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Impact of Rainfall and Meteorological Factors on Wastewater Treatment in Palm Oil Mills

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Abstrak

This study investigates the influence of rainfall and meteorological factors on wastewater treatment performance in a palm oil mill, recognizing that CPO processing requires large volumes of water and generates complex liquid waste. The objective is to analyze how rainfall affects wastewater volume, characteristics, and treatment efficiency, and to evaluate the effects of temperature, humidity, and wind speed on the performance of the wastewater treatment plant (WTP). A case study approach was applied at a palm oil mill in Nagan Raya Regency. Primary data were collected by sampling wastewater at critical points in the open pond system and WTP unit, while secondary data were obtained from operational reports and meteorological records from the Cut Nyak Dhien Meteorological Station. Laboratory analysis was conducted to measure parameters such as BOD, COD, TSS, pH, and oil and grease content, aiming to assess the fluctuation in waste quality influenced by weather variables. The study also reviewed the management of hazardous emissions methane, CO_2, ammonia, and hydrogen sulfide to evaluate their environmental impact. Results indicated that increased rainfall led to higher wastewater volumes and altered pollutant concentrations, reducing treatment efficiency. Other meteorological factors, particularly temperature and wind speed, also influenced the biological decomposition process in open ponds. These findings highlight the need for adaptive treatment strategies to enhance resilience, improve system performance, and support sustainable operations in the palm oil industry.

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1. Introduction

The processing of palm oil wastewater into crude palm oil (CPO) is carried out through a wet processing process, where almost all stages use water, either in the form of clean water or steam. Each ton of fresh fruit bunches (FFB) requires approximately 1 m^3 of water to be processed, with a planned production capacity of 20 hours per day. This process produces large amounts of wastewater that must be managed properly so as not to pollute the environment (Erdiwansyah et al., 2025; Nizar et al., 2025; Pranoto et al., 2025; Saravanan et al., 2021). Palm oil mill effluent (POME) contains various organic and inorganic compounds that have the potential to pollute surface and groundwater. Therefore, an effective wastewater treatment system is needed to reduce pollutant levels before being discharged into the environment. One commonly used method is the ponding system, which involves sedimentation, anaerobic, facultative, and aerobic processes to decompose organic compounds in waste (Erdiwansyah, Gani, Desvita, et al., 2024; Lahiri et al., 2018; Mufti et al., 2025; Selvakumar et al., 2025). However, the effectiveness of this system can be affected by external factors such as rainfall and other meteorological conditions.

Heavy rainfall can have a significant impact on the efficiency of wastewater treatment. Increased water volume due to rainfall can cause untreated wastewater to mix with rainwater, reducing the efficiency of the treatment system (Gani, Adisalamun, et al., 2023; Muhibbuddin et al., 2025; Rosdi et al., 2025; Singh & Tiwari, 2019). In addition, heavy rainfall can also cause overflow from the waste pond, increasing the risk of environmental pollution. Temperature, humidity, and wind speed also affect biological processes in the treatment pond, especially in the aerobic and facultative stages that depend on the oxygen content in the water. Given the importance of climate factors in palm oil mill wastewater treatment, this study aims to analyze the impact of rainfall and other meteorological factors on the effectiveness of the wastewater treatment system (Akhbari et al., 2020; Fitriyana et al., 2025; Gani, Erdiwansyah, Desvita, Saisa, et al., 2024; Khalisha et al., 2025). By understanding the relationship between weather conditions and the performance of the treatment system, it is expected that more effective mitigation strategies can be found to optimize waste management and reduce the environmental impacts caused.

Palm Oil Mill Effluent (POME) treatment has a significant impact on the environment, especially if not managed properly (Erdiwansyah, Gani, Mamat, et al., 2024; Febrina & Anwar, 2025; Mohammad et al., 2021; Sumbodo et al., 2025). One of the main impacts is pollution of water sources, both surface water and groundwater. POME contains high concentrations of organic matter, such as oil and fat, as well as organic compounds that can cause eutrophication if discharged directly into water bodies. Eutrophication can reduce dissolved oxygen levels in water, thus impacting aquatic life and river or lake ecosystems that receive waste runoff. In addition to water pollution, palm oil waste processing also contributes to greenhouse gas emissions (Gani, Mahidin, et al., 2024; Rosli et al., 2025; Silalertruksa et al., 2017; Xiaoxia et al., 2025). The decomposition process of organic matter in anaerobic ponds produces methane gas (CH_4) which has a much greater global warming potential than carbon dioxide (CO_2). If not managed properly, methane emissions from POME can increase the impact of climate change (Erdiwansyah et al., 2023; Iqbal et al., 2025; Jalaludin et al., 2025; Putro, 2022). Several factories have adopted biogas utilization technology from POME to generate electricity as a mitigation measure against greenhouse gas emissions.

Another impact is the possibility of soil contamination due to leaks or seepage from the waste treatment pond. Wastewater that is not managed properly can seep into the soil and contaminate groundwater sources used by the surrounding community (Gani et al., 2025; Gani, Erdiwansyah, Desvita, Meilina, et al., 2024; Lamma, 2021; Muhtadin et al., 2025). In addition, the high content of organic compounds in waste can cause changes in the physical and chemical properties of the soil, which has the potential to reduce soil fertility and disrupt plant growth around the palm oil mill area. Although palm oil wastewater treatment has various negative impacts, if managed with the right system, this waste can also be used as a source of energy and organic fertilizer (Gani, Erdiwansyah, Desvita, Munawar, et al., 2024; Gani, Erdiwansyah, et al., 2023; Rashid et al., 2025; Supriatna et al., 2022). Further treatment, such as biogas production from POME or the use of residual sludge as fertilizer, can be a solution to reduce environmental impacts while increasing the efficiency of the palm oil industry. Therefore, the application of more environmentally friendly processing technology is very necessary to ensure the sustainability of the palm oil industry and minimize its negative impacts on the ecosystem.

