

LIFE CYCLE ASSESSMENT OF MBBR-BASED WASTEWATER TREATMENT PLANT (CASE STUDY: WWTP OF A SOAP AND COSMETIC INDUSTRY)

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Abstract

Wastewater treatment plants (WWTPs) in the soap and cosmetics industry are often assessed primarily through effluent compliance, overlooking environmental burdens from electricity, chemical use, and sludge management. This study applies Life Cycle Assessment (LCA), following ISO 14040/14044, to a full-scale Moving Bed Biofilm Reactor (MBBR)-based WWTP treating high-strength wastewater at a soap and cosmetics manufacturing facility in West Java, Indonesia. The gate-to-gate system was modeled using 36 months of operational data and ecoinvent v3.10 background data, with impacts assessed for 1,000 m³ of treated wastewater using ReCiPe 2016 Midpoint (H) in openLCA. The impact assessment showed a global warming potential of 216,928.1 kg CO₂ eq, fossil resource scarcity of 60,277.8 kg oil eq, terrestrial ecotoxicity of 511,267.9 kg 1,4-DCB, freshwater ecotoxicity of 4,730.3 kg 1,4-DCB, and human non-carcinogenic toxicity of 203,723.9 kg 1,4-DCB. The MBBR aeration blower, EQ tank pump, centrifuge decanter motor, and DAF transfer pump accounted for over 85% of electricity consumption. Terrestrial Ecotoxicity and Human Non-Carcinogenic Toxicity were primarily associated with chemical production and sludge-borne contaminants, while Global Warming and Fossil Resource Scarcity were mainly linked to electricity consumption and fossil-based power generation. Overall, chemical use and electricity consumption were key contributors to the WWTP's environmental footprint, highlighting chemical dosage optimization and energy efficiency as potential improvement strategies.

Keywords: Life Cycle Assessment (LCA), Wastewater Treatment Plant (WWTP), Moving Bed Biofilm Reactor (MBBR), Soap and Cosmetics Industry, ReCiPe 2016

INTRODUCTION

The soap and cosmetics industry produces wastewater that is difficult to treat because it contains high levels of surfactants, fluctuating organic loads, and irregular discharge patterns driven by batch production and clean-in-place (CIP) cleaning cycles. In practice, wastewater treatment plants (WWTPs) serving these factories are usually measure by whether their effluent meets discharge limits for pH, total suspended solids (TSS), surfactants, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) set by industrial estates and national regulations (Bogacki et al., 2017). Meeting these limits shows that the plant controls direct pollutant releases, but it does not reveal whether the treatment system itself creates a low overall environmental burden. In reality, WWTPs consume large amounts of electricity for aeration and pumping, require continuous chemical dosing, and generate sludge and direct emissions.

Life Cycle Assessment (LCA), following ISO 14040 and ISO 14044, offers a structured way to quantify these hidden burdens across the entire treatment system. Beyond calculating total impacts, LCA helps identify environmental hotspots—the specific processes or material inputs that drive most of the impact—so improvements can be targeted rather than guessed. This is especially important for avoiding burden shifting, where a change reduces one impact category (Laouane et al., 2026).

Although there is a large body of wastewater LCA research, its coverage is uneven. Most studies focus on municipal systems, conventional activated sludge, and membrane technologies, while full-scale Moving Bed Biofilm Reactor (MBBR) systems treating industrial wastewater are under-represented. Existing MBBR research tends to emphasize technical performance rather than life-cycle environmental performance (Andreottola et al., 2002). At the same time, literature on cosmetics wastewater has concentrated on removal technologies and effluent

quality, with little attention to the life-cycle burdens of the chemical inputs these processes rely on, such as polyaluminium chloride (PAC), polymers, sodium hydroxide, nutrients, and silicone-based antifoam. Two additional methodological gaps limit the usefulness of current evidence. First, many wastewater LCAs are based on short-term or single-point inventory data, which cannot capture the temporal variability inherent to industrial treatment systems whose influent changes with production activity. Second, quantitative uncertainty analysis is still uncommon: a review of wastewater LCA in developing countries found that fewer than one in four studies (Rashid et al., 2023b). This study addresses these gaps through an LCA of a full-scale MBBR-based WWTP serving a soap and cosmetics manufacturing facility in West Java, Indonesia. The assessment modeled using 36 months of primary site-measured operational data, with cradle-to-gate background data for purchased chemicals and electricity. This allows upstream production burdens to be attributed to individual chemical products rather than lumped into a single inventory flow.

