Terbit *online* pada laman web jurnal :http://jurnaldampak.ft.unand.ac.id/

Dampak: Jurnal Teknik Lingkungan Universitas Andalas

| ISSN (Print) 1829-6084 |ISSN (Online) 2597-5129|

Artikel Penelitian

Technical Evaluation and Improvement Strategies for Banjardowo Leachate Treatment Plant, Jombang District

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Diterima: 6 Mei 2026 Diperbaiki: 13 Juni 2026 Disetujui: 26 Juli 2026

ABSTRACT

Banjardowo Landfill in Jombang Regency operates a Leachate Treatment Plant (LTP) with a treatment capacity of 300 m³/day to minimize the environmental impacts of landfill leachate. However, monitoring results in 2025 indicated that Total Nitrogen concentrations in the treated effluent exceeded the discharge standard, indicating suboptimal treatment performance. This study aimed to evaluate the technical performance of the LTP and develop improvement strategies to support sustainable leachate management. A descriptive quantitative approach was employed through field observations, measurements of treatment units, technical document reviews, stakeholder questionnaires, and leachate quality analyses during the dry and rainy seasons. Technical performance was assessed by comparing existing unit conditions with design criteria and evaluating pollutant removal efficiencies, while SWOT analysis was used to formulate improvement strategies. The results showed that the LTP performance was constrained by excessive hydraulic retention time in the Leachate Storage Pond, insufficient biofilter media volume, low DO and MLSS concentrations, and unstable nitrogen removal. During the dry season, removal efficiencies for BOD, COD, TSS, Total Nitrogen, Cd, and Hg were 59.2%, 58.4%, 98.2%, 17.2%, 89.7%, and 95.5%, respectively. In the rainy season, removal efficiencies increased to 71.0%, 86.1%, 98.7%, and 99.6% for BOD, COD, TSS, and Total Nitrogen, while Cd and Hg complied with effluent standards. The SWOT analysis places LTP in Quadrant III with coordinates (-0.28; 0.88), indicating a turn-around strategy focused on optimizing the aeration and nitrification–denitrification processes, rehabilitating the constructed wetland, and strengthening operational monitoring.

Keyword: Leachate Treatment Plant, Technical Aspects, SWOT, Banjardowo Landfill.

1. INTRODUCTION

Municipal solid waste management remains a major environmental challenge in developing countries, including Indonesia. Landfilling continues to be the predominant disposal method, but the decomposition of waste and infiltration of rainwater generate leachate containing high concentrations of organic matter, nutrients, heavy metals, and pathogenic microorganisms. If inadequately managed, leachate may contaminate soil and groundwater, posing significant environmental and public health risks (Kjeldsen et al., 2002; Renou et al., 2008). Therefore, an effective leachate collection and treatment system is essential to ensure environmentally sustainable landfill operation.

Banjardowo Landfill is the only municipal landfill serving Jombang Regency, East Java, Indonesia. Since 2023, the landfill has been upgraded through the Emission Reduction in Cities–Solid Waste Management (ERIC-SWM) Program, including the development of a 4.45-ha sanitary landfill area and the construction of a 300 m³/day Leachate Treatment Plant (LTP). The LTP comprises a leachate storage pond, anaerobic treatment units, a membrane bioreactor (MBR) integrating denitrification and nitrification processes with ultrafiltration (UF), and a constructed wetland as the final polishing unit (Aulivia W, 2023). Despite these improvements, routine monitoring conducted by the Jombang Environmental Agency revealed that Total Nitrogen (TN) concentrations in the final effluent of the Banjardowo Landfill Leachate Treatment Plant (LTP) remained above the discharge standard (60 mg/L) specified in the Indonesian regulation on *Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 59 Tahun 2016*.

Monitoring data obtained from the Jombang Environmental Agency showed that TN concentrations between January and March 2025 were 120 mg/L, 94 mg/L, and 123 mg/L, respectively. These findings indicate that the biological nitrogen removal process, particularly within the membrane bioreactor (MBR) system, may not yet

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be operating at its optimum performance. Therefore, a comprehensive technical evaluation is required to identify operational constraints, improve treatment efficiency, and ensure long-term compliance with environmental discharge standards.

