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Life cycle assessment of produced water treatment: Carbon footprint and environmental hotspot analysis

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ABSTRACT

Produced water can cause environmental pollution because it contains hydrocarbon compounds as well as organic and inorganic substances. The high volume of produced water requires an appropriate treatment system to reduce its concentration. However, the treatment process can cause other environmental impacts from the equipment and machinery used, which have not been widely evaluated. The study aims to analyze the environmental impacts of the MGS WTP using a life cycle assessment (LCA) with gate-to-gate system boundaries. Operational data on energy consumption, chemicals, materials, and emissions were used for life cycle inventory and modeled in SimaPro using the CML-IA Baseline method. The analysis results show that climate change has the largest impact of 81.34 million kg CO_2-eq, followed by marine aquatic ecotoxicity of 141.32 million kg 1.4-DB-eq and abiotic depletion (fossil fuels) at 13.51 million MJ. The contribution analysis identified air stripping and biological processes as environmental hotspots, which contribute more than 75% of carbon emissions due to high electrical energy consumption. The study results show that energy efficiency can be achieved in high-energy consumption units by using low-carbon electricity sources and improving sustainable wastewater management in the oil and gas sector.

Keywords: life cycle assessment; produced water; environmental impact; hotspot analysis; carbon footprint.

INTRODUCTION

Produced water is waste generated in the oil and gas industry, accounting for 70–80% of the total waste (Eldos et al., 2022; Son et al., 2025). Produced water contains dissolved hydrocarbons, oil, heavy metals, inorganic salts, and chemical residues, which can potentially pose environmental pollution risk if not managed properly (Elkahlout, AlMomani and Furlan, 2024). Furthermore, wastewater quality standards are regulated by the Minister of Environment Regulation No. 19 of 2010, and produced water management is expected to support global commitments to reduce greenhouse gas emissions under the Paris Agreement and the 2060 Net Zero Emission target (Al-Kaabi et al., 2021). Several studies on the environmental impacts of wastewater treatment indicate that electrical energy consumption for operating pumps and aeration systems is a major contributor to the carbon footprint of both domestic clean water and wastewater treatment (Monatisa et al., 2023). A comparative life cycle assessment (LCA) study in Indonesia and Taiwan identified electricity consumption as the primary source of greenhouse gas (GHG) emissions, highlighting the importance of improving energy efficiency for sustainable wastewater management (Ouattara et al., 2024). Furthermore, the LCA showed that the environmental impact of operational energy consumption was greater than chemical use (Ouattara et al., 2024).

LCA is a method used (ISO 14040/14044) to evaluate the environmental impact of a product or process throughout its entire life cycle (Viotti et al., 2024). This approach is used to measure carbon footprints, identify environmental hotspots, and mitigate environmental impacts (Viotti et al., 2024). However, the LCA study still focuses on domestic wastewater treatment plants in urban domestic areas (Majid Al Zarkani et al., 2023). The LCA approach is applied to offshore facilities to evaluate the contribution of each process to environmental impacts from oil separation, biological process, physical-chemical process, and filtration (Al Zarkani and El Fadel, 2024). A study on wastewater treatment in offshore facilities shows that the integration of energy consumption and wastewater characterization can identify environmental hotspots (Mashrafi et al., 2022). The application of LCA to wastewater treatment using operational data to evaluate relationships between energy consumption, treatment process characteristics, and potential emissions in onshore oil and gas facilities remains relatively limited, particularly in Southeast Asia.

To address this gap, the novelty of this study lies in the application of operational data-driven LCA to wastewater treatment within gate-to-gate system boundaries. Unlike previous studies, which generally used secondary data or focused on domestic wastewater treatment or offshore facilities, this study evaluates wastewater treatment under actual operational conditions. The study integrates an operational energy consumption inventory, LCA modeling, and environmental hotspot identification. This approach represents environmental impact categories for operational conditions, identifies energy consumption, and identifies the contribution of each process unit to potential emissions. This study contributes to the development of LCA-based energy efficiency mitigation strategies for sustainable wastewater treatment facilities from oil and gas activities.

METHODOLOGY

Study approach and system limitations

This study uses an LCA approach based on ISO 14040 and ISO 14044 standards to evaluate the environmental impacts of the produced water treatment at the main gathering station (MGS) wastewater treatment plant (WTP), as shown in Figure 1. The study's system boundaries were defined using a gate-to-gate approach. Hence, the analysis only included the process stages within the WTP facility, from the inflow of produced water to the production of treated water that meets quality standards (Figure 2). This analysis does not include stages outside the WTP operational boundaries, such as exploration and production processes, raw material and chemical transportation, manufacturing, treated water distribution, or final waste management. Determining these system boundaries involves evaluating environmental impacts during operations, allowing more accurate identification of the main sources of emissions.

Study stages

The study's methodological framework consists of four stages: goal and scope definition, life cycle inventory (LCI) analysis, life cycle environmental impact assessment (LCIA) analysis, and interpretation. The first stage is the determination of the research objectives and scope, namely to evaluate the environmental impacts of the treatment process at the MGS WTP. The second is the inventory analysis, where primary data are collected through observations and operational activities, while secondary data is obtained from literature studies and related references. The collected inventory includes electrical energy consumption, chemical use, produced water volume, sludge production volume, and process characteristics for each operating unit (Table 1). The third stage is the life cycle impact assessment using SimaPro version 9 with the CML-IA baseline method. The fourth is the interpretation of results from the contribution of each process unit to emissions and hotspot identification.

Study areas and functional units

The functional unit used in this study is 33,000 barrels of water per day (BWPD), or equivalent to 5,246,571 liters/day of treated water at the MGS WTP. The functional unit was selected to quantify all materials, energy consumption, chemical use, and emissions, so that all analysis results can be compared at each process stage. The use of uniform functional units in LCA analysis ensures consistent results and validity across process units, in accordance with ISO 14040/14044. The process stages analyzed include the oil catcher, air stripping, biological process, physical-chemical process, multimedia filter, absorption process, treated water pond, and dewatering system. All input streams in the form of produced water, electrical energy, chemicals, filtration media, nutrients, and microorganisms, as well as output streams in the form of treated water, sludge, and CO_2, CH_4, and N_2O emissions, are included in the life cycle inventory. The entire process inventory is visualized in SimaPro to identify each operating unit's contribution to potential emissions.