LITERATURE REVIEW

Characteristics of Soap and Cosmetic Industry Wastewater

Wastewater from soap and cosmetic manufacturing originates from equipment washing, product changeovers, CIP cycles, rejected batches, spills, and residual raw materials, and typically contains surfactants, oils and grease, emulsifiers, preservatives, fragrances, colorants, suspended solids, nutrients, and a mixture of readily biodegradable and recalcitrant organic compounds. Because these contributions are tied to production scheduling, concentrations of COD, BOD, TSS, oil and grease, and surfactants fluctuate substantially over time rather than approaching a stable influent characteristic (Bogacki et al., 2017). Surfactants are the defining pollutant in this stream. By lowering surface tension and stabilizing emulsions, they promote persistent foaming that can disrupt pumping, aeration, DAF, and solid-liquid separation; oils, suspended particles, polymers, and hydrophobic cosmetic ingredients further stabilize the resulting foam. Operationally, this foaming behaviour is the mechanism that drives antifoam demand (Dlangamandla et al., 2023).

Moving Bed Biofilm Reactor Technology Biological Treatment

Biological treatment relies on microbial degradation of dissolved organics. Conventional activated sludge remains widely applied but is sensitive to variation in hydraulic and organic loading, dissolved oxygen, temperature, pH, and inhibitory substances conditions more challenging in surfactant-bearing industrial wastewater than in municipal systems (di Biase et al., 2019). Biofilm-based systems retain biomass on solid surfaces, permitting higher biomass concentrations and greater resistance to shock loading, as part of the microbial community is protected within the biofilm matrix (Ødegaard, 2006). Comparative studies indicate that MBBR can match or exceed conventional activated sludge under appropriate operating conditions. Environmental performance, however, cannot be inferred from removal efficiency alone: aeration and pumping electricity, carrier production, chemical pretreatment, excess-sludge management, and direct greenhouse gas emissions all contribute to the system's footprint advantage (Rashid et al., 2023b).

LCA Methodology In Wastewater Treatment

LCA, structured by ISO 14040 and ISO 14044 across goal and scope definition, inventory analysis, impact assessment, and interpretation and thereby reveals burden shifting invisible to effluent-compliance monitoring. Reviews nonetheless report considerable inconsistency across wastewater LCAs in functional unit definition, system boundaries, impact categories, allocation, and data-quality requirements, making transparent methodological reporting (International Organization for Standardization, 2006).

Volume-based functional units of 1 m³ or 1,000 m³ are common and suit facility-level operational assessment and comparison across operating periods or improvement scenarios, though they do not independently reflect differences in influent concentration or removal efficiency between facilities. System boundaries for operational assessments typically encompass chemical and electricity supply, on-site treatment, direct emissions, sludge production, and effluent discharge, with construction and decommissioning excluded where the objective is operational hotspot identification, provided the exclusion is stated (Larsen, 2017).

Inventory quality is a recurring constraint because plant-specific operational records are necessary, as actual electricity and chemical consumption often diverge substantially from generic database or literature values, particularly in industrial systems where influent characteristics vary with production activities, cleaning schedules, and product changeovers. Extended monitoring periods therefore represent normal operating performance more reliably than short-term sampling and enable the detection of atypical conditions, such as peaks in chemical consumption or

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sludge production. Background processes are commonly modelled using databases such as ecoinvent; however, these databases may not fully reflect national electricity generation mixes, transport distances, or local supplier technologies. ReCiPe 2016 then converts inventory flows into midpoint and endpoint indicators, with midpoint categories relevant to chemical-intensive WWTPs including global warming, fossil and mineral resource scarcity, eutrophication, acidification, ecotoxicity, human toxicity, particulate-matter formation, water consumption, and land use (Tran & Weidhaas, 2024).