Based on these conditions, this study aimed to evaluate the technical performance of the Leachate Treatment Plant (LTP) at Banjardowo Landfill and to formulate improvement strategies for sustainable and effective leachate management. The technical evaluation was conducted by comparing the operational performance of each treatment unit with established design criteria and assessing pollutant removal efficiencies under dry and rainy season conditions. Furthermore, a quantitative SWOT analysis was employed to identify the key internal and external factors influencing LTP performance and to develop appropriate improvement strategies for enhancing treatment efficiency, optimizing operational performance, and ensuring long-term compliance with environmental regulations (Gürel & Tat, 2017). The findings are expected to provide both scientific evidence and practical recommendations for local governments and landfill operators to improve the sustainability and effectiveness of leachate management systems.

2. METHOD

This study was conducted at the LTP of Banjardowo Landfill, Jombang Regency, East Java, Indonesia. Data collection and leachate sampling were carried out during the dry season (September 2025) and rainy season (January 2026) to evaluate treatment performance under different seasonal conditions.

2.1. Data Collection Techniques

Data were collected through field observations, technical measurements, leachate quality analyses, and stakeholder questionnaires. Field observations and measurements were conducted to obtain operational and design data for the treatment units, including the Leachate Storage Pond, Anaerobic Pond, Anaerobic Biofilter, Denitrification Unit, Nitrification Units 1 and 2, Ultrafiltration (UF), and Constructed Wetland that shown at the Figure 1. Leachate samples were collected during the dry and rainy seasons from 9 sampling points, consisting of one influent point at the inlet of the LTP and 8 outlet points representing each treatment unit. The nine sampling points were selected to evaluate pollutant concentration changes throughout the treatment process, determine the removal efficiency of individual treatment units, and assess the overall performance of the LTP. Parameters analyzed such as pH, BOD, COD, TSS, Total Nitrogen, Cd, and Hg. Additional parameters, including temperature, DO, MLSS, and ammonia (NH_3-N), were measured in the denitrification and nitrification units to evaluate biological treatment performance. Treatment effectiveness was assessed based on pollutant removal efficiencies and compliance of the final effluent with applicable leachate quality standards. Questionnaire surveys involving relevant stakeholders were conducted to identify internal and external factors affecting LTP performance and to support the SWOT analysis.