Greenhouse gas emission calculation

Potential GHG emissions are calculated based on the electrical energy consumption of each process unit. Emissions analyzed include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as these three gases are the main contributors to the Global Warming Potential (GWP) of the electricity generation sector. This approach assumes that all electricity consumption comes from the national electricity grid, so the applicable electricity generation emission factor influences the amount of emissions. Emission calculations are carried out following the Intergovernmental Panel on Climate Change (IPCC) guidelines using an activity-based approach, which involves multiplying electrical energy consumption by the GHG emission factor and the GWP value, thereby expressing emissions in kg CO_2 -equivalent (kg CO_2-eq). Conversion to CO_2-equivalent units is used for GHG emissions in environmental impact indicators. Potential CO_2, CH_4, and N_2O emissions are calculated using the following Equation 1:

$$E = KE \times FE \times GWP \qquad (1)$$

where: E is potential emissions of CO_2, CH_4, and N_2O; KE is total energy consumption (kWh); FE is emission factor (0.774 kgCO_2 kWh^{-1}; 1.594 × 10^5 kgCH_4 kWh^{-1}; 8.768 × 10^6 kgN_2O kWh^{-1}); and GWP is global warming potential (CO_2 = 1; CH_4 = 28; N_2O = 268).

Electrical energy consumption was calculated using the installed power of each piece of equipment and actual operating time. The energy inventory included all major equipment contributing to the produced water treatment process, including aeration blowers, transfer pumps, circulation pumps, dewatering systems, and other supporting equipment. All energy consumption was accumulated for each process unit to serve as the basis for compiling a life-cycle inventory. The calculated CO_2, CH_4, and N_2O emissions were used as inventory data in the LCA modeling. The integration of emission inventory data, materials, and energy consumption was used for environmental impact assessment using SimaPro software with the CML-IA baseline method to evaluate impact categories such as global warming potential, human toxicity, marine aquatic ecotoxicity, acidification,

Figure 1. Main gathering station wastewater treatment plant of Balongan

eutrophication, terrestrial ecotoxicity, abiotic depletion (fossil fuels), and freshwater aquatic ecotoxicity, expressed in units (kg CO_2-eq). This approach establishes relationships among emission sources, impact categories, environmental consequences and identifies process units that contribute to environmental hotspots.

Sensitivity and uncertainty analysis

A sensitivity analysis was conducted to evaluate the effects of changes in electrical energy consumption on potential emissions generated during wastewater treatment. This analysis was conducted to test the sensitivity of electrical energy efficiency and energy savings in terms of carbon emission reductions. The analysis was conducted using an energy-consumption-change scenario approach, simulating electrical energy consumption relative to baseline conditions. Energy consumption scenarios were conducted with efficiency increases of 5%, 10%, and 15%, and efficiency decreases of 5%, 10%, and 15%. The change value represents realistic variations in operational conditions, including the effects of aeration system optimization and pump efficiency improvements.

Energy consumption under baseline conditions was calculated as the total actual electrical energy consumption multiplied by the national electricity emission factor. Next, new energy consumption was calculated by adjusting energy consumption based on the simulated efficiency percentage. Total emissions from each scenario were calculated by multiplying the simulated energy consumption by the corresponding electricity emission factor, ensuring that all emission changes were attributable only to variations in energy efficiency. The calculation of energy consumption and emissions for each scenario uses Equations 2, 3, 4 (Rashid et al., 2023) as follows:

$$E_{baseline} = E_{consumption} \times FE_{electricity} \quad (2)$$

$$E_{new} = E_{baseline} \times (1 \pm \Delta_{efficiency}) \quad (3)$$

$$Emissi_{new} = E_{new} \times FE_{electricity} \quad (4)$$

where: $E_{baseline}$ is the initial electrical energy consumption (kWh), $E_{consumption}$ is the total annual energy consumption (kWh), $\Delta_{efficiency}$ is the percentage change in efficiency (typically 0.15 to 15%), $FE_{electricity}$ is the electricity emission factor (kg CO_2-eq/kWh), E_{new} is the new energy consumption after efficiency changes, and $Emissi_{new}$ is the total new emissions resulting from energy efficiency changes.

This study assumes that electricity emission factors, production capacity, wastewater characteristics, process unit configuration, and chemical usage remain constant, so that changes in total emissions are only influenced by variations in electricity consumption. This assumption limits the influence of energy efficiency on LCA results and avoids bias in the parameter.

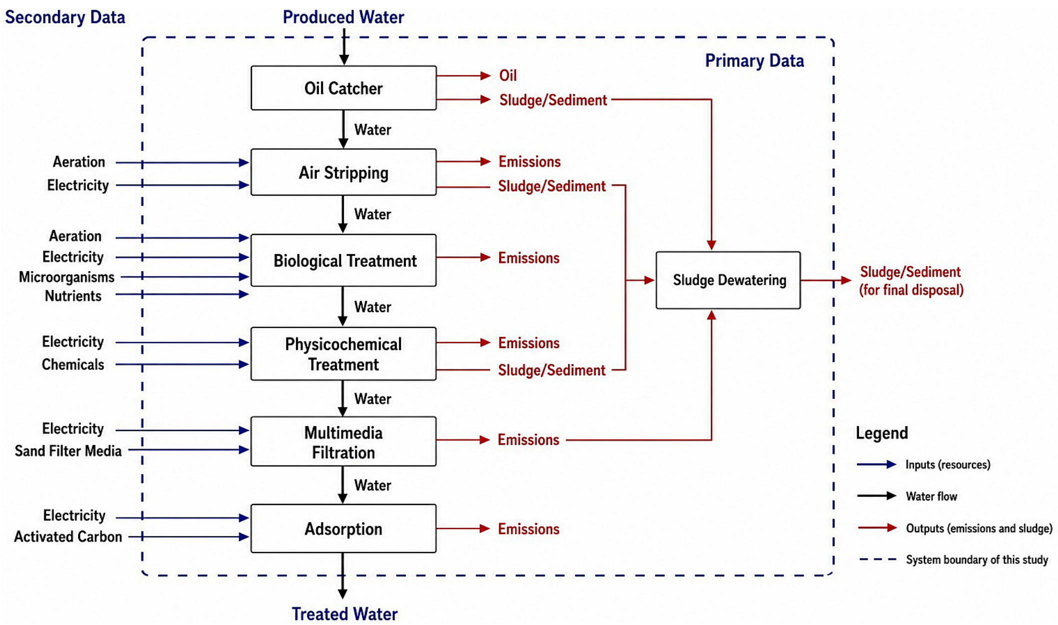

Figure 2. Study system boundaries

Sensitivity simulation results are compared with baseline conditions to calculate the magnitude of emission changes (kg CO_2-eq/year) and the percentage emission reduction. This comparison evaluates the effectiveness of energy efficiency as a carbon emissions mitigation measure in produced water treatment. Monte Carlo analysis was not used for interpretation because it utilizes inventory operational data such as electricity consumption and electricity grid emission factors, and secondary data from the Ecoinvent database, which is modeled deterministically and does not have uncertainty distributions in SimaPro. Therefore, sensitivity analysis was chosen as a representative approach to evaluate the robustness of the results to variations in actual operational parameters.