Research Gap

Table 2.1 Research Gap

Author(s)	Research focus	Principal contribution	Identified limitation	Contribution of the present study
(Corominas et al., 2020)	Best-practice guidance for wastewater LCA	Provided guidance for goal, scope, inventory, assessment, and interpretation	Guidance mainly derived from municipal wastewater applications	Operationalizes the guidance using long-term industrial data
(Gkika et al., 2022)	Cosmetic-wastewater treatment technologies	Reviewed physicochemical, biological, and advanced treatments	Did not quantify full-scale life-cycle impacts	Quantifies environmental impacts of an operational cosmetic-industry WWTP
(Madan et al., 2022)	MBBR technology and performance	Reviewed MBBR design, applications, and operational variables	Focused on technical performance rather than environmental impacts	Links MBBR operation with life-cycle impact categories
(di Biase et al., 2019)	Municipal MBBR applications	Reviewed process performance and municipal applications	Limited industrial and chemical-hotspot analysis	Examines chemical-intensive industrial wastewater
(Singh et al., 2018)	Full-scale MBBR sustainability	Integrated technical, economic, hygiene, and life-cycle indicators	Different wastewater characteristics and geographical context	Evaluates soap/cosmetic wastewater using Indonesian operational data
(Yang et al., 2020)	Comparison of CAS, MBR, and MBBR	Examined technical, economic, and environmental trade-offs	Focused on textile wastewater	Evaluates a full-scale soap/cosmetic facility and chemical-specific hotspots

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(Zebua & Manik, 2025)	LCA of a physicochemical WWTP at a lead-acid battery manufacturing facility in Indonesia	Identified NaOH consumption and electricity as the dominant environmental hotspots, contributing 51.3% and 47.9% of impact respectively, through Sankey-diagram contribution analysis	Background processes modelled using a database (Agribalyse) developed for agri-food systems rather than industrial chemical and electricity inputs, limiting the representativeness of background data	Evaluates a biologically based treatment technology (MBBR) absent from this comparator study; applies monthly time-resolved inventory data with descriptive statistics
Present study	LCA of an MBBR-based soap/cosmetic WWTP	Integrates 36-month inventory, ReCiPe 2016, hotspot analysis, scenarios, and uncertainty	Limited by cradle-to-gate scope and background-data representativeness	Produces site-specific evidence and operational recommendations

METHOD
Research Framework

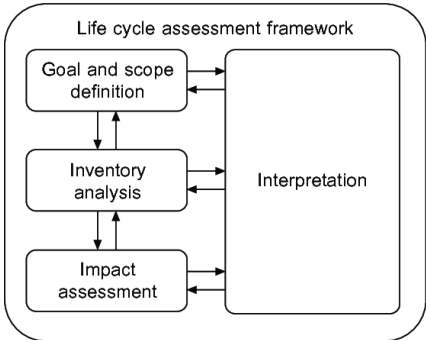


Figure 1. Research Framework of LCA

This study applies a quantitative Life Cycle Assessment (LCA) to evaluate the environmental impacts of a wastewater treatment plant (WWTP) serving a soap and cosmetic manufacturing facility. The assessment follows ISO 14040 and ISO 14044 and is implemented in OpenLCA (Finkbeiner, 2014). The system boundary is defined as cradle-to-gate for the foreground treatment system (from influent entry to treated effluent discharge and sludge), with cradle-to-gate background data for purchased electricity and chemicals.

Data Collection & Modelling

Operational data were collected from plant records over 36 months, from January 2023 until December 2025. Monthly data were compiled, validated, and used as Life Cycle Inventory (LCI) inputs. Primary data included:

Table 3.1 Data Collected Parameters

Category	Parameters
Volumetric	Influent volume, effluent volume
Energy	Electricity consumption (total and per unit process)
Chemical input	PAC, anionic/cationic polymer, NaOH, antifoam, nutrients, lubricants
Water quality	COD (influent/effluent), NH ₃ -N (influent/effluent)
Output	Sludge production, used lubricants

Electricity consumption data for pumps, blowers, mixers, compressors, motors, and sludge-handling equipment were disaggregated by treatment unit. Descriptive statistics were used to summarize operational parameters and characterize variability over the study period. The functional unit was defined as 1,000 m³ of wastewater treated. All monthly inventory flows were normalized to this unit to ensure comparability across inputs and outputs. This normalization was applied consistently to all input flows (electricity, chemicals) and output flows (sludge, effluent, emissions), yielding 36 normalized data points per parameter for subsequent statistical and uncertainty analysis.