This study aims to analyze the effect of rainfall on wastewater treatment by identifying and analyzing how rainfall affects the volume, characteristics, and efficiency of wastewater treatment in palm oil mills. Increased rainfall can cause increased waste discharge, changes in organic matter concentration, and potential environmental pollution if the treatment system is unable to adapt to these changes. Examining the impact of meteorological factors on the performance of Wastewater Treatment Plants (WWTP) by examining other meteorological factors, such as air temperature, humidity, and wind speed, can affect the liquid waste treatment process.

2. Methodology

This study uses a quantitative approach with a case study method in a palm oil mill that has an open pond-based wastewater treatment system (WWTP) and a Water Treatment Plant (WTP) unit. The main objective of the study is to analyze the effect of rainfall on the volume, characteristics, and efficiency of wastewater treatment, as well as to examine the impact of other meteorological factors such as air temperature, humidity, and wind speed on the performance of the treatment plant.

Methods Used
Primary data were obtained through direct measurements in the field, including wastewater sampling at several critical points (such as the outlet of the wastewater treatment plant) for analysis of quality parameters (BOD, COD, TSS, pH, oil and fat, etc.). Measurement of rainfall and other meteorological factors was carried out using weather measuring instruments at the study site, as well as historical data from the BMKG Cut Nyak Dhien Station. Secondary data were also collected from internal factory reports and relevant technical documents, to support the analysis of the relationship between meteorological variables and the performance of the wastewater treatment system.

Data retrieval
Data collection is carried out systematically by:

- Field Measurement: Conducting wastewater sampling at various production periods, especially during rainy and non-rainy periods to obtain data variations.
- Meteorological Data: Collecting rainfall, temperature, humidity, and wind speed data from BMKG Stations and local measuring instruments installed in the factory area.
- Historical Data and Plant Reports: Access plant operational archives and reports regarding wastewater discharge and waste treatment parameters over the past several years.

Data processing
The collected data will be processed using descriptive statistical analysis to describe the conditions of rainfall fluctuations, wastewater volume, and water quality parameters. Furthermore, inferential analysis, such as regression analysis, is used to identify and measure the effects of rainfall and other meteorological variables on the volume and characteristics of waste, as well as the efficiency of the treatment system. Data processing is carried out with the help of statistical software (Excel) to obtain accurate and accountable results. The results of this analysis are expected to provide a comprehensive picture of how weather fluctuations impact the performance of the wastewater treatment plant and provide strategic recommendations for improving the wastewater treatment system in the palm oil industry.

3. Result & Discussion

Climatological conditions in the research area were analyzed based on data from the Station Meteorology, Climatology and Geophysics Agency (MCGA) Cut Nyak Dhien Airport located in Nagan Raya Regency. This station is located at coordinates 04º 02' 56” N and 96º 14' 51” E. The climate parameters considered include rainfall, average monthly number of rainy days, air temperature, duration of sunshine, air pressure, relative humidity, and wind speed. In general, this area, like other regencies in the western and southern parts of Aceh, has a higher humidity level than the northern and eastern regions of Aceh. This is due to the influence of the topography of the Bukit Barisan Mountains which increases the intensity of rainfall. Based on monthly rainfall data from the BMKG Cut Nyak Dhien Meteorological Station during the period 2012-2021, there was only one dry month with rainfall of less than 60 mm, namely in June 2018. The ratio between the average number of dry months and the average number of wet months over the past ten years was obtained at Q = 0.9%. Referring to the Schmidt-Ferguson climate classification, this area is included in the type A climate category, which indicates very wet conditions. Meanwhile, according to the Oldeman classification, the study area is categorized as a type A1 climate, which is characterized by a wet month period of more than nine consecutive months and a dry month period of less than two months.

The average annual rainfall recorded in this area over the past decade is relatively high, at around 3,743 mm, with an average monthly rainfall of 312 mm. In addition, the average annual number of rainy days reaches 138 days, with a monthly average of around 12 days. The high intensity of rainfall has a direct impact on environmental conditions, especially in terms of water resource management and wastewater treatment. In the context of wastewater treatment in palm oil mills, high rainfall can increase the volume of wastewater that must be treated. In addition, fluctuations in rainfall intensity also have the potential to affect the concentration of pollutants in wastewater, which can reduce the efficiency of the treatment process. Therefore, a deeper understanding of rainfall patterns and other climatological factors is essential to optimize waste management systems in the palm oil industry. Mitigation efforts, such as increasing the capacity of treatment ponds and implementing adaptive technologies, are important strategies in dealing with climate challenges in areas with high rainfall such as this study area.