RESULTS

Wastewater treatment at the MGS

Produced water generated from oil and gas production activities is treated at the MGS WTP before being reused as injection water or discharged into water bodies. Produced water is a liquid waste that accounts for up to 90% of the total waste, making its management crucial for minimizing the risk of environmental pollution and ensuring the sustainability of industrial operations. The MGS WTP consists of eight process units: oil catcher, air stripping, biological process, physical-chemical process, multimedia filter, absorption process, treated water pond, and dewatering system. Each process unit reduces pollutant content and contributes differently to energy consumption, chemical use, and sludge.

The oil catcher works by separating oil and suspended solids based on the density difference between oil and water, with a processing time of 4.5 hours. The separated oil is returned to the production facility as part of the oil recovery, while the settled sludge is directed to the dewatering system unit. The separated water is processed by air stripping to remove volatile compounds, such as H_2S, NH_3, and light hydrocarbons, for 45 minutes. Furthermore, processed water sent to a biological process using aerobic microorganisms to degrade dissolved organic compounds. The availability of dissolved oxygen and nutrients influences the effectiveness of biological processes. This unit requires a continuous air supply using an aeration blower, with a processing time of 2.9 hours. The physical-chemical process aims to remove particles that are difficult to settle and organic compounds that are difficult to degrade biologically through coagulation, flocculation, and sedimentation using coagulant and flocculant chemicals. In this process, coagulation is achieved using an aeration system, followed by floc formation and sedimentation, with a total process time of 2.9 hours. The sludge resulting from sedimentation is separated and sent to the dewatering system, while the processed water is sent to the multimedia filter. In this stage, the filtration process uses sand media to remove any remaining suspended solids, and the processed water is sent to the absorption stage. The absorption process uses coconut-shell-derived activated carbon to remove residual organic compounds from the filtered water. In the final stage, the processed water is stored in a treated water pond before being reused as production regeneration for injection wells or discharged into water bodies.

The WTP produces sludge as a major byproduct. Sludge generated from the oil catcher, air stripping, biological process, and physical-chemical process reaches 3,700 kg/day. This sludge has a moisture content of 80%, meaning its mass is mostly water, requiring a dewatering process to reduce water content. Dewatering can reduce sludge weight by 30–50%, depending on the sludge characteristics and operating conditions. This process minimizes transportation costs and increases efficiency in sludge handling. The resulting sludge solid weighs 650 kg/day, while the water filtrate is returned to the oil catcher unit for reprocessing. PT WASTEC transports the solid sludge as the manage and handler of Hazardous and Toxic Waste (LB3). Sludge management must be carried out effectively and appropriately based on sludge characteristics, which are influenced by the source, industry type, WTP processing, physical properties, and chemical compounds (Hu et al., 2019).

Life cycle inventory

The LCA inventory includes produced water, electrical energy, chemicals, filtration media, activated carbon, nutrients, and microorganisms. The outputs include treated water, separated oil, sludge, and emissions generated by each unit. This study includes functional units and assumptions for the LCA analysis, including:

The functional unit of produced water used in the LCA analysis is 33,000 BWPD (±5,246,571 liters/day). The functional unit of mass weight used is 1 kg/month. The LCA analysis uses SimaPro 9.x software with the same functional unit so that the system can read the analysis.

Water evaporation in open ponds is assumed to be 5% of the volume of treated wastewater (Khater et al., 2016). Meanwhile, evaporation in closed ponds is very small and insignificant, so it is negligible. A study by Khater et al. (2016) found that the treatment using open ponds has an average water loss of 5%–10%, influenced by factors such as air temperature, humidity, wind speed, pond surface area, and air humidity (Khater et al., 2016).

Inventory results show that the volume of produced water entering the treatment system reaches 157,397,130 liters/month (±990,000 BWPM). After a series of processes, the water volume is 149,683,105 liters/month (±941,462 BWPM). The difference in water volume is due to evaporation or a loss of 5% of the total treated water. This is influenced by temperature, humidity, pond surface area, and the WTP treatment method. Furthermore, the total sludge generated during the treatment process is 28,333 kg/month from the oil catcher, air stripping, biological process, and physical-chemical units. After dewatering, the sludge weighs 4.817 kg/month. Details of the material, energy, and emission inventories for each process unit are presented in Table 1.

The energy inventory shows that electricity consumption comes from the air stripping, biological process, physical-chemical, and treated water pond, which uses aeration blowers and pumps. In contrast, the oil catcher, multimedia filter, and absorption process units require lower energy consumption because most processes occur by gravity or use physical separation mechanisms. These differences in operating characteristics cause variations in the system's total energy consumption. An inventory was compiled as the basis for LCA modeling using SimaPro software (Table 2). This inventory serves as the basis for the LCIA analysis and the identification process of units that make the largest contribution (environmental hotspots) to potential emissions and environmental impact categories.

GHG emission inventory

The emission inventory shows that energy consumption in each process contributes to CO_2, CH_4, and N_2O emissions. This is influenced by the electrical energy required to operate the aeration blowers, pumps, and process support equipment in the WTP. The CO_2, CH_4, and N_2O emission inventory results for each process unit are presented in Tables 3, 4, and 5. The air stripping and biological process generate the largest CO_2 emissions, each amounting to 1,003,622.40 kg CO_2-eq/month, followed by the physical-chemical process at 430,219.47 kg CO_2-eq/month. Potential CH_4 and N_2O emissions from the air stripping and biological processes of 578.55 kg CH_4-eq/month and 3,011.33 kg N_2O-eq/month, respectively. The high contribution of these two units is due to the use of aeration blowers and pumps that operate continuously, which require relatively higher electrical energy consumption compared to other process units. An example of calculating $CO_{2,}$ CH_4, and N_2O emissions in air stripping, with a power of 1.800 kWh, and an operating time of 24 hours × 30 days, is as follows:

- Potential CO_2 emission = 1.800 kWh × 24 hours × 30 days × 0.774 kg CO_2/kWh × 1 = 1,003,622.40 kg CO_2-eq
- Potential CH_4 emission = 1.800 kWh × 24 hours × 30 days × 1.594 × 10^5 kg CH_4/kWh × 28 = 578.55 kg CH_4-eq
- Potential N_2O emission = 1.800 kWh × 24 hours × 30 days x 8.768 × 10^6 kg N_2O/kWh × 268 = 3,045.42 kg N_2O-eq

The total inventory of potential emissions reached 2,661,718.12 kg CO_2-eq/month, 1,534.39 kg CH_4-eq /month, and 7,986.37 kg N_2O-eq/month, respectively. The dominance of CO_2 emissions indicates that electricity consumption is the primary contributor to climate change potential. In contrast, CH_4 and N_2O emissions are relatively small, but influential due to their higher GWP values compared to CO_2. The emissions inventory distribution indicates that air stripping, biological, and physical-chemical processes are the operating units with the highest energy intensity in the MGS WTP. These three units rely on aeration, mixing, and pumping operations, which require higher electrical energy consumption than the separation and filtration units.