Life Cycle Assessment Analysis

Life Cycle Assessment (LCA) was applied to evaluate the environmental impacts of WWTP operation, following ISO 14040 and ISO 14044. The four phases, Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation, were implemented to identify environmental hotspots and improvement opportunities (Rebello *et al.*, 2021).

Goal and Scope Definition

The goal was to quantify environmental impacts from WWTP operations and identify the processes contributing most significantly, to support performance improvement and sustainable wastewater management. The functional unit was defined as 1,000 m³ of wastewater treated; all inventory data were normalized to this unit.

A cradle-to-gate system boundary was applied, covering all treatment stages from influent intake to treated effluent discharge and sludge stabilization. The system included the Equalization Tank, DAF, MBBR, Drum Filter, Sludge Holding Tank, Centrifuge Decanter, and Greenhouse Sludge Drying System. Inputs comprised electricity, chemicals, and lubricants; outputs included treated effluent, sludge, used lubricant, and gaseous emissions. Downstream activities such as final sludge disposal and wastewater reuse were excluded (Kartikasari & Santoso, 2023).

Inventory Analysis

The LCI phase involved collecting and quantifying all relevant inputs and outputs for WWTP operation. Primary operational data were obtained from plant records over 36 months. Inventory flows included influent and effluent volumes, electricity consumption, chemical consumption (PAC, anionic and cationic polymers, NaOH, nutrients, antifoam), lubricant usage, sludge generation, and greenhouse gas emissions. Mass balance calculations were used to quantify material flows across treatment units (Rashid *et al.*, 2023a).

Impact Assessment

LCIA was performed in openLCA 3.2 using the ecoinvent database and the ReCiPe 2016 midpoint method. Five impact categories were selected for detailed analysis:

Table 3.2 Selected Midpoint Impact Categories

Impact category	Unit
Terrestrial ecotoxicity	kg 1,4-DCB
Fossil resource scarcity	kg oil eq
Global warming	kg CO ₂ eq
Human non-carcinogenic toxicity	kg 1,4-DCB

RESULTS AND DISCUSSION

Wastewater Treatment at a Soap and Cosmetic Industry (PT X)