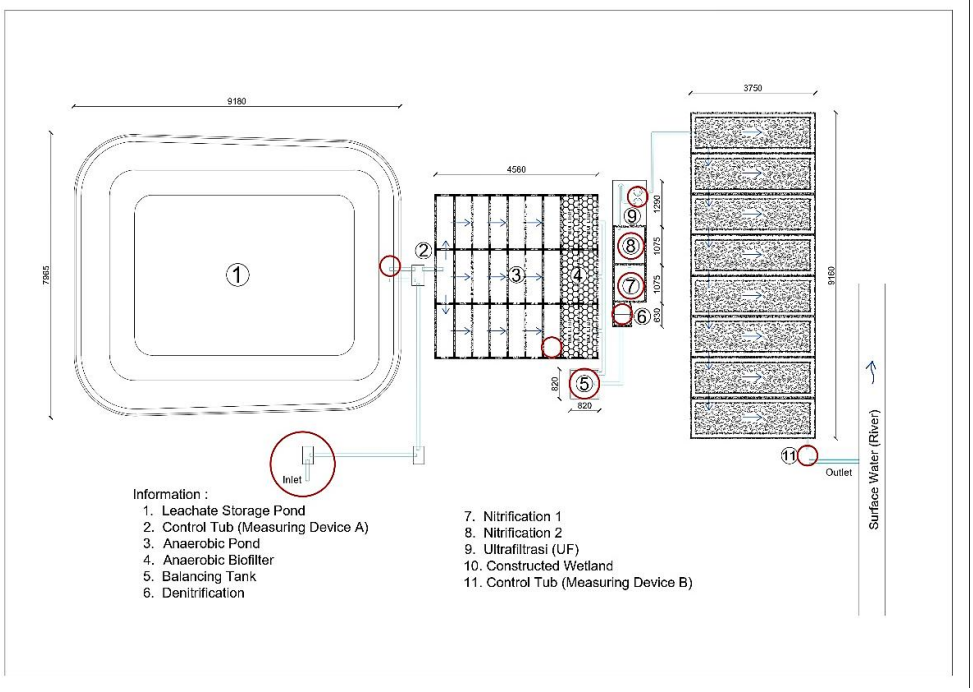


Figure 1. Leachate Sampling Points

2.2. Data Analysis Techniques

2.2.1. Comparative Analysis Based on Design Criteria

The technical performance of each treatment unit was evaluated by comparing existing operational conditions with established design criteria obtained from relevant literature and engineering guidelines. Key parameters assessed included HRT, dissolved oxygen (DO), mixed liquor suspended solids (MLSS), loading rates, and unit-specific design characteristics. This analysis was used to assess the conformity of the LTP operation with recommended design standards and to identify factors limiting treatment performance.

2.2.2. Removal Efficiency Analysis

Removal efficiency analysis was conducted to evaluate the performance of the LTP in reducing pollutant concentrations. Removal efficiency is widely used as a key indicator for assessing the effectiveness of landfill leachate treatment systems. The analyzed parameters included pH, BOD, COD, TSS, TN, Cd, and Hg. Laboratory analyses were performed in accordance with standardized analytical methods, namely SNI 6989.11:2019 for pH, SNI 6989.72:2009 for BOD, SNI 6989.2:2019 for COD, SNI 6989.3:2019 for TSS, JIS K 0102 Section 45.2:2008 for TN, Standard Methods for the Examination of Water and Wastewater (APHA), 24th Edition, Method 3113 B (2023) for Cd, and QI/LKA/116 (ICP) for Hg analysis. Removal efficiencies were calculated for both individual treatment units and the overall treatment system to determine the contribution of each treatment stage to pollutant reduction. The performance of the LTP was further evaluated by comparing the final effluent quality with the leachate discharge standards specified in the *Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 59 Tahun 2016.* Removal efficiency (%) were calculated using Eqs. (1) (Asaithambi et al., 2018):

$$Removal\ Efficiency\ (\%) = \frac{C_{in} - C_{out}}{C_{in}} \text{ x } 100\% \qquad (1)$$

Explanation:
C_{in} = Influent pollutant concentration entering the treatment unit (mg/L)
C_{in} = Effluent pollutant concentration leaving the treatment unit (mg/L)

2.2.3. Quantitative SWOT Analysis using IFAS–EFAS Matrices

Quantitative SWOT analysis using the Internal Factor Analysis Summary (IFAS) and External Factor Analysis Summary (EFAS) matrices was employed to assess internal strengths and weaknesses as well as external opportunities and threats affecting LTP performance (Gürel & Tat, 2017). Factors identified from technical evaluation results and stakeholder assessments were assigned weights and ratings to generate weighted scores, which were used to determine the strategic position of the LTP and formulate improvement strategies. Ratings were determined from the average scores assigned by respondents based on the actual conditions of each internal and external factor. Weights were assigned according to the relative importance of each factor as assessed by experts and professionals experienced in leachate treatment plant management. The weighted score for each factor was calculated by multiplying the rating by its corresponding weight. Thus, the score is calculated as the rating multiplied by the weight.

3. RESULTS AND DISCUSSION

This study focuses on evaluating the performance of the technical aspects of the LTP at the Banjardowo Landfill through analysis of design criteria and sampling test results. Furthermore, this study aims to provide recommendations for improving the leachate management system to be more effective and sustainable from a technical aspect.

3.1. Process-Based Technical Evaluation

3.1.1. Engineering Assessment Design of LTP Unit Processes

The engineering assessment revealed varying levels of compliance among the treatment units. While several units operated within the recommended design ranges, others exhibited deviations in key operational parameters, indicating potential constraints that could reduce overall treatment efficiency. Detailed comparison between the existing operating conditions and design criteria for each treatment unit is presented in **Table 1.**

Table 1. Technical Evaluation of the Leachate Treatment Plant

Unit	Design Criteria	Study	Evaluation Result
Leachate Storage Pond (LSP)	HRT (4 – 10 days) Freeboard (min 0.9 meter)	(Indiana Departement of Environmental Management, 2000)	HRT of 38 days exceeded the design criteria of 4–10 days.
Anaerobic Pond	HRT (5 – 50 days) Height (2.5 – 5 m)	(Spellman & Drinan, 2014) (World Health	HRT of 27 days met the design criteria. Height of 5 meter met the design criteria. and BOD loading rate