Monthly rainfall data taken from the MCGA Cut Nyak Dhien Station shows that the study area has a high and relatively stable rainfall pattern throughout the year, with an average monthly rainfall reaching around 312 mm and a total annual rainfall reaching 3,743 mm during the period 2012-2021; quite significant monthly variations are seen, where for example January records low to high rainfall (between 132 to 626 mm), while other months such as August and November also show high rainfall values, indicating the dominance of the rainy season, while there is only one dry month (less than 60 mm) which occurred in June 2018, thus confirming that this area is classified as very wet according to the Schmidt-Ferguson and Oldeman climate classification , which conditions require careful adjustment and management in the wastewater treatment system, especially in industrial sectors such as palm oil mills. Based on data obtained from the MCGA Meteorological Station at Cut Nyak Dhien Airport, Nagan Raya Regency, climatological conditions in the study area are determined by several main parameters, including monthly rainfall, rainy days, temperature, sunshine, air pressure, relative humidity, and wind speed. This meteorological station is located at coordinates 04º 02' 56” N and 96º 14' 51” E and provides a complete picture of the weather patterns that dominate the area. This area, like other areas in the west and south of Aceh, tends to be wetter than the north and east because it is significantly influenced by the Bukit Barisan Mountains.

Rainfall data recorded during the period 2012-2021 shows that the total annual rainfall reached 3,743 mm, with a monthly average of around 312 mm. During the ten years, there was only one month recorded as a dry month June 2018, where the rainfall was less than 60 mm. This results in a ratio between dry months and wet months of Q = 0.9%. Based on the Schmidt-Ferguson climate classification, this area is categorized as a type A climate (very wet), while according to the Oldeman classification, this area is classified as a type of A1 climate, which is characterized by a sequence of wet months for more than nine months and dry months for less than two consecutive months. In addition, the data also revealed that the average number of annual rainy days reached 138 days, with an average of around 12 rainy days per month, as shown **Table 1**. This consistent rainfall pattern not only plays an important role in maintaining the balance of the local ecosystem but also poses its own challenges in water resource management, especially in the industrial and agricultural sectors. This condition requires adaptive and careful water management planning to anticipate potential flooding, optimize water utilization, and ensure operational sustainability and environmental preservation.

Table 1. Monthly Rainfall (mm) MCGA Cut Nyak Dhien Station

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Jan	132	151	220	255	495	626	100	209	574	61	282
Feb	356	373	195	169	261	195	141	120	236	113	216
Mar	88	230	325	167	271	215	387	154	333	488	266
Apr	322	335	234	498	354	265	429	372	494	178	348
May	208	289	324	269	653	268	99	73	380	220	278
June	145	499	293	394	303	63	48	230	148	232	235
Jul	298	176	337	215	105	109	335	178	536	523	281
Aug	199	230	517	215	566	288	353	263	244	277	315
Sep	185	395	346	355	170	210	351	206	186	117	252
Oct	348	169	348	450	477	546	731	727	452	260	451
Nov	537	361	704	422	523	364	532	376	437	498	475
Dec	427	251	327	381	262	574	331	339	155	376	342
Amount	**3245**	**3459**	**4170**	**3790**	**4440**	**3723**	**3837**	**3246**	**4174**	**3343**	**3743**

Monthly rainy days data obtained from the MCGA Cut Nyak Dhien Station shows that the study area experiences rain during most months of the year, with an average of around 12 rainy days per month and a total annual average of 138 rainy days, as shown **Table 2**. This pattern reflects the consistent dominance of the rainy season, which has implications for high humidity and rainfall intensity that have a direct impact on water resource management and wastewater treatment, especially in industrial sectors such as palm oil mills. This condition requires adaptation in the treatment system to handle high fluctuations in the number of rainy days, to ensure water quality and operational efficiency are maintained.

Table 2. Monthly Rainy Days Number of MCGA Cut Nyak Dhien Station

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Jan	15	3	9	11	15	4	9	16	11	8	10
Feb	17	4	10	7	8	17	14	9	11	10	11
Mar	12	11	19	18	16	10	15	17	16	21	16
Apr	15	6	14	11	12	6	13	3	6	9	10
May	11	12	5	4	10	7	6	12	10	15	9
June	7	1	4	3	12	4	5	12	11	12	7
Jul	10	4	1	10	5	10	12	12	16	16	10
Aug	10	10	2	7	11	14	11	8	6	12	9
Sep	18	13	12	12	17	10	8	13	13	11	13
Oct	10	11	20	21	19	8	15	14	20	19	16
Nov	11	9	14	17	15	14	6	11	15	27	14
Dec	15	11	14	17	18	10	17	15	10	20	15
Amount	151	95	124	138	158	114	131	142	145	180	138

Monthly average climatological data from the MCGA Cut Nyak Dhien Station illustrates the climate conditions in the study area which tend to be warm and humid throughout the year, with minimum temperatures ranging from 18–22°C, average temperatures around 26–28°C, and maximum temperatures reaching 32–33°C, as shown **Table 3**. The intensity of sunlight varies between 40% and 70%, which is influenced by clouds and high rainfall, while relative humidity remains high, generally in the range of 85% to 91%. The average wind speed is recorded at around 3–5 m/s, indicating stable air circulation. This condition reflects a climate that supports consistent rainfall and plays an important role in water resource management and industrial operations, including wastewater treatment in palm oil mills in the area. In the impact forecast, in addition to rainfall data on wastewater treatment, air temperature and humidity data also affect the treatment process, such as the occurrence of evaporation. Air temperature and humidity data in Kab. Nagan Raya can be seen in the data below.