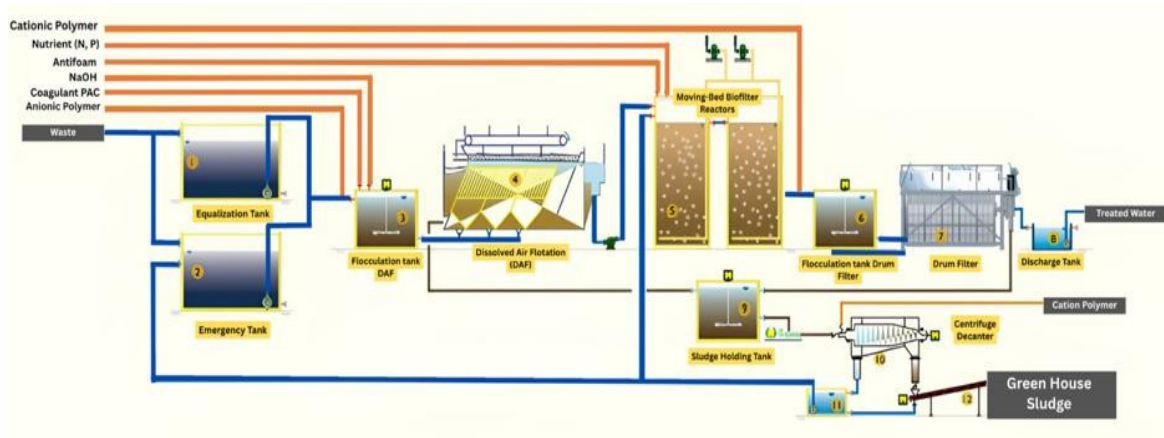


Figure 2. Flow of WWTP Process at PT X

Wastewater from PT X's soap and cosmetics plant is dominated by surfactants (mean 57 mg/L) from detergents, CIP cleaning, and production activities, together with substantial oils and greases derived from vegetable oils, fatty acids, and other lipid-based raw materials. This results in high organic loading, with average BOD and COD of 1,746 mg/L and 7,038 mg/L, respectively, while influent pH varies between 3 and 7 due to acidic formulation ingredients such as fatty acids.

Goal

The LCA was performed to pinpoint environmental hotspots throughout the WWTP's operational chain, from influent equalization to final effluent discharge and sludge handling. Given the plant's reliance on diverse mechanical and chemical processes, each unit contributes unequally to overall environmental pressure. Major impacts stem from chemical use, MBBR aeration, and energy-intensive equipment such as blowers, pumps, compressors, decanters, and the sludge-turning robot. The assessment seeks to locate the largest and to identify units where targeted measures would be most effective. Ultimately, the goal is to ensure that the WWTP not only meets effluent compliance but also reduces its footprint in terms of energy use, chemical consumption, and emissions.

Scope

The LCA scope encompasses all WWTP operational stages from influent intake to final effluent discharge and sludge handling, covering the Equalization Tank, DAF, MBBR, Drum Filter, Sludge Holding Tank, Centrifuge Decanter, and assisted greenhouse sludge drying. Inventory flows include electricity use by mixers, pumps, compressors, dosing systems, blowers, motors, and centrifuges; consumption of treatment chemicals (PAC, polymers, NaOH,

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nutrients, antifoam); and direct outputs of treated wastewater, sludge, and relevant air or water emissions. This boundary was chosen to capture operational hotspots while acknowledging that a large share of the environmental burden arises upstream from electricity and chemical production; for instance, PAC impacts include not only its dosing in DAF but also raw material extraction, manufacturing, energy use, and delivery. Foreground inventory data (electricity, chemical doses, flows, sludge generation, equipment runtime, and process outputs) were obtained from plant records, flow meters, equipment specs, laboratory results, and operator input, while upstream background data for electricity, chemicals, fuels, and supporting materials were drawn from ecoinvent v3.10, with datasets selected according to chemical composition, production technology, geographical context, and electricity mix, and documented assumptions where exact matches were unavailable.

Functional Unit

The functional unit was defined as 1,000 m³ of wastewater treated. This unit is representative of actual operations and proportional to the plant's capacity (~17,000 m³ month⁻¹), while remaining compact enough to allow detailed normalization of environmental impacts across treatment stages.

Life Cycle Inventory

The Life Cycle Inventory (LCI) involved systematic compilation and quantification of all relevant input and output flows within the defined system boundaries. A Linked Flow diagram was developed to represent connections between material, energy, chemical, recycle, emission, and product flows across treatment units, providing the basis for assigning each flow to the corresponding process and background dataset.

Inventory Collection

Mass balance analysis was conducted to ensure consistency of material flows and support a robust Life Cycle Inventory (LCI) for the WWTP. Based on monthly operational data, total input amounted to 4,442,561.82 kg month⁻¹, dominated by influent wastewater (4,022,685.55 kg month⁻¹) and supplemented by treatment chemicals (PAC, anionic and cationic polymers, NaOH, antifoam, nutrients, and lubricants). The LCI was compiled from 36 months of plant records, covering influent and effluent flows, chemical and lubricant use, sludge generation, and direct emissions.