Unit	Design Criteria	Study	Evaluation Result
	BOD loading rate (0.3 – 0.4 kg/m^3/day)	Organization, 1987) (Lin & Brown, 1980)	of 0.008 kg/m^3/day was below the standard.
Anaerobic Biofilter	HRT (1 – 7 days) BOD load per media volume (0.4 – 4.7 kg/m^3/day) BOD load per media surface area (5 – 30 gBOD/m^2.day) Media Volume to Tank Ratio (50 – 70%)	(Metcalf & Eddy, 2014) (Said, 2017)	HRT of 7.8 days exceeded the design criteria. BOD load per media volume of 1.25 kg/m^3/hari met the design criteria. BOD load per media surface area (8.35 gBOD/m^2.day) met the design criteria. and Media Volume to Tank Ratio (32%) was too small.
Denitrification Unit	HRT (< 1 days) MLSS (1,500 – 5,000 mg/L)	(Chandrasekeran et al., 2007) (Schneider et al., 2023) (Kuznets, 2019)	HRT of 0.87 days met the design criteria. MLSS concentration (750 -1,590 mg/L) was too low.
Nitrification 1	HRT (12 hour) DO (> 2 mg/L) Amonia loading rate (0.121 - 0.144 kg NH_3-N/m^3/day) MLSS (1,500 – 2,500 mg/L)	(Liu & Wang, 2016) (Awolusi et al., 2016) (Côté et al., 2015)	HRT of 65.79 hour exceeded the design criteria. DO (0.53–0.65 mg/L) was too low. Amonia loading rate (0.228 kg NH_3-N/m^3/day) exceeded the design criteria. MLSS (680 – 880 mg/L) was too low.
Nitrification 2	HRT (12 hour) DO (> 2 mg/L) Amonia loading rate (0.121 - 0.144 kg NH_3-N/m^3/day) MLSS (1,500 – 2,500 mg/L)	(Liu & Wang, 2016) (Awolusi et al., 2016) (Côté et al., 2015)	HRT of 65.79 hour exceeded the design criteria. DO (0.5–0.61 mg/L) was too low. Amonia loading rate (0.198 kg NH_3-N/m^3/day) exceeded the design criteria. MLSS (1,220 – 1,290 mg/L) was too low.
Ultrafiltration (UF)	Flux rate (20 – 100 L/m^2/h (LMH))	(Metcalf & Eddy, 2014)	Flux of 76.59 LMH was still within the design range.
Constructed Wetland	HRT (3 – 7 days) Depth (0.8 – 1.5 m) BOD loading rate (2 – 20 g BOD/m^2/day)	(Metcalf & Eddy, 2014) (Headley & Tanner, 2006)	HRT of 8.01 days exceeded the design criteria. Depth 1.38 meter and BOD loading rate 14.98 g BOD/m^2/day met the design criteria.

In the technical evaluation of the Banjardowo Landfill's LTP, the treatment system consists of pre-treatment, secondary treatment, and tertiary treatment stages aimed at reducing the pollutant load before the effluent is discharged into water bodies. In pre-treatment, the Leachate Storage Pond (LSP) unit serves as an initial reservoir and balances fluctuations in leachate discharge and quality. However, the evaluation results indicated a HRT of 38 days, exceeding the design criteria of 4–10 days, this indicates suboptimal unit performance (Indiana Departement of Environmental Management, 2000). This extended retention is caused by reduced actual inflow due to landfill aging, as the progressive depletion of biodegradable organic matter decreases leachate generation over time (Tchobanoglous et al., 2014). Although deviating from the design standard, this condition does not impair the equalization function; rather, the excess capacity improves sedimentation and pollutant homogenization, and can therefore be regarded as an operational advantage under the prevailing low-flow regime.