Table 3. Monthly Average Climatology of MCGA Cut Nyak Dhien Station

Month	Minimum temperature (°C)	Average temperature (°C)	Maximum temperature (°C)	Sunlight (%)	Relative humidity (%)	Wind speed (m/s)
Jan	22.0	28.0	31.0	40.0	87.3	3.5
Feb	22.2	27.5	33.7	79.7	87.4	3.6
Mar	22.0	26.7	32.8	53.5	85.4	5.2
Apr	22.2	26.9	32.8	63.4	82.9	4.7
May	22.6	27.3	33.2	45.0	88.4	4.3
June	21.0	26.4	33.2	39.5	81.9	3.6
Jul	18.8	26.6	33.4	52.3	79.2	3.7
Aug	21.0	26.4	33.0	50.9	85.9	3.8
Sep	20.0	26.5	34.0	54.0	89.0	4.3
Oct	21.0	26.5	33.2	58.3	90.4	3.7
Nov	21.8	26.3	32.4	38.4	91.3	3.7
Dec	21.8	26.6	32.4	70.8	90.0	3.6
Average	21.4	26.8	32.9	53.8	86.6	4.0

The characteristics of wastewater from the main and supporting activities of palm oil mills show significant differences, where in the main activities, the waste produced comes from the processing of fresh fruit bunches (FFB) which is water intensive and produces waste with high concentrations of decomposed and non-decomposed organic compounds, sediment, suspended solids, and oil and fat, with parameters such as BOD, COD, TSS, and pH values that vary, as shown **Table 4.** While in supporting activities, especially those from domestic activities and employee housing, wastewater generally contains grey water and black water with relatively lower concentrations of solids, organics, and nutrients, so that both types of waste require management and processing according to quality standards to prevent environmental pollution and maintain the sustainability of factory operations.

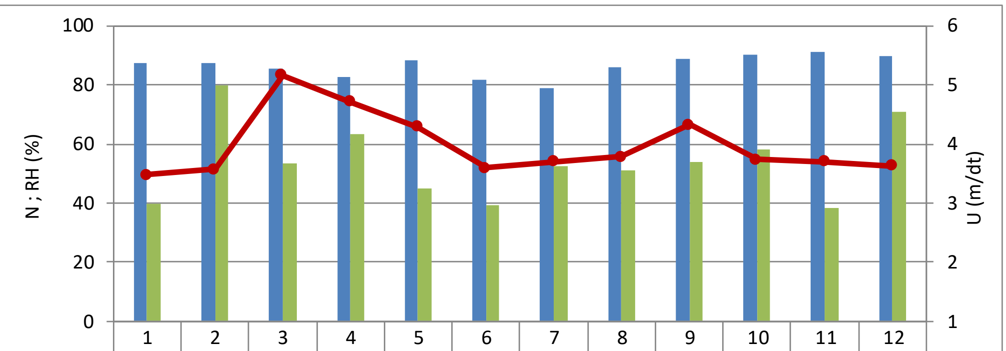
Table 4. Characteristics of Wastewater from Main and Supporting Activities of Palm Oil Mills

No	Pollution Group	Explanation	Parameter
1.	Biodegradable *Organics*	- Consists of various organic compounds that can be broken down by microbes: carbohydrates, proteins, sucrose, glucose and fat. - It causes specific impacts, namely the decomposition of water bodies, resulting in septic conditions that are black and smelly.	BOD
2.	*Non-*Biodegradable Organics	- Consisting of various organic compounds that are difficult to decompose by microbes: pesticides, herbicides, detergents, oils and grease. - To group the types of organic compounds that are not included in decomposable organic compounds. - Although they do not cause water spoilage, some of these types are toxic to living things/microbes.	COD
3.	Nutrients	- Consists of various chemical elements needed by plants, such as phosphate and nitrogen. - Causing specific impacts such as eurofication or algae *blooms* in water bodies.	Ammonia

No	Pollution Group	Explanation	Parameter
4.	Sediment	- Consisting of various types of solids which due to their weight will settle by themselves, such as sand, soil and mud. - It is a type of solid that is not included as a suspended solid or dissolved solid.	Sludge
5.	Suspended *Solids*	- Consists of solids that are not large enough and heavy enough to settle on their own. - Causes cloudiness.	TSS
6.	Floatable *Material*	- Consisting of various types of liquids or solids whose specific gravity is lower than water so that they float on the surface of the water. - Causes aesthetic disturbances, blocks the flow of light, and blocks the rate of deoxygenation.	Oils and Fats
7.	Acid Base	- Have the same reaction principle. - Affects the pH value of wastewater.	Acidic compounds and basic compounds
8.	Pathogen	- Causes specific impacts, namely disease in humans, especially.	Total Coliform

The effect of rainfall on wastewater treatment

In this wastewater treatment process, the open pond system plays an important role, especially in the anaerobic pond which is the place for the decomposition of organic compounds. In the pond, organic pollutants in wastewater are decomposed by microbes into methane gas (CH_4) and carbon dioxide (CO_2) which are then released into the atmosphere. However, not all compounds undergo complete degradation; ammonia gas and hydrogen sulfide gas (H_2S) tend not to be lost through this process, so their presence remains a concern because they can pollute the air and contribute to the greenhouse effect. Therefore, for the processed results to meet the established quality standards, the wastewater treatment process is carried out anaerobically, where pollutants are decomposed in such a way as to produce cleaner water, with the transformation of compounds such as ammonia which is oxidized into nitrite and then into nitrate, and H_2S which is converted into sulfat. However, a small portion of pollutants is still released into the atmosphere as emissions, which have a negative impact on the environment. To overcome this problem, wind direction analysis becomes crucial, because data on wind patterns can help identify the potential spread of harmful gas emissions, so that more effective mitigation measures can be designed to reduce the greenhouse effect and maintain the quality of the surrounding environment.