This indicates that improving energy efficiency in these three units has the potential to reduce total GHG emissions. Based on the inventory results, mitigation focused on optimizing energy consumption in high-energy-intensity units by implementing high-efficiency pumps

Table 1. LCA inventory of produced water treatment

Input			Output		
Materials	Quantity	Units	Materials	Quantity	Units
Oil catcher					
Produced water	157,397,130	L/month	Sludge	6666.67	Kg/month
			Oil	300,000	Kg/month
			Produced water	155,823,159	L/month
Air stripping					
Produced water	155,823,159	L/month	Sludge	2,500.00	Kg/month
Electricity	43,200	kWh	Produced water	154,264,927	L/month
			Emissions CO_2	1,003,622.40	Kg/month
			Emissions CH_4	578.55	Kg/month
			Emissions N_2O	3,045.42	Kg/month
Proses biological process					
Produced water	154,264,927	L/month	Produced water	152,722,278	L/month
Electricity	43,200	kWh	Emissions CO_2	1,003,622.40	Kg/month
Microorganisms	300,000	Kg/month	Emissions CH_4	578.55	Kg/month
Nutrient	300,000	Kg/month	Emissions N_2O	3,011.33	Kg/month
Physical-chemical process					
Produced water	152,722,278	L/month	Sludge	28,333.33	Kg/month
Electricity	18,518.40	kWh	Produced water	151,195,055	Kg/month
Coagulant	90,000	Kg/month	Emissions CO_2	430,219.47	Kg/month
Flocculant	60,000	Kg/month	Emissions CH_4	248.01	Kg/month
			Emissions N_2O	1,290.86	Kg/month
Multimedia filter					
Produced water	151,195,055	L/month	Produced water	151,195,055	L/month
Sand Filter	56,000	Kg/month			
Absorption					
Produced water	151,195,055	L/month	Produced water	151,195,055	L/month
Activated carbon	16,000	Kg/month			
Treated produce water					
Produced water	151,195,055	L/month	Produced water	149,683,105	L/month
Electricity	9,600	kWh	Emissions CO_2	223,027.20	Kg/month
			Emissions CH_4	128.57	Kg/month
			Emissions N_2O	669.18	Kg/month
Dewatering system					
Sludge	28,333.33	Kg/month	Sludge	4,816.67	Kg/month
Electricity	52.8	kWh	Emissions CO_2	1,226.65	Kg/month
			Emissions CH_4	0.71	Kg/month
			Emissions N_2O	3.68	Kg/month
			Produced water	22,667	L/month

and blowers, and on optimizing chemical dosage through an intensive monitoring system. This approach is expected to reduce electrical energy consumption and GHG emissions without compromising the performance of produced water treatment (Su et al., 2025).

Life cycle impact assessment

The LCIA results show that the environmental impacts of wastewater treatment vary across process units (Table 6). Characterization values indicate that GWP reaches 81,342,244.20 kg CO_2-eq,

Table 2. LCA system data inventory in the Software Simapro

Product		Inputs		Outputs					
Outputs to Techno-sphere	Amount	Inputs from the technosphere	Amount	Emiss-ions to water	Amount	Emissions to air	Amount	Outputs to the technosphere	Amount
Oil catcher	157,397,130	Materials/Fuels: Water discharge from petroleum extraction, onshore| treatment of | APOS, S	157,397,130	Waste-water	1,573,971			Wastewater, treated|OC	155,823,159
								Sludge|OC	6,666.67
								Oil, seperated	300,000
Air stripping	155,823,159	Materials/Fuels: Wastewater, treated|OC	155,823,159	Waste-water	1,558,232	Carbon-dioxide	30,108,672	Wastewater, treated|AS	154,264,927
		Electricity/Heat: Electricity, medium voltage {RoW} | APOS, S	43,200			Methane	17,356.63	Sludge|AS	2,500
						Nitrousoxide	90,339.80		
Biological process	154,264,927	Materials/Fuels: Wastewater, treated|AS	154,264,927	Waste-water	1,542,649	Carbon-dioxide	30,108,672	Wastewater, treated|BP	152,722,278
		Materials/ Fuels:Wastewater{RoW}| with biological treatment | APOS , S	600,000			Methane	17,356.63		
		Electricity/Heat: Electricity,medium voltage {RoW}| APOS , S	43,200			Nitrousoxide	90,339.80		
Physical chemical process	152,722,278	Materials/Fuels: Wastewater, treated|BP	152,722,278	Waste-water	1,527,223	Carbon-dioxide	12,906,584.06	Wastewater, treated|CP	151,195,055
		Materials/Fuels: Chemicals, unspecified, physical treatment	60,000			Methane	7,440.21	Sludge|CP	28,333.33
		Materials/Fuels: Poly aluminum Chloride	90,000			Nitrouso-xide	38,725.66		
		Electricity/Heat: Electricity, medium voltage {RoW} | APOS, S	18,518.40						
Multimedia filter	151,195,055	Materials/Fuels: Wastewater, treated|CP	151,195,055					Wastewater, treated|MF	151,195,055
		Materials/Fuels: Wastewater {RoW}|,direct filtration treatment| APOS, S	56,000						
Absorption process	151,195,055	Materials/Fuels: Wastewater, treated|MF	151,195,055					Wastewater, treated|AP	151,195,055
		Materials/Fuels: Wastewater, Activated carbon	16,000						
Treated produce water	151,195,055	Materials/Fuels: Wastewater, treated|AP	151,195,055	Waste-water	1,511,951	Carbon-dioxide	6,690,816.00	Wastewater, unpolluted {RoW}| treatment of| APOS,S	149,683,104
		Electricity/Heat: Electricity, medium voltage {RoW}|APOS,S	9,600			Methane	3,857.03		
						Nitrouso-xide	20,075.51		
Dewatering system	37,500	Materials/Fuels: Sludge|OC	6,666.67			Carbon-dioxide	36,799.49	Sludge	7,500
		Materials/Fuels: Sludge|AS	2,500.00			Methane	21.21	Water	30,000
		Materials/Fuels: Sludge|CP	28,333.33			Nitrouso-xide	110.42		
		Electricity/Heat: Electricity, medium voltage {RoW}| APOS,S	52.8						