In the secondary treatment stage, evaluations were conducted on the Anaerobic Pond, Anaerobic Biofilter, Denitrification Unit, Nitrification Units 1st and 2nd. The anaerobic pond met the HRT (27 days) and depth (5 m) criteria, but the BOD loading rate was critically low at 0.008 kg/m³/day, far below the design standard of 0.05–0.2 kg/m³/day (Lin & Brown, 1980; World Health Organization, 1987). This underloaded condition is attributable to the aging landfill producing leachate with substantially lower BOD concentrations than the design value, combined with reduced actual inflow. Below the minimum substrate threshold, methanogens and acetogens cannot maintain metabolic activity, thereby suppressing organic matter degradation and increasing vulnerability to hydraulic disturbances (Rittmann & McCarty, 2001; Tchobanoglous et al., 2014). Optimizing

sludge management and improving hydraulic flow distribution are recommended to enhance treatment stability and overall reactor performance.

The anaerobic biofilter exhibited suboptimal performance due to an HRT slightly exceeding the recommended range and a media filling ratio of only 32%, considerably below the design criterion of 50–70% (Said, 2017; Tchobanoglous et al., 2014). The elevated HRT resulted from reduced actual inflow through a fixed reactor volume, whereas the low media filling ratio was primarily attributed to the original reactor design, which provided a media volume substantially lower than the recommended criterion. In addition, several carrier media had deteriorated during long-term operation, causing them to float and be removed during routine maintenance, thereby further reducing the effective media volume. Since the available media surface area directly determines biofilm attachment and biomass development, the limited effective media volume restricts microbial growth and consequently reduces the reactor capacity for organic matter degradation and nitrogen removal, regardless of hydraulic conditions. Therefore, increasing the media filling ratio to 50–70% by installing additional carrier media and replacing damaged media with improving hydraulic flow distribution, is recommended to enhance reactor performance.

Furthermore, The denitrification unit met the HRT criterion (0.87 days), but MLSS was low at 750–1,590 mg/L, below the design range of 1,500–5,000 mg/L (Chandrasekeran et al., 2007; Kuznets, 2019). The low MLSS is primarily caused by the deficient biomass in the upstream nitrification units, whose internal recycle limits the active biomass delivered to the denitrification zone; additionally, the low BOD:N ratio of the aging leachate provides insufficient carbon for denitrifying heterotrophs (Aimia & JAR, 2023). Strengthening the internal recycle flow and ensuring adequate carbon availability are recommended to improve nitrogen removal performance.

Both Nitrification units 1 and 2 showed similar operational deficiencies, excessive HRT (65.79 h), critically low DO (0.50–0.65 mg/L), insufficient MLSS (680–1,290 mg/L), and ammonia loading rates (0.198–0.228 kg NH_3-N/m^3/day) exceeding the design range (Gerardi, 2002; Tchobanoglous et al., 2014). These conditions indicate that the biological treatment process was not operating under optimum design conditions. he low DO was primarily caused by malfunctioning aerators that supplied insufficient oxygen to the reactors. Since nitrifying bacteria are obligate aerobes, DO concentrations below 2 mg/L limit oxygen availability and substantially inhibit ammonia oxidation (Fadillah & Slamet, 2023). Prolonged oxygen deficiency also suppresses microbial growth and reduces biomass retention, resulting in low MLSS concentrations because biomass growth cannot compensate for biomass loss through sludge wasting and washout. Consequently, the reduced MLSS further decreases the population of nitrifying microorganisms, leading to unstable nitrification performance and lower ammonia removal efficiency. Therefore, repairing the aeration system to maintain DO at 2–4 mg/L, improving sludge retention, and optimizing internal recycle to the denitrification unit are recommended to restore biological treatment performance.

In tertiary treatment, the ultrafiltration (UF) unit operated at a membrane flux of 76.59 LMH, within the recommended range of 20–100 LMH (Metcalf & Eddy, 2014), confirming adequate membrane performance. However, the high operating flux combined with elevated TSS from the underperforming upstream biological units risks accelerating membrane fouling through cake layer formation, progressively increasing transmembrane pressure and reducing filtration efficiency (Gong et al., 2024; Palli et al., 2024). Maintaining stable upstream pretreatment, implementing routine backwashing and chemical cleaning, and monitoring transmembrane pressure are recommended to sustain long-term UF performance.