	1	2	3	4	5	6	7	8	9	10	11	12
RH (%)	87	87	85	83	88	82	79	86	89	90	91	90
N (%)	40	80	54	63	45	40	52	51	54	58	38	71
U (m/dt)	3.5	3.6	5.2	4.7	4.3	3.6	3.7	3.8	4.3	3.7	3.7	3.6

Fig. 1. Monthly Average Meteorological Data of MCGA Cut Nyak Dhien Station

Based on the 2021 daily average wind speed data from the MCGA Meteorology Station at Cut Nyak Dhien Airport, Kuala District, Nagan Raya Regency, the wind rose analysis shows that the most dominant wind blows from the Southwest (SW) with a proportion of 24.93% and from the West (W) 24.11%. Furthermore, winds from the South (S) reached 13.97% and from the Northwest (NW) 12.33%, while winds from the Northeast (NE) reached 8.77%, from the North (N) 4.66%, and from the Southeast (SE) also 4.66%. The least frequent wind direction is from the West (W) with only 3.01%. It is known that winds from the West, Southwest, and South generally come from the Indonesian Ocean, while winds blowing from other directions come from land. In terms of speed magnitude, the data shows that the most common wind speed recorded at the station is in the range of 3–5 m/s, which accounts for 63.84% of the total measurements. Winds with speeds between 5–7 m/s account for 22.74%, while winds with speeds of less than 3 m/s account for 6.30%. The rest, namely winds with speeds of more than 7 m/s, only account for 3.56% of the total events, indicating that most wind activity in the area tends to be at low to moderate speeds. In addition, the data also revealed that the highest wind speed ever recorded at the location was more than 11 m/s, but the occurrence of such extreme speeds is very rare, only 0.28% and occurs exclusively from the West (W) direction. This information is important for the analysis of the impact of emissions and the spread of pollutants around the area, because the varying wind patterns and intensities can affect the distribution of gases and pollutant particles produced during the wastewater treatment process, thus providing a basis for mitigation efforts and planning a wastewater treatment system that is more responsive to meteorological conditions.

The water requirement for PKS is relatively large and continuous has been producing clean water with a reservoir capacity of 65 m3 / hour and WTP 40 m^3/hour obtained from the Alue Gajah river. From the main process of PKS processing, various types of wastewaters will be produced. The need for clean water for operational activities of the palm oil processing plant is 600 m3 / day and the amount of wastewater produced is 70% or 420 m^3/day. While the water requirement for domestic is 7.6 m^3/day and According to the Directorate General of Human Settlements in 1996, the percentage of domestic water that will become waste is 80% or 6 m3 / day. Furthermore, according to Hansen & Kjellerup, 1994 in Prasetyo, 2018, the volume of domestic liquid waste consists of 75% *grey water* (non-toilet) and *black water* (toilet waste) is around 25% so that the amount of *grey water* and *black water* is 4.5 m3 / day and 1.5 m^3/day. The water requirement is taken from the Alue Gajah River Water, then collected in a reservoir and then processed at *the Water Treatment Plant* (WTP) located at the factory location. Water from the river is pumped and then collected in a water reservoir *(Water Reservoir).* PT Ensem Lestari Jaya provides a reservoir with a capacity of 63 m^3. Furthermore, the water is processed with *a water treatment plant* (WTP) with a filtration clarification process to obtain the established standards.

Water from the river is pumped into a reservoir with a capacity of 65 m3 / hour, from the reservoir it is pumped to the WTP with a capacity of 40 m3 / hour with operating hours of 20 hours a day. In the WTP unit, water from the reservoir will be pumped into the clarifier *tank.* In this clarifier tank, the water is stirred quickly while being mixed with alum and soda ash chemicals. Alum functions to form flocs, while soda ash is useful for neutralizing water hardness. While continuous stirring will form dark flocs as sediment at the bottom. Disinfectant materials are not used. Clear water that overflows *will* flow into the reservoir, here the sedimentation process occurs by gravity. In this sedimentation tank, more perfect sedimentation of dirt particles occurs. Then the water is pumped into the *sand filter tank.* Furthermore, the water is pumped into *the basin tank,* which is a place to store water that is ready to be distributed. Next, the water will be pumped to the water tower *(tower tank)* with a capacity of 35 m3 / hour to be distributed to the factory. Water is used for the purposes of making *steam* and boiler feed water. In addition to being used as an auxiliary material for production, water is also used for various supporting activities of the PKS.