Table 4.1 Mass Balance of WWTP PT X (Functional Unit 1,000 m³)

No	Input	kg/month	No	Output	kg/month
1	Influent	1,002,073.66	1	Effluent	799,612.28
2	PAC	4,260.60	2	Sludge to transport	227,629.74
3	Anion	2,215.36	3	Used lubricants	0.15
4	NaOH	14,661.34	4	N2O Emission	3.69
5	Antifoam	9,914.89	5	CH4 Emission	73.29
6	Nutrient	6,701.95	6	CO2 Emission	13,435.88
7	Cationic	4,320.66	7	Others Losses (Evaporated, dll)	3,393.90
8	Lubricants	0.47			
Total		1,044,148.93	Total		1,044,148.93

Monthly electricity consumption across all unit processes within the WWTP. The MBBR aeration blower and the EQ tank pump were identified as the largest electricity consumers, each accounting for 371.8 kWh/month, followed by the Centrifuge Decanter's primary motor (287.1 kWh/month) and the DAF transfer pump (301.5 kWh/month). Collectively, these four equipment items contributed to more than 85% of the WWTP's total electricity consumption, which amounted to 1546.2 kWh/month.

Life Cycle Impact Assesment (LCIA) Result
LCIA Result

Environmental impacts of WWTP operation were assessed using the ReCiPe 2016 Midpoint (H) method. Results for the functional unit are summarized. Because each impact category uses a different reference substance and unit, numerical values cannot be compared directly; instead, contribution analysis was used to identify the processes and inventory flows driving impacts within each category.

Table 4.2 WWTP Impact Category Result

Impact category	Unit	Result
Terrestrial ecotoxicity	kg 1,4-DCB	511,267.9
Human non-carcinogenic toxicity	kg 1,4-DCB	203,723.9
Global warming	kg CO ₂ eq	216,928.1
Fossil resource scarcity	kg oil eq	60,277.8
Freshwater ecotoxicity	kg 1,4-DCB	4,730.3

Interpretation

Eighteen midpoint impact categories were generated; five were selected for detailed interpretation based on their relevance to WWTP operations: Terrestrial Ecotoxicity, Human Non-Carcinogenic Toxicity, Global Warming, Fossil Resource Scarcity, and Freshwater Ecotoxicity. These categories reflect key environmental aspects of the plant, including greenhouse gas emissions, chemical consumption, energy use, sludge generation, and potential effects on human health and ecosystems.



Figure 3. Sankey Diagram of Terrestrial Ecotoxicity

Terrestrial Ecotoxicity (511,267.9 kg 1,4-DCB eq) was the largest impact, driven mainly by intensive use of treatment chemicals (PAC, NaOH, polymers) and sludge containing residual contaminants. Upstream chemical production contributes substantially to emissions affecting soil organisms and terrestrial ecosystems, underscoring the need for chemical optimization and improved sludge management.



Figure 4. Sankey Diagram of Human Non-Carcinogenic Toxicity

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Human Non-Carcinogenic Toxicity (203,723.9 kg 1,4-DCB eq) ranked second, primarily associated with upstream emissions from chemical manufacturing and electricity generation. Resource-intensive production of PAC, NaOH, and polymers releases substances with potential non-carcinogenic effects on human health.

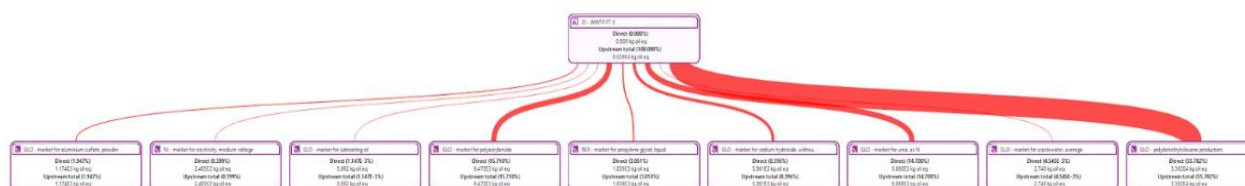


Figure 5. Sankey Diagram of Global Warming

Global Warming (216,928.1 kg CO₂ eq) was largely influenced by electricity consumption for continuous aeration in the MBBR and direct greenhouse gas emissions from biological treatment. Energy use and biological processes are thus the main drivers of climate impacts.



