kw simulation results [Y]	$[X-Y]^2$	$[X-Xrat]^2$
Headwater	3.67	3.67	0.00	9.64
ST 2	2.99	3.64	0.42	0.013
ST 3	2.95	3.35	0.16	0.024
ST 4	2.81	3.07	0.07	0.087
Model Validation Results			RMSe = 0.4	NSE =0.93
Interpretation			The model fits perfectly.	

Source: own study

Table 7: RMSE and NSE values for COD parameters.

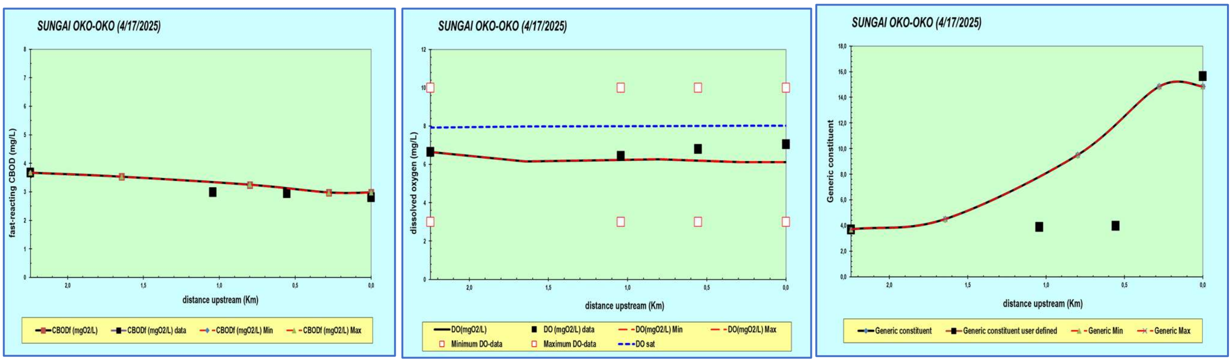
Sampling point	Observation Results [X]	Qual2Kw simulation results [Y]	$[X-Y]^2$	$[X-Xrat]^2$
Headwater	3.703	3.703	0.00	46.277
ST 2	3.878	4.752	0.76	8.554
ST 3	3.98	9.744	33.22	7.967
ST 4	15.65	15.086	0.32	78.273
Model Validation Results			RMSe = 2,93	NSE =0,757
Interpretation			The model is quite good.	

Source: own study

Table 8: RMSE and NSE values for DO parameters.

Sampling point	Observation Result [X]	Qual2Kw simulation results [Y]	$[X-Y]^2$	$[X-Xrat]^2$
Headwater	6.64	6.64	0.00	45.326
ST 2	6.44	6.14	0.09	0.086
ST 3	6.8	6.26	0.29	0.005
ST 4	7.05	6.09	0.92	0.1
Qual2Kw simulation results (Y)			RMSe = 0.57	NSE =0.97
Interpretation			The model fits perfectly.	

Source: own study



(a) (b) (c)

Source: own study.

Fig. 3: Spatial variation of QUAL2Kw in the 30% reduction scenario (a) BOD, (b) DO, (c) COD.

According to Moriasi et al. (2007), results with NSE values ≥ 0.50 indicate acceptable model performance. Camargo et al. (2010) noted that the tropical river model's accuracy is acceptable when the root-mean-square error (RMSE) is less than 20% of the data range.

Simulation of River Water Quality Scenarios

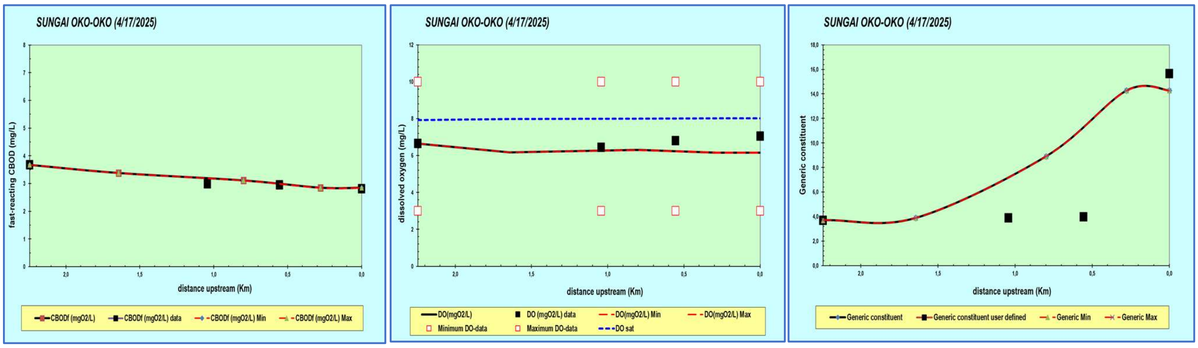
The Oko-oko River water scenario was modeled with a 30% reduction in palm oil mill effluent (POME) load and a 70% reduction at four monitoring points (ST 1-ST 4), then compared with field measurement data. Simulation 1 (Sim1) serves as the baseline model for river water quality, using measurement data of discharge and concentration of POME at the outlet. Simulation 2 (Sim2) was performed with a 30% POME reduction scenario, assuming improved efficiency at the initial stage of waste treatment (anaerobic reactor optimization). Simulation 3 (Sim3) involved a 70% POME reduction scenario, assuming an integrated waste treatment system (anaerobic-aerobic and filtration).