Table 3. Calculation of CO_2 emissions

Processes	Power electricity	Operating time	Total energy consumption	Emission factor	GWP	Emission CO_2
	(kWh)	(Hours x Days)	(kWh)	(kg CO_2/kWh)		(kg CO_2 eq)
			(1)	(2)	(3)	(4) = (1)*(2)*(3)
Air stripping	1,800	24 × 30	1,296,000	0.7744	1	1,003,622.40
Biological process	1,800	24 × 30	1,296,000	0.7744	1	1,003,622.40
Physical chemical	772	24 × 30	555,552	0.7744	1	430,219.47
Treated produce water	400	24 × 30	288,000	0.7744	1	223,027.20
Dewatering system	2.2	24 × 30	1,584	0.7744	1	1,226.65
		Total potential emissions of CO_2			2,661,718.12	

Table 4. Calculation of CH_4 emissions

Processes	Power electricity	Operating time	Total energy consumption	Emission factor	GWP	Emission CH_4
	(kWh)	(Hours x Days)	(kWh)	(kg CH_4/kWh)		(kg CH_4 eq)
			(1)	(2)	(3)	(4) =(1)*(2)*(3)
Air stripping	1,800	24 × 30	1,296,000	1.594×10^5	28	578.55
Biological process	1,800	24 × 30	1,296,000	1.594×10^5	28	578.55
Physical chemical	772	24 × 30	555,552	1.594×10^5	28	248.01
Treated produce water	400	24 × 30	288,000	1.594×10^5	28	128.57
Dewatering system	2.2	24 × 30	1,584	1.594×10^5	28	0.71
		Total potential emissions of CH_4			1,534.39	

Table 5. Calculation of N_2O emissions

Processes	Power electricity	Operating time	Total energy consumption	Emission factor	GWP	Emisi N_2O
	(kWh)	(Hours x Days)	(kWh)	(kg N_2O/kWh)		(kg N_2O eq)
			(1)	(2)	(3)	(4) = (1)*(2)*(3)
Air stripping	1.800	24	1,296,000	8.768×10^6	265	3,045.42
Biological process	1.800	24	1,296,000	8.768×10^6	265	3,045.42
Physical chemical	772	24	555,552	8.768×10^6	265	1,290.86
Treated produce water	400	24	288,000	8.768×10^6	265	669.18
Dewatering system	2.2	24	1.584	8.768×10^6	265	3.68
		Total potential emissions of N_2O			7,986.37	

marine aquatic ecotoxicity 141,322,310.58 kg 1.4-DB-eq, abiotic depletion (fossil fuels) 13,515,109.68 MJ, and freshwater aquatic ecotoxicity 51,141.00 kg 1.4-DB-eq. Meanwhile, human toxicity, acidification, photochemical oxidation, terrestrial ecotoxicity, and eutrophication showed lower emission values. The characterization results cannot be used to compare impact magnitudes across categories, as the results have different units and operate through different environmental mechanisms. Therefore, interpretation focuses on the contribution of each process unit to each impact category to identify environmental hotspots at the MGS WTP.

Contribution analysis shows that air stripping and biological processes dominate the GWP, human toxicity, marine aquatic ecotoxicity, photochemical oxidation, and acidification categories. The biological process contributed the highest to the GWP category, with 30,626,748.12 kg CO_2-eq (37.65%), followed by air stripping at 30,626,392.03 kg CO_2-eq (37.65%). The physical-chemical processes

Table 6. LCIA results of characterization indicators with the CML-IA baseline method

Impact category	Unit	Total	Oil catcher	Air stripping	Biological process	Physical chemical process	Multimedia filter	Absorption process	Treated produce water	Dewatering system
Abiotic depletion (fossil fuels)	MJ	13,515,109.68	12,597,705.93	344,371.17	348,318.00	147,620.44	146.32	0.00	76,526.93	420.90
Global warming (GWP100a)	kg CO_2-eq	81,342,244.20	0.00	30,626,392.03	30,626,748.12	13,128,513.41	13.56	117,280.00	6,805,864.93	37,432.16
Ozone layer depletion	kg CFC-11-eq	0.004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human toxicity	kg 1.4-DB-eq	38,251.88	6,440.16	11,927.36	12,100.96	5,112.86	5.43	0.00	2,650.53	14.58
Freshwater aquatic ecotoxicity	kg 1.4-DB-eq	51,141.00	16,464.62	13,008.99	13,178.80	5,576.52	5.28	0.00	2,890.89	15.90
Marine aquatic ecotoxicity	kg 1.4-DB-eq	141,322,310.58	8,813,703.01	49,744,359.66	50,304,778.25	21,323,748.84	20,620.00	0.00	11,054,302.15	60,798.66
Terrestrial ecotoxicity	kg 1.4-DB-eq	737.54	556.97	67.80	68.54	29.06	0.03	0.00	15.07	0.08
Photochemical oxidation	kg C_2H_4-eq	290.64	0.00	109.56	109.63	46.96	0.00	0.00	24.35	0.13
Acidification	kg SO_2-eq	372.44	6.34	137.39	139.06	58.89	0.06	0.00	30.53	0.17
Eutrophication	kg PO_4-eq	2,676.48	2,502.27	65.42	66.11	28.04	0.03	0.00	14.54	0.08

contributed 13,128,513.41 kg CO_2-eq (16.14%), and treated water contributed 6,805,864.93 kg CO_2-eq (8.37%). These contributions indicate that electrical energy consumption for aeration, pumping, and biological treatment is the primary source of carbon emissions in the WTP. Dependence on electricity generated by coal-fired power plants leads to increased carbon emissions, the formation of acidifying compounds, and increased toxicity to humans and aquatic ecosystems.