Figure 6. Sankey Diagram of Fossil Resource Scarcity

Fossil Resource Scarcity (60,277.8 kg oil eq) reflects the plant's dependence on non-renewable resources, mainly through electricity consumption and upstream chemical production, both heavily reliant on fossil fuels. This indicates that supporting activities, rather than the treatment process alone, dominate resource-related burdens.



Figure 7. Sankey Diagram of Freshwater Ecotoxicity

Freshwater Ecotoxicity (4,730.3 kg 1,4-DCB eq), while lower than terrestrial ecotoxicity, remains relevant due to its direct link to wastewater treatment and effluent management. Impacts arise from chemical additives and potential release of residual contaminants to receiving waters, posing risks to aquatic organisms.

CONCLUSION

The Life Cycle Assessment (LCA) of the MBBR-based WWTP at PT X shows that the largest environmental burdens do not stem from the biological treatment process itself, but from supporting activities particularly chemical consumption and electricity use. Using the ReCiPe 2016 Midpoint (H) method for a functional unit of 1,000 m³ of treated wastewater, the five most relevant impact categories were Terrestrial Ecotoxicity (511,267.9 kg 1,4-DCB eq), Human Non-Carcinogenic Toxicity (203,723.9 kg 1,4-DCB eq), Global Warming (216,928.1 kg CO₂ eq), Fossil Resource Scarcity (60,277.8 kg oil eq), and Freshwater Ecotoxicity (4,730.3 kg 1,4-DCB eq). Terrestrial Ecotoxicity and Human Non-Carcinogenic Toxicity, the two largest impacts, are mainly driven by upstream production of treatment chemicals (PAC, NaOH, polymers) and residual contaminants in the sludge. Global Warming, meanwhile, is primarily driven by electricity consumption for continuous MBBR aeration and direct greenhouse gas emissions from the biological process, while Fossil Resource Scarcity reflects the plant's dependence on electricity and chemicals derived from fossil-based resources. Freshwater Ecotoxicity, though smaller in magnitude, remains relevant given its direct link to the potential release of contaminants into receiving water bodies. These findings confirm that the WWTP's environmental hotspots are concentrated in two main areas: (1) the highest electricity-

consuming units — the MBBR aeration blower, the EQ tank pump, the centrifuge decanter's primary motor, and the DAF transfer pump, which together account for more than 85% of the WWTP's total electricity consumption; and (2) the use of treatment chemicals (PAC, NaOH, polymers, antifoam) and their upstream production chains. Consequently, efforts to reduce the WWTP's environmental impact would be most effective when directed at chemical dose optimization, energy efficiency improvements for aeration and pumping equipment, and improved sludge management rather than at improving biological treatment performance alone. These results provide a quantitative basis for prioritizing improvement scenarios aimed at reducing electricity consumption and optimizing chemical use at the PT X WWTP.