Fig. 3 illustrates the spatial variation of the simulation results for BOD, DO, and COD parameters in the scenario of a 30% POME load reduction (Sim2). It demonstrates the water quality trends from upstream to downstream, heavily influenced by effluent discharge. The BOD concentration shows a relatively steady decline along the river (represented by the red line), indicating that a 30% reduction in POME load helps decrease the organic matter easily broken down by microorganisms. Regarding the DO variation, there is a slight fluctuation in the middle of the river segment, likely caused by deoxygenation due to the organic load, which remains relatively high despite the reduction. Overall, Simulation 2 (Sim2) improved water quality compared to the baseline (Sim1), but it has not yet achieved optimal removal of the organic load. This is evident from the still relatively high BOD and COD values in the middle of the river.

Fig. 4 displays the spatial distribution of the 70% POME load reduction scenario in the Oko-oko River for the three main water quality parameters. The simulation results confirm that a 70% reduction in pollutant load can lower BOD and COD levels and raise DO levels above the Class II water quality standard. Fig. 5 compares field data with simulation results for three pollutant load scenarios: Sim1 (baseline), Sim2 (30% reduction), and Sim3 (70% reduction). The 70% POME reduction scenario (Sim3) produces the best improvement in water quality.

Paired *t*-Test Statistical Analysis

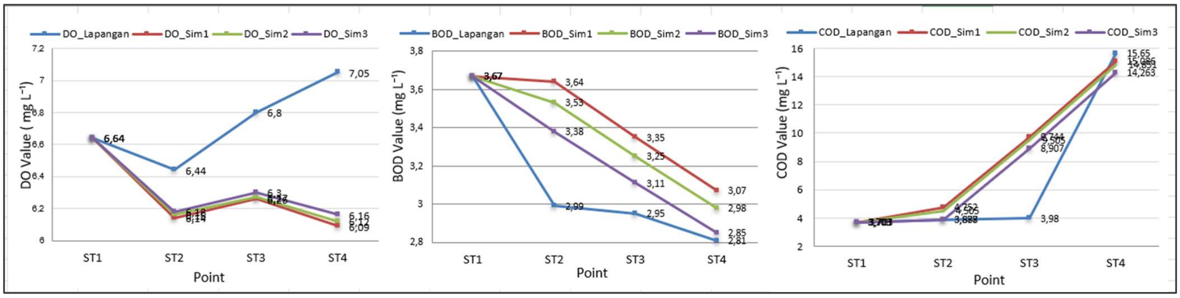
A paired t-test was performed to compare simulation 1 with



(a) (b) (c)

Source: own study.

Fig. 4: Spatial variation of QUAL2Kw in the 70% reduction scenario (a) BOD, (b) DO, (c) COD.



(a) (b) (c)

Fig. 5: Longitudinal profile of QUAL2Kw simulation results for (a) DO, (b) BOD, (c) COD parameters.

simulation 2 and simulation 1 with simulation 3 across the DO, COD, and BOD parameters at four monitoring points, to evaluate the significance of differences between the modeling scenarios. Tests were conducted at a significance level of $\alpha = 0.05$. The results showed that differences between the existing and treatment scenarios were highly significant ($p < 0.05$) for BOD and COD. For the DO parameter, the difference between S_1 and S_3 was not statistically significant ($p = 0.071$), despite an increase in numerical values. The BOD parameter exhibited a significant difference between S_1 and S_3 ($p = 0.032$), confirming the impact of load reduction on BOD levels. Similarly, the COD parameter showed a significant difference between S_1 and S_3 ($p = 0.017$), highlighting the effectiveness of improved treatment processes in reducing dissolved organic compounds. Table 8 indicates that the 70% load reduction scenario (Sim3) markedly enhances water quality, especially regarding BOD and COD parameters.

For all parameter–scenario combinations, the Shapiro–Wilk test yielded p-values greater than 0.05, so the null hypothesis was not rejected. Therefore, the assumption of normality was met for the paired differences used in the paired t-test. The sample size per comparison ($n = 4$) results in relatively low statistical power. Independence between pairs is confirmed because each pair of observations comes from spatially distinct points (ST1–ST4 represent the upstream, midstream, and downstream segments).

Discussion

BOD and COD are essential parameters for assessing organic matter pollution in palm oil industry waste (Andika et al. 2020). The BOD analysis results at point ST 1 (upstream) exceeded quality standards, while at points ST 2, ST 3, and ST 4, the standards were still met. The BOD concentration

Table 8: Results of the paired t-test of DO, BOD, and COD parameters between QUAL2Kw modelling scenarios.