In addition, oil catchers contribute to the high categories of abiotic depletion (fossil fuels), freshwater aquatic ecotoxicity, terrestrial ecotoxicity, and eutrophication. The abiotic depletion (fossil fuels) category is dominated by oil catchers, which account for 12,597,705.93 MJ, or 93.2% of the total impact, indicating high demand for fossil energy. The eutrophication and terrestrial ecotoxicity categories indicate that the influent still contains hydrocarbons and organic compounds, which cause a high potential environmental burden during processing. Meanwhile, the physical-chemical process has a moderate contribution to the environmental impact category. The contributions of multimedia filters, absorption, treated produced water, and dewatering systems are relatively small, so their influence on the total environmental impact is insignificant. These findings indicate that the performance of the MGS WTP focuses on increasing energy efficiency in the air stripping unit and biological process to reduce emissions and toxicity impacts, as well as optimizing the oil catcher to improve oil separation. To identify environmental hotspots, LCIA results were analyzed based on the percentage contribution of each process unit to the total impact in each environmental category. Presenting relative contribution values provides a more comprehensive interpretation than absolute values, as each impact category uses different indicators and units. The contribution of each process unit to the environmental impact category, based on the LCIA characterization results, is shown in Figure 3. The analysis shows that environmental

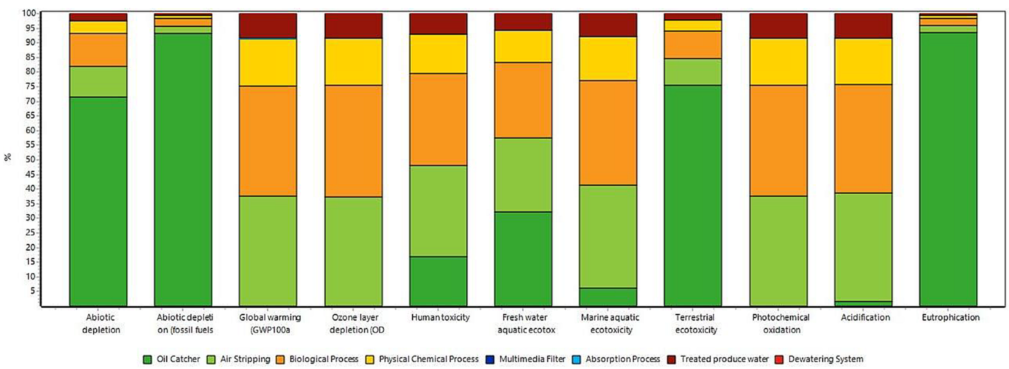

Figure 3. Relative contribution (%) of each treatment unit to the characterized environmental impact categories. These contributions are expressed as a percentage of the total impact in each category to facilitate comparisons between impact categories with different characterization units

impacts are not evenly distributed among the process units. Air stripping and biological processes consistently contribute the most to impact categories related to emissions and toxicity, while the oil catcher is associated with fossil resource consumption and eutrophication. Physical-chemical processes have a moderate contribution, while multimedia filters, absorption, and dewatering contribute a small amount of emissions. This condition shows that mitigation of environmental impacts prioritizes increasing energy efficiency, which uses more electrical energy.

The contribution of each process unit to the environmental impact category based on the LCIA results is shown in Figure 4(A–H). The visualization results show that the air stripping and biological processes are environmental hotspots that consistently dominate the GWP, human toxicity, marine aquatic ecotoxicity, and acidification categories (Figure 4 A–D). In the GWP category,

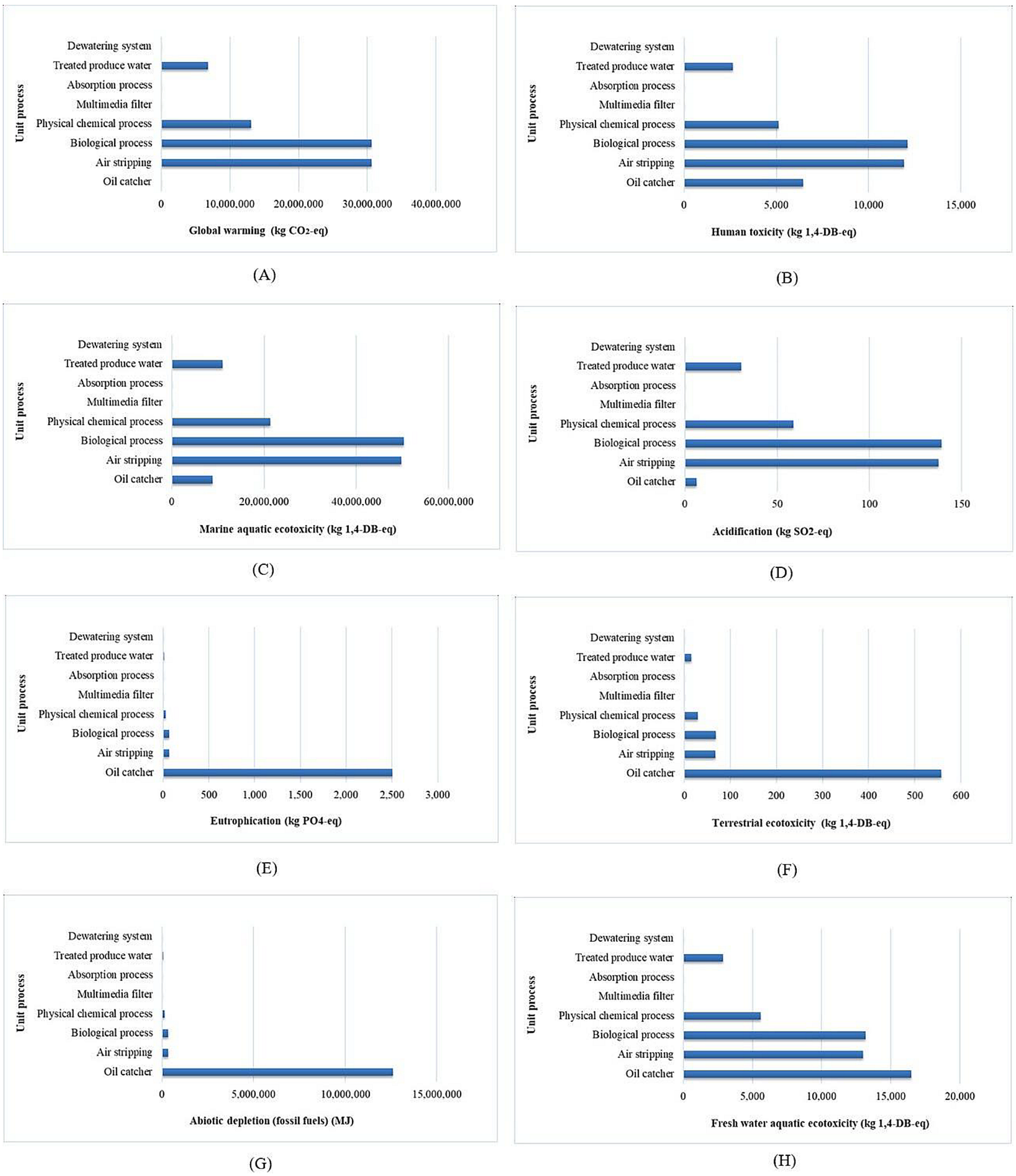

Figure 4. Contribution of each process unit to the environmental impact category based on LCIA results using the CML-IA baseline method: (A) global warming potential, (B) human toxicity, (C) marine aquatic ecotoxicity, (D) acidification, (E) eutrophication, (F) terrestrial ecotoxicity, (G) abiotic depletion (fossil fuels), and (H) freshwater aquatic ecotoxicity