The constructed wetland satisfied the depth and BOD loading criteria, but the HRT of 8.01 days exceeded the recommended range of 3–7 days, reflecting a hydraulic loading rate lower than design due to reduced inflow from the aging landfill (Metcalf & Eddy, 2014). An HRT exceeding 7 days promotes strongly anaerobic conditions in the substrate, suppressing rhizosphere nitrification and triggering ammonification of sediment-bound organic nitrogen effectively reversing upstream treatment gains (Wang et al., 2022). In addition, limited vegetation density due to harvesting and prolonged media operation may have reduced pollutant uptake capacity and adsorption efficiency, thereby decreasing the overall treatment performance of the wetland (Kadlec & Wallace, 2009; Vymazal, 2007). Furthermore, reduced vegetation density from harvesting limits macrophyte oxygen transfer and nitrogen uptake capacity (da Silva et al., 2020). Optimizing the hydraulic loading rate, periodically harvesting vegetation, and improving upstream nitrification performance are recommended to restore treatment balance.

3.1.2. Process Efficiency Assessment of Leachate Treatment Plant (LTP)

In addition to the engineering assessment, the effectiveness of the LTP was evaluated through analysis of pollutant removal efficiencies and effluent quality under different seasonal conditions. Seasonal evaluation is important because variations in rainfall can influence leachate characteristics, hydraulic loading, and treatment performance. Therefore, laboratory analyses were conducted on samples collected during the dry season (September 2025) and rainy season (January 2026). The results of the laboratory analyses are presented in Tables 2 and 3 and serve as the basis for evaluating treatment efficiency and regulatory compliance.

Table 2. Dry Season Test Sampling Results in September 2025

Unit	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TN (mg/L)	Cd (mg/L)	Hg (mg/L)
Influent	8.7	190.4	429.6	199.5	339.5	0.003	0.0287
Leachate Storage Pond	8.4	173.7	378.4	180	206	0.001	0.0013
Anaerobic Pond	8.3	94.42	308.3	164.4	280	0.001	0.0013
Anaerobic Biofilter	8.4	112.9	231.8	252.5	338	0.001	0.0013
Denitrification	7.6	111	282.9	710	488	0.002	0.0013
Nitrification 1	7.4	127.6	275.8	846.7	555	0.002	0.0013
Nitrification 2	7.3	144.2	262.1	866.7	610.5	0.002	0.0013
Ultrafiltrasi	7.5	109.5	219.1	46.03	247	0.00031	0.0013
Constructed Wetland/Effluent	8.1	77.63	178.9	3.5	281	0.00031	0.0013
Efficiency	-	59.2%	58.4%	98.2%	17.2%	89.7%	95.5%
Quality Standards	6-9	150	300	100	60	0.1	0.005
Description	Compliant	Compliant	Compliant	Compliant	Non-compliant	Compliant	Compliant

Table 3. Rainy Season Test Sampling Results in January 2026

Unit	pH	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TN (mg/L)	Cd (mg/L)	Hg (mg/L)
Influent	8.64	403.2	2,051	407.5	3,209	0.002	0.0013
Lecheate Storage Pond	8.7	236.5	999.9	165.7	212	0.0005	0.0013
Anaerobic Pond	8.6	313.8	1,483	1,145	2,168	0.002	0.0013
Anaerobic Biofilter	8.6	362.5	1,230	328	2,040	0.002	0.0013
Denitrification	8.8	285.3	1,444	730	2,192	0.002	0.0013
Nitrification 1	8.9	265	1,346	460	1,809	0.002	0.0013
Nitrification 2	8.8	315.8	1,346	670	1,843	0.002	0.0013
Ultrafiltrasi	8.9	171.5	1,100	2.7	407	0.00031	0.0013
Constructed Wetland/Effluent	8.6	116.9	285.8	5.3	11.3	0.011	0.0013
Efficiency	-	71.0%	86.1%	98.7%	99.6%	-	0%
Quality Standards	6-9	150	300	100	60	0.1	0.005
Description	Compliant	Compliant	Compliant	Compliant	Compliant	Compliant	Compliant