Parameter	Scenario Comparison	p-value	Description
DO	Sim1 vs. Sim3	0.071	Not significant
BOD	Sim1 vs. Sim3	0.032	Significant ($p < 0,05$)
COD	Sim1 vs. Sim3	0.017	Significant ($p < 0,05$)

Source: own study

decreased due to the decomposition of organic compounds, influenced by Dissolved Oxygen. The high BOD levels in the river indicate abundant organic matter that can be biologically broken down from domestic and industrial wastewater discharges (Wifarulah & Marlina 2021). Measurements of COD across different points showed values that complied with Class II water quality standards. The Oko-oko River's water quality characteristics suggest a relatively good oxygen supply, as indicated by BOD and COD parameters. The river has the capacity for self-purification, allowing organic matter to naturally diminish in the recovery zone (Patel & Jariwala 2023).

The results of the Oko-oko River water quality simulation conducted with the QUAL2Kw model showed that the BOD reduction scenario at the source (up to 70%) significantly improved the water quality of the Oko-Oko River, characterized by a decrease in BOD and COD. An integrated sewage treatment system (anaerobic-aerobic) is recommended to achieve the river water quality target, according to PP No. 22 Year 2021 Class II.

The longitudinal profile of dissolved oxygen (DO) showed an increasing trend in scenarios S_1 to S_3. This suggests that reducing organic load from POME directly enhances the river's re-aeration capacity. The decrease in BOD and COD in scenarios S_2 and S_3 highlights the effectiveness of the anaerobic-aerobic treatment system for POME. The integrated anaerobic-aerobic bioreactor system is designed to treat wastewater with high levels of organic pollutants like POME. Research by Chan et al. (2015) demonstrates that this system can achieve COD and BOD removal efficiencies of 96.3% and 97.9%, respectively. These findings align with the theory of organic degradation kinetics, which states that substrate concentration reduction (BOD/COD) is directly proportional to increased DO through a higher re-aeration coefficient (Pelletier & Chapra 2008).

Statistical test results show that the 70% load reduction scenario (S_3) significantly decreases BOD ($p = 0.032$) and COD ($p = 0.017$), while the increase in DO is not yet statistically significant ($p = 0.071$), despite showing a positive trend. This suggests that improving the water quality of the Oko-Oko River can be achieved through organic load reduction at the source, highlighting the importance of technological interventions for Palm Oil Mill Effluent (POME) treatment.

The anaerobic-aerobic treatment approach is recommended as a suitable option for managing POME (palm oil mill effluent) in Kolaka. During the anaerobic stage, which can involve a covered anaerobic lagoon or anaerobic digester, biochemical oxygen demand (BOD) can be reduced by over 70%, while producing biogas that serves as an alternative energy source, thereby decreasing reliance on fossil fuels. Following this, the aerobic stage—implemented through an aerated lagoon or an activated sludge system-focuses on oxidizing organic residues, reducing chemical oxygen demand (COD), and increasing dissolved oxygen (DO) levels in the effluent before it is discharged into water bodies. However, there are some barriers to implementing the anaerobic-aerobic treatment system in Kolaka. These include an initial investment that is 25-40% higher than that required for conventional open ponds, as well as the need for additional land to accommodate the aerobic units, which require optimal hydraulic retention time.

The findings of this study provide a solid scientific foundation for developing wastewater treatment policies in the palm oil industry within Kolaka Regency, particularly in the Oko-Oko River basin. Spatial simulations indicate that the downstream segments (ST 3 and ST 4) are critical areas that require regular monitoring of water quality. The model results can also be utilized to assess pollutant load capacity and to create pollution control strategies based on the river's natural assimilation capabilities.

However, this study has limitations due to the narrow spatial coverage of water quality data, which includes only four monitoring points. This limitation decreases the accuracy of the simulation in reflecting the actual conditions along the river. Furthermore, the lack of seasonal data may impact the effectiveness of the river's natural dilution processes. Therefore, it is recommended that future research expand the number of monitoring points and incorporate seasonal hydrological data to enhance the validity and accuracy of the model.

CONCLUSIONS

This study demonstrates that the simulation results for the water quality of the Oko-oko River indicate that enhancing the efficiency of the wastewater treatment system can lead to increased levels of dissolved oxygen (DO) and reduced concentrations of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in the river. Among the three scenarios tested, the scenario that involved a 70% reduction in palm oil mill effluent (POME) produced the best outcomes at all monitoring points, meeting the national water quality standards for Class II as established by Indonesian Government Regulation No. 22 of 2021, Annex IV. Model validation showed a strong correlation between the simulation results and the observational data, with Nash-Sutcliffe Efficiency (NSE) values exceeding 0.8 for all parameters. These findings highlight the potential of using numerical models as decision-support tools in scenario-based water quality management.

This study also emphasises the importance of optimising wastewater treatment systems, particularly in the palm oil industry, to reduce systemic pollution impacts. Future research should be conducted with a broader spatial scope, integrating hydrological and land use factors to enhance model accuracy and the relevance of results for sustainable watershed management policies.

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