Table 5. Characteristics of Palm Oil Processing Plant Wastewater

No	Parameter	Unit	Water Quality Value (average value)	Water Quality Value (range)
1	pH	mg/l	4.2	3.4 – 5.2

No	Parameter	Unit	Water Quality Value (average value)	Water Quality Value (range)
2	TSS	mg/l	40,000	11,500 – 78,000
3	BOD_5	mg/l	25,000	10,250 – 43,750
4	COD	mg/l	50,000	15,000 – 100,000
5	$NH3_{-}N$	mg/l	35	4 -80
6	Total Nitrogen	mg/l	750	180 – 1,400
7	Oil	mg/l	6,000	150 – 18,000

Source: The oil palm industry forms pollution to zero waste, the planter 72,840 pp 145,1996

The quality standards for wastewater produced by PT Ensem Lestari Jaya processing plant before being discharged into surface water bodies are determined based on Government Regulation Number 22 of 2021, which refers to the provisions of the Minister of Environment Regulation No. 05 of 2014 concerning Palm Oil Industry Wastewater Quality Standards. This standard covers various physical, chemical, and biological parameters, such as BOD, COD, TSS, pH, oil and fat, and nutrient content, all of which must be below the specified threshold to ensure that the waste produced does not pollute water bodies. In practice, PT Ensem Lestari Jaya implements a strict wastewater treatment system, including regular monitoring and testing at every stage of the processing process, so that each batch of waste to be discharged into the environment meets the applicable quality standards. This not only supports the sustainability of factory operations but also protects the quality of the surrounding waters and ecosystems, by reducing the potential for pollution that can have a negative impact on biodiversity and public health. The use of advanced treatment technology and systematic monitoring procedures are part of ongoing efforts to ensure that the waste produced is always below the specified threshold. Thus, the implementation of this standard also serves as a guideline for other palm oil industries in implementing best practices to achieve zero waste targets and improve overall environmental protection.

Table 6. Standards for Wastewater Quality Permitted to be Discharged into the Environment

No	Parameter	Highest Level (mg/L)	Highest Pollution Load (kg/ton)
1	BOD	100	0.25
2	COD	350	0.88
3	TSS	250	0.63
4	Oils and Fats	25	0.063
5	Total Nitrogen (As N)	50	0.125
6	pH	6.0 – 9.0	
7	Highest Waste Discharge	2.5 m^3/ton of palm oil products (CPO)	

The impact of meteorological factors on the performance of Wastewater Treatment Plants (WWTP)

The quality standard used for testing the quality of surface water bodies is the National Water Quality Standard in accordance with PP 22 of 2021 Appendix VI Class II. Water samples were taken from two locations, namely upstream and downstream of the Alue Gajah River in the area, to ensure that the overall water conditions meet the established standards.

The results of the sample analysis showed that the physical and chemical properties of the water at both intake points were still below the permitted quality standard threshold. The parameters tested, such as turbidity, pH, dissolved oxygen, and concentrations of other pollutants, showed values consistent with the provisions of Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management, Appendix VI (Class II). This indicates that the water quality in the Alue Gajah River is generally still in good condition.

These conditions support the sustainability of palm oil processing activities, because the available water has adequate quality to support industrial processes without causing environmental pollution risks. The success of water quality management and monitoring also reflects the effectiveness of the environmental management system in the industrial area, which of course needs to be maintained through routine supervision to remain in accordance with established national standards.

Wastewater from Palm Oil Processing Process

Wastewater management at PKS PT Ensem Lestari Jaya includes the process of decomposing compound organic materials into simple organic materials through microbiological activity under anaerobic and aerobic conditions. This process aims to decompose organic pollutants contained in waste so that before being discharged into the environment, the pollutant content can be reduced to a safe level according to applicable standards. The Wastewater Treatment Plant (WWTP) implemented at PT Ensem Lestari Jaya consists of 17 ponds with various functions, ranging from Cooling Pond, Mixing Pond, to Anaerobic Pond and Aerobic Pond. In addition, there is also a Sedimentation Pond and Final Pond which play an important role in the process of separating and reducing the concentration of pollutants before the wastewater is discharged.

Wastewater produced from the washing process of the equipment, condensate sterilizer, sludge separator, and purifier are directly collected in the Fat-pit pool. In this pool, wastewater undergoes a separation process based on differences in specific gravity, which allows the oil content to be separated from the water. The relatively small amount of oil-containing wastewater is then returned to the cleaning section for further processing. The parameters that must be monitored in the processing of palm oil mill wastewater refer to the quality standards stipulated in the Regulation of the Minister of Environment of the Republic of Indonesia Number 5 of 2014. This monitoring includes various physical, chemical, and biological parameters to ensure that each batch of wastewater coming out of the WTP has met the maximum permissible pollutant limits. After going through a series of processing processes in the WTP, the outlet wastewater that has met the quality standards is channelled to the downstream of the Alue Gajah River. At this location, the wastewater flows into the Alue Gajah River with the guarantee that all quality parameters are below the permitted threshold, so that this condition supports factory operational activities while protecting the environment from potential pollution. The results of routine monitoring show that the applied processing system is running effectively and consistently meets the established environmental standards.