REFERENCES

- Andreottola, G., Foladori, P., Ragazzi, M., & Villa, R. (2002). Dairy wastewater treatment in a moving bed biofilm reactor. *Water Science and Technology*, 45(12), 321–328. <https://doi.org/10.2166/wst.2002.0441>
- Bogacki, J. P., Marcinowski, P., Naumczyk, J., & Wiliński, P. (2017). Cosmetic wastewater treatment using dissolved air flotation. *Archives of Environmental Protection*, 43(2), 65–73. <https://doi.org/10.1515/aep-2017-0018>
- Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A., & Short, M. D. (2020). The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. *Water Research*, 184, 116058. <https://doi.org/10.1016/j.watres.2020.116058>
- di Biase, A., Kowalski, M. S., Devlin, T. R., & Oleszkiewicz, J. A. (2019). Moving bed biofilm reactor technology in municipal wastewater treatment: A review. *Journal of Environmental Management*, 247, 849–866. <https://doi.org/10.1016/j.jenvman.2019.06.053>
- Dlangamandla, C., Ntwampe, S. K. O., Basitere, M., Chidi, B. S., & Okeleye, B. I. (2023). Biodefoamer-Supported Activated Sludge System for the Treatment of Poultry Slaughterhouse Wastewater. *Applied Sciences*, 13(16), 9225. <https://doi.org/10.3390/app13169225>
- Finkbeiner, M. (2014). The International Standards as the Constitution of Life Cycle Assessment: The ISO 14040 Series and its Offspring. In W. Klöpffer (Ed.), *Background and Future Prospects in Life Cycle Assessment* (pp. 85–106). Springer Netherlands. https://doi.org/10.1007/978-94-017-8697-3_3
- Gkika, D. A., Mitropoulos, A. C., Lambropoulou, D. A., Kalavrouziotis, I. K., & Kyzas, G. Z. (2022). Cosmetic wastewater treatment technologies: a review. *Environmental Science and Pollution Research*, 29(50), 75223–75247. <https://doi.org/10.1007/s11356-022-23045-1>
- International Organization for Standardization. (2006). *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*. ISO.
- Kartikasari, I. B., & Santoso, R. I. B. (2023). Impact of Drinking Water Treatment Process Using Life Cycle Assessment (LCA) to Minimize Environmental Impact Risk. *Journal of Social Research*, 2(9), 3218–3230. <https://doi.org/10.55324/josr.v2i9.1294>
- Laouane, H., El Joumri, L., Halhaly, A., Arid, Y., Labjar, N., & El Hajjaji, S. (2026). Life-Cycle Assessment of Wastewater Treatment: Enhancing Sustainability Through Process Optimization. *Sustainability*, 18(2), 605. <https://doi.org/10.3390/su18020605>
- Larsen, H. F. (2017). LCA of wastewater treatment. In *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_34
- Madan, S., Madan, R., & Hussain, A. (2022). Advancement in biological wastewater treatment using hybrid moving bed biofilm reactor (MBBR): a review. *Applied Water Science*, 12(6), 141. <https://doi.org/10.1007/s13201-022-01662-y>
- Ødegaard, H. (2006). Innovations in wastewater treatment: –the moving bed biofilm process. *Water Science and Technology*, 53(9), 17–33. <https://doi.org/10.2166/wst.2006.284>

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- Rashid, S. S., Harun, S. N., Hanafiah, M. M., Razman, K. K., Liu, Y.-Q., & Tholibon, D. A. (2023a). Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview. *Processes*, 11(1), 208. <https://doi.org/10.3390/pr11010208>
- Rashid, S. S., Harun, S. N., Hanafiah, M. M., Razman, K. K., Liu, Y. Q., & Tholibon, D. A. (2023b). Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview. In *Processes* (Vol. 11). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/pr11010208>
- Rebello, T. A., Roque, R. P., Gonçalves, R. F., Calmon, J. L., & Queiroz, L. M. (2021). Life cycle assessment of urban wastewater treatment plants: A critical analysis and guideline proposal. *Water Science and Technology*, 83, 501–514. <https://doi.org/10.2166/wst.2020.608>
- Singh, A., Kamble, S. J., Sawant, M., Chakravarthy, Y., Kazmi, A., Aymerich, E., Starkl, M., Ghangrekar, M., & Philip, L. (2018). Technical, hygiene, economic, and life cycle assessment of full-scale moving bed biofilm reactors for wastewater treatment in India. *Environmental Science and Pollution Research*, 25(3), 2552–2569. <https://doi.org/10.1007/s11356-017-0605-y>
- Tran, D., & Weidhaas, J. (2024). Life Cycle Assessment of Industrial Wastewater Treatment Trains. *Advanced Sustainable Systems*, 8. <https://doi.org/10.1002/adsu.202400246>
- Yang, X., López-Grimau, V., Vilaseca, M., & Crespi, M. (2020). Treatment of Textile Wastewater by CAS, MBR, and MBBR: A Comparative Study from Technical, Economic, and Environmental Perspectives. *Water*, 12(5), 1306. <https://doi.org/10.3390/w12051306>
- Zebua, S. N., & Manik, Y. B. S. (2025). Life Cycle Assessment (LCA) of the Wastewater Treatment Plant of a Lead-Acid Battery Manufacturing Industry. *JST (Jurnal Sains Dan Teknologi)*, 14(3), 577–589. <https://doi.org/10.23887/jst-undiksha.v14i3.102724>