these two units account for approximately 37.6% of total emissions, much higher than those of the physical-chemical and other process units. The ecotoxicity and acidification categories indicate that these processes require high electrical energy, such as aeration, air stripping, and fluid circulation. Indirect emissions from electricity consumption are a dominant factor increasing the potential for global warming, the formation of acidifying compounds, and toxicity to humans and aquatic ecosystems. Conversely, the categories of eutrophication, terrestrial ecotoxicity, abiotic depletion, and freshwater aquatic ecotoxicity (Figure 4 E–H) are dominated by the oil catcher unit, which contributes more than other process units. This dominance value indicates that the oil and water separation contributes to resource consumption and potential impacts on terrestrial and aquatic ecosystems. This high contribution is due to wastewater still containing hydrocarbons and other organic compounds, requiring more energy for treatment. Meanwhile, the physical-chemical processes contribute moderately to the environmental impact, while multimedia filters, absorption, treated produced water, and dewatering contribute small emissions to the total environmental burden. These findings suggest that environmental impact mitigation is achieved by increasing energy efficiency in air stripping and biological processes to reduce carbon emissions and toxicity, and by optimizing the oil catcher unit.

Environmental hotspot analysis

The identification of the largest contributors to emissions is based on the results of an LCIA that integrates an inventory of energy consumption, material use, and emissions for each operating unit. The analysis shows that air stripping, biological processes, and physical-chemical processes contribute the most to the total environmental impact. The air stripping and biological units account for approximately 35.7% of the total impact, while the physical-chemical process contributes 15.3%. Cumulatively, these units account for more than 85% of the total environmental impact, thereby categorizing them as environmental hotspots and prioritizing them in environmental performance improvement strategies. The dominant environmental impact of air stripping and biological processes due to the high electrical energy consumption required to operate the aeration blowers, transfer pumps, and circulation systems during the treatment process. In the air-stripping unit, an aeration system is necessary to remove volatile compounds such as H_2S, NH_3, and light hydrocarbons. Meanwhile, the biological process requires a continuous supply of oxygen for the activity of aerobic microorganisms in degrading organic compounds. Both units consume more energy than other process units, resulting in higher emissions of CO_2, CH_4, and N_2O. Meanwhile, the physical-chemical processes contribute to emissions from the use of electrical energy and coagulant and flocculant chemicals. In addition, the energy required for rapid and slow mixing, as well as chemical production, has an embodied environmental burden, which is accounted for in the LCA inventory. Therefore, the environmental impact of this unit stems not only from electricity consumption but also from the chemicals used during the processing. In contrast, the oil catcher unit, multimedia filter, absorption process, and dewatering system contribute relatively small amounts to the total environmental impact. These units rely on a gravity separation process and require lower electrical energy. Therefore, mitigation strategies aimed at improving energy efficiency and providing greater environmental benefits than reducing chemical use.

Sensitivity analysis

A sensitivity analysis was conducted to determine the effect of scenario changes on emissions. Sensitivity analysis indicates the potential CO_2-eq emissions at the MGS WTP, influenced by operational energy efficiency and electricity emission factors. The combination of improved internal energy efficiency and a low carbon electricity transition will have a synergistic effect, resulting in significant total emissions reductions. The mitigation strategies at the MGS WTP focus on process optimization and energy transformation to achieve optimal results.

Energy efficiency scenario

Optimization was applied to the air stripping and biological processes because both have the greatest influence on the carbon footprint, accounting for 68–72% of total CO_2-eq emissions. Energy efficiency scenarios of ±5%, ±10%, and ±15% were determined for carbon emission reductions (Tsalas et al., 2024). The assumptions used in the energy efficiency scenarios are:

- Current electricity consumption at the hotspot:
  - Air stripping: ±210 kWh/day,
  - Biological process: ±320 kWh/day,

- Indonesian electricity emission factor: 0.73 kg CO_2-eq/kWh (PT PLN Persero, 2023),
- The total annual energy consumption of the MGS WTP (baseline) is 45,330,956.00 kWh.
- Scenario simulation – an increase in energy efficiency (+15%) will reduce the total emissions.

A decrease in energy efficiency (–15%) will increase total emissions. This indicates the high sensitivity to electricity consumption in hotspots. Therefore, an example of calculating energy efficiency using Equation 2, 3 and 4 with a baseline energy consumption of 45,330,956 kWh/year at the MGS WTP is obtained:

- $E_{baseline}$ = 45,330,956 kWh × 0.73 kg CO_2-eq/kWh = 33,091,598 kg CO_2-eq
- Efficiency scenario calculation (+15%), electricity consumption decreases by 15%
- E_{new} = 45,330,956 kWh × (1 - 0.15) = 38,531,312 kWh
- $Emissions_{new}$ = 38,531,312 kWh × 0.73 kg CO_2-eq/kWh = 28,127,858 kg CO_2-eq
- Efficiency scenario calculation (+10%), electricity consumption decreases by 10%
- E_{new} = 45,330,956 kWh × (1 - 0.10) = 40,797,860 kWh
- $Emissions_{new}$ = 40,797,860 kWh × 0.73 kg CO_2-eq/kWh = 29,782,438 kg CO_2-eq
- Efficiency scenario calculation (+5%), electricity consumption decreases by 5%
- E_{new} = 45,330,956 kWh × (1 - 0.05) = 43,064,408 kWh
- $Emissions_{new}$ = 43,064,408 kWh × 0.73 kg CO_2-eq/kWh = 31,437,018 kg CO_2-eq
- Efficiency scenario calculation (-5%), electricity consumption increases by 5%
- E_{new} = 45,330,956 kWh × (1 + 0.05) = 47,597,503 kWh
- $Emissions_{new}$ = 47,597,503 kWh × 0.73 kg CO_2-eq/kWh = 34,746,178 kg CO_2-eq
- Efficiency scenario calculation (-10%), electricity consumption increases by 10%
- E_{new} = 45,330,956 kWh × (1 + 0.10) = 49,864,051 kWh
- $Emissions_{new}$ = 49,864,051 kWh × 0.73 kg CO_2-eq/kWh = 36,400,758 kg CO_2-eq
- Efficiency scenario calculation (-15%), electricity consumption increases by 15%
- E_{new} = 45,330,956 kWh × (1 + 0.15) = 52,130,599 kWh
- $Emissions_{new}$ = 52,130,599 kWh × 0.73 kg CO_2-eq/kWh = 38,055,338 kg CO_2-eq