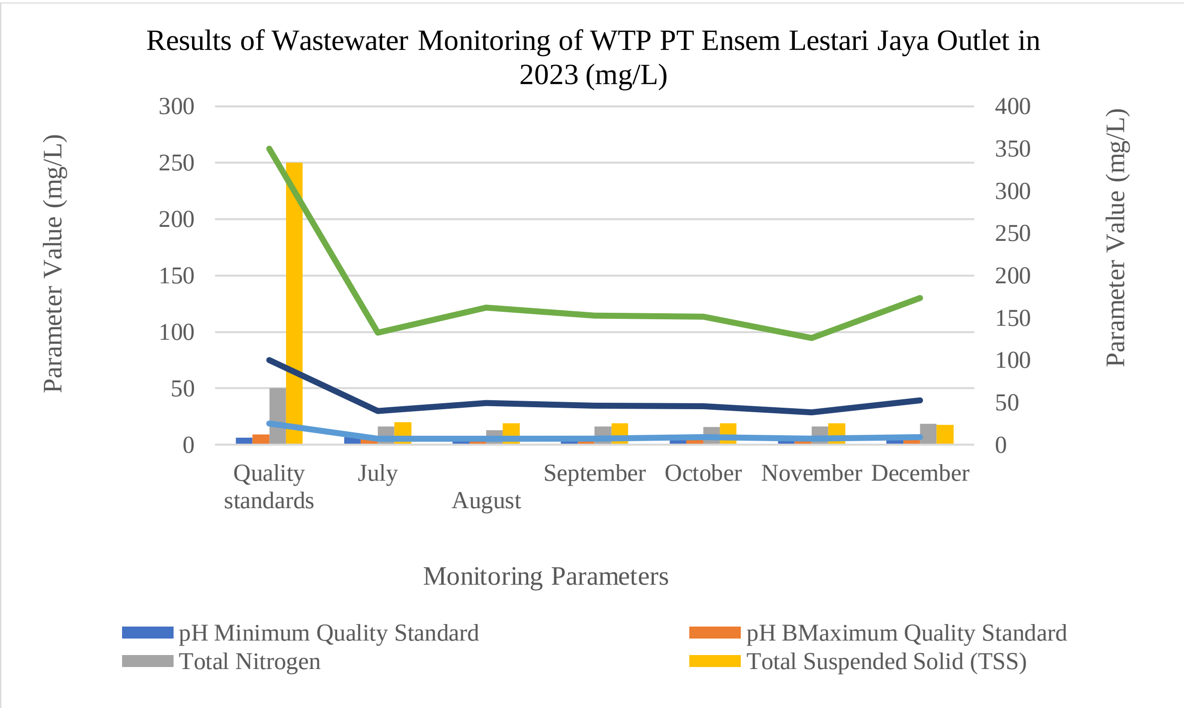


Fig. 3. Results of Wastewater Monitoring of WTP PT Ensem Lestari Jaya Outlet in 2024

The results of PT Ensem Lestari Jaya internal wastewater monitoring in 2024 showed that the pH parameters were consistently in the range of 6–9, with recorded values ranging from 6.74 to 7.03 during the period from January to August. This stable pH value indicates that the acidity of the wastewater is well maintained, thus supporting the biological treatment process taking place in the wastewater treatment plant (WTP). Furthermore, the Total Nitrogen, TSS, and Oil and Fat parameters show very effective treatment performance. Total Nitrogen is in the range of 14.3 to 18.4 mg/L, which is far below the maximum limit of 50 mg/L, so the potential for nutrient pollution can be minimized. Likewise, TSS which ranges from 16.1 to 19.9 mg/L and the Oil and Fat content which is around 7.1–7.3 mg/L also show very low values when compared to their respective thresholds (250 mg/L for TSS and 25 mg/L for Oil and Fat). This indicates that the treatment system has worked optimally in separating particles and fat from wastewater. COD and BOD measurement parameters also showed satisfactory results, with COD values ranging from 124.8 to 137.9 mg/L and BOD values between 38.1 to 41.8 mg/L, both far below their respective quality standards (350 mg/L for COD and 100 mg/L for BOD). These results confirm that the organic material oxidation process is running efficiently, so that the quality of the wastewater produced is safe to be discharged into surface water bodies. Overall, the 2024 monitoring data confirms that wastewater treatment at PT Ensem Lestari Jaya has met applicable environmental standards and supports the sustainability of factory operations with minimal environmental impact.

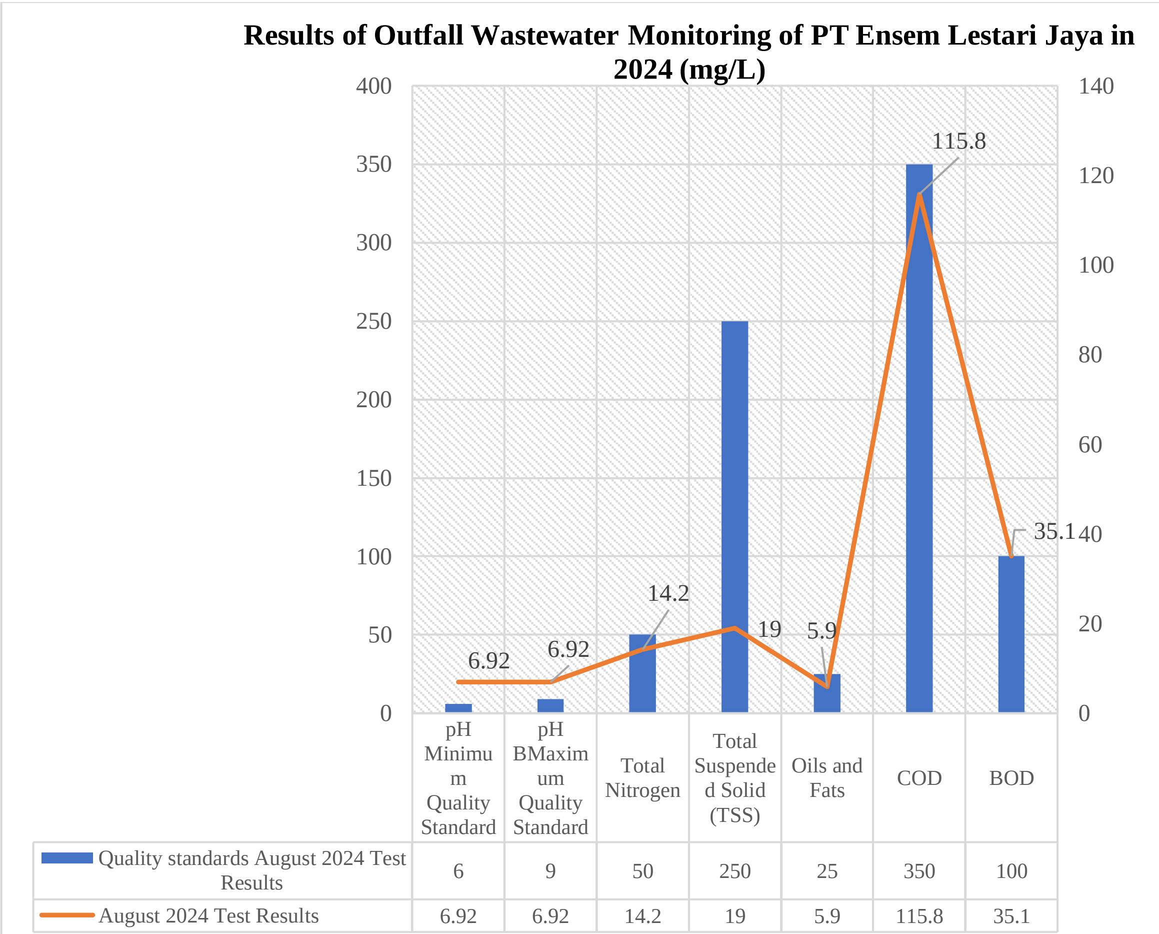


Fig. 4. Results of Outfall Wastewater Monitoring of PT Ensem Lestari Jaya in 2024

Quality Standards: Regulation of the Minister of Environment No. 5 of 2014 concerning Wastewater Quality Standards. The results of monitoring PT Ensem Lestari Jaya outfall wastewater in August 2024

showed that the measured water quality parameters were far below the set standard quality limits, thus reflecting the performance of an effective wastewater treatment system. The pH parameter was recorded at 6.92, which is within the standard range of 6–9, indicating that the acidity of the water is stable and in accordance with the operational requirements needed to support biological processes in the treatment plant. Furthermore, the Total Nitrogen parameter shows a value of 14.2 mg/L, TSS is 19 mg/L, and oil and fat content reach 5.9 mg/L. These three values are much lower than their respective thresholds (50 mg/L for Total Nitrogen, 250 mg/L for TSS, and 25 mg/L for oil and fat). This indicates that the treatment system has succeeded in reducing the pollutant load contained in wastewater, thereby minimizing the potential impact of pollution on surface water bodies.
Furthermore, the measurement results of COD and BOD parameters reached 115.8 mg/L and 35.1 mg/L respectively, both of which are far below the maximum permitted limits (350 mg/L for COD and 100 mg/L for BOD). These data indicate that the oxidation process of organic matter in the treatment system is running efficiently, so that the quality of the outfall wastewater produced meets applicable environmental standards. Overall, these monitoring results confirm that wastewater treatment at PT Ensem Lestari Jaya has achieved optimal performance, supported the implementation of factory operational activities while maintained environmental quality. Wastewater quality measurement is carried out with reference to PermenLH No. 5 of 2014, especially Appendix III which regulates Palm Oil Processing Liquid Waste. In carrying out the test, wastewater samples are taken systematically at the Wastewater Treatment Plant outlet and analyzed using standard laboratory methods to determine important parameters such as BOD, COD, TSS, oil and fat, nitrogen, and pH. Each parameter is measured and compared with the standard quality limits set by government regulations, thus ensuring that each value obtained can be used as the main indicator to assess the effectiveness of the wastewater treatment process. This measurement method not only involves representative sampling techniques, but also the use of accredited analytical instruments and procedures so that the test results can be scientifically accounted for and meet national environmental standards.
The analysis results show that all tested parameters BOD, COD, TSS, oil and fat, nitrogen, and pH at the outlet of the wastewater treatment plant have met and are even far below the threshold limits permitted by government regulations. This indicates that the treatment system implemented by PT Ensem Lestari Jaya has been running optimally, significantly reducing the concentration of pollutants before the wastewater is discharged into the environment. The success of meeting these quality standards not only reflects the effectiveness of the treatment technology used but also confirms the factory's commitment to implementing sustainable environmental management practices. By achieving the established standards, negative impacts on surface water bodies and surrounding ecosystems can be minimized, thus supporting the goal of protecting and managing the environment in accordance with applicable regulations.

4. Conclusion

Increased rainfall has a significant impact on the volume and characteristics of treated wastewater. High rainfall tends to increase the volume of wastewater that must be processed, while also diluting the concentration of several pollutant parameters. However, this condition also causes fluctuations in the concentration of pollutants such as organic matter, which affects the efficiency of the treatment process in the WTP. Thus, rainfall variability requires operational adjustments and intensive monitoring to ensure that the treatment system remains optimal in meeting the established quality standards. Meteorological factors such as air temperature, humidity, and wind speed play an important role in influencing the performance of wastewater treatment plants. Optimal temperature and humidity conditions support the microbiological activity required for the waste decomposition process, while wind speed can affect the evaporation rate and the distribution of gas emissions from the treatment system. An in-depth analysis of these factors shows that changes in weather conditions can result in variations in wastewater treatment efficiency, so that the application of adaptive strategies that are responsive to environmental dynamics is crucial to maintaining the stability of WTP performance and reducing negative impacts on the environment.

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