The sensitivity analysis illustrates projected changes in energy efficiency of ±5%, ±10%, and ±15%, which will affect total emissions (Figure 5). Seven scenarios were analyzed: increases in energy efficiency of +15%, +10%, and +5%; the baseline condition; and decreases of -15%, -10%, and -5%. The sensitivity results show that the annual energy consumption at the MGS WTP under baseline conditions was 45,330,956 kWh, equivalent to 33,091,598 kg CO_2-eq, using Indonesia's electricity emission factor of 0.73 kg CO_2-eq/kWh. An increase in energy efficiency of (+15%) can reduce energy consumption to 38,531,312 kWh, resulting in emissions of 28,127,858 kg CO_2-eq. On the other hand, a decrease in energy efficiency of (-15%) increases consumption to 52,130,599 kWh, resulting in emissions of 38,055,338 kg CO_2-eq. The difference in efficiency scenarios between (+15%) and (-15%) is 9,927,479 kg CO_2-eq/year. This shows that energy efficiency management is one of the mitigation measures to reduce the carbon footprint in wastewater treatment. An increase in energy efficiency of (+15%) can provide technical and environmental benefits, and support the energy transition towards low carbon industrial facility management.

DISCUSSION

The results of this study indicate that electrical energy consumption is the dominant factor determining the environmental impact of wastewater treatment plants. Global warming potential, marine aquatic ecotoxicity, and abiotic depletion (fossil fuels) are the main impacts, with the largest contributions coming from air stripping, biological processes, and physical-chemical processes. High energy consumption for operating aeration blowers, pumps, and mixing systems increases CO_2-eq emissions, and electricity consumption is a significant contributor to the carbon footprint. A study by He et al. (2023) stated that wastewater treatment processes can contribute approximately 87%, while the utilization of low-carbon electricity can reduce emissions by up to 69.7% (He et al., 2023). Previous studies have shown that aeration and high-power pumps are the major sources of environmental impact in wastewater treatment plants, particularly in

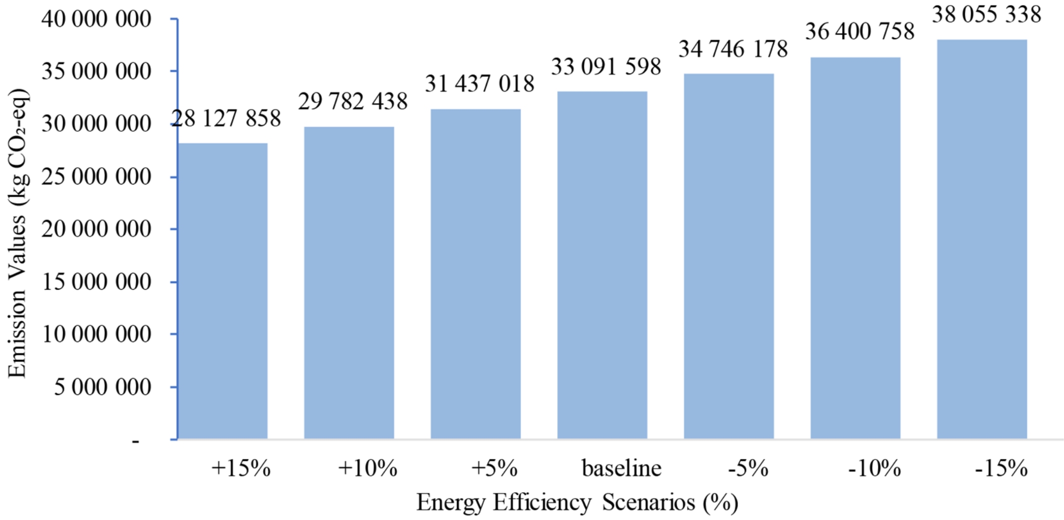

Figure 5. Graph of carbon emissions (kg CO_2-eq) based on energy efficiency scenarios

tropical regions with high dissolved oxygen demands (He et al., 2023; Li, Lu and Lu, 2024; Ouattara et al., 2024).

Analysis of environmental impact contributions shows that air stripping and biological processes are environmental hotspots, accounting for more than 75% of the total GWP. Both units are equipped with continuous oxygen transfer and aeration processes to remove organic and volatile compounds that increase electricity consumption and carbon emissions. The high emission contribution is influenced by the characteristics of the produced water, which still contains hydrocarbons, ammonia, and volatile organic compounds, thereby requiring air-stripping and biological aeration processes. In addition, oil catchers have large contributions to the categories of abiotic depletion (fossil fuels) and eutrophication, indicating that separating oil from water still affects hydrocarbons. In addition, ecotoxicity is the process of identifying the cycling of compounds that are harmful to living things and the environment. Identification of ecotoxicity is the basis for policy in selecting chemicals for more environmentally friendly processes, aimed at reducing the risk of environmental pollution (Taelman et al., 2024).

The results of this study show that increasing energy efficiency is an effective mitigation measure to reduce environmental impacts without compromising produced water treatment performance. Optimizing blower and pump operations through the use of high-efficiency equipment, dissolved oxygen-based aeration control, and low-carbon electricity utilization. Integrating internal energy-efficiency strategies and increasing the use of clean electricity can help reduce emissions optimally (Wu et al., 2025).

CONCLUSIONS

The results show that electrical energy consumption is the largest source of emissions, particularly from the aeration blower and pump units, which cumulatively account for more than 70% of total CO_2-eq emissions. The results indicate that global warming potential is the primary environmental impact, followed by marine aquatic ecotoxicity and abiotic depletion (fossil fuels), reflecting the importance of managing resource consumption and emissions during operations. Air stripping, biological processes, and physical-chemical processes have the largest environmental impacts and require electrical energy to operate the systems. The results show that the sustainability of wastewater treatment depends not only on pollutant removal but also on operational energy efficiency through the utilization of low-carbon technologies and intensive process optimization.

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