Tables 2 and **3** present the water quality performance of the leachate treatment plant during the dry season in September 2025 and the rainy season in January 2026, respectively. Overall, the treatment process reduced several key pollutants from the influent to the final effluent of the constructed wetland. During the dry season, the final effluent had a pH of 8.1 and contained 77.63 mg/L BOD, 178.9 mg/L COD, 3.5 mg/L TSS, 281 mg/L TN, 0.00031 mg/L Cd, and 0.0013 mg/L Hg. The corresponding removal efficiencies were 59.2% for BOD, 58.4% for COD, 98.2% for TSS, 17.2% for TN, 89.7% for Cd, and 95.5% for Hg. All parameters met the applicable quality standards except TN, which remained above the standard limit of 60 mg/L. Compared with other studies, the BOD removal efficiency similar to the pilot-scale horizontal subsurface flow constructed wetland study, which reported that maximum BOD and COD removal efficiencies of about 60.4% and 56.7%, respectively. It's indicating that the organic matter removal performance of the present system is comparable to other constructed wetland-based leachate treatment systems (Ntountounakis et al., 2025). However, TN remained above the quality standard, with a final concentration of 281 mg/L compared to the standard limit of 60 mg/L, and the removal efficiency was only 17%, indicating that nitrogen removal is still the main limitation of the leachate treatment system in both dry and rainy seasons. It was in contrast at the rainy season, the effluent when rainy season met the standard regulation. The pH of 8.6 and contained 116.9 mg/L BOD, 285.8

mg/L COD, 5.3 mg/L TSS, 11.3 mg/L TN, 0.0011 mg/L Cd, and 0.0013 mg/L Hg. The reported rainy-season removal efficiencies were 71.0% for BOD, 86.1% for COD, 98.7% for TSS, and 99.6% for TN, while no removal was reported for Cd and Hg.

The markedly higher TN removal observed during the rainy season (99.6%) was attributed to the combined contribution of the upstream ultrafiltration (UF) unit and the polishing function of the constructed wetland. Prior to entering the wetland, the UF unit had already reduced TN concentration substantially from 1,843 mg/L to 407 mg/L, indicating that a considerable fraction of particulate and organic nitrogen had been removed in the previous treatment stage. The constructed wetland subsequently provided further nitrogen removal through coupled nitrification–denitrification, microbial assimilation, plant uptake, and adsorption processes within the rhizosphere, resulting in a final TN concentration of 11.3 mg/L (Kadlec & Wallace, 2009; Vymazal, 2007). In addition, the rainy season increased hydraulic input, producing a dilution effect that further reduced the measured TN concentration because the removal efficiency was calculated based on concentration rather than pollutant mass loading (Kjeldsen et al., 2002; Renou et al., 2008). The slightly alkaline pH (8.6–8.9) in the open wetland may also have promoted limited ammonia volatilization by increasing the fraction of unionized ammonia (NH_3), although this mechanism generally contributes less to nitrogen removal than biological processes under typical wetland operating conditions (Islam et al., 2020; Jamieson et al., 2003; Lee, 2009; Macphee et al., 2009). Therefore, the exceptionally high TN removal observed during the rainy season reflects the combined effects of efficient upstream treatment, polishing processes within the constructed wetland, and seasonal hydrological conditions, rather than the performance of the wetland alone.

3.2. Strategy Formulation for Improving LTP Efficiency and Performance

3.2.1. SWOT-Based Strategy Formulation

SWOT analysis was performed using IFAS and EFAS matrices to assess internal and external factors influencing LTP performance. Each factor was assigned a weight and rating based on its relative importance and actual condition to calculate weighted scores, which were subsequently used to determine the strategic position of the LTP and develop improvement strategies. The results of the IFAS and EFAS assessments are presented in **Tables 4** and **5**.

Table 4. IFAS Assessment

Code	Factor	Rating	Weight	Score
	Strengths			
S1	The MBR-based wastewater treatment plant (WWTP) combines biological and membrane technology (MBR + UF + Wetland) with a capacity of 300 m^3/day.	3.00	0.06	0.17
S2	Most of the wetland unit's design parameters met the design criteria (media, gravel size, BOD loading).	3.00	0.03	0.08
S3	The UF unit has high TSS and Cadmium removal efficiency.	3.14	0.04	0.13
S4	The LSP pond volume of 11.423,6 m^3 indicates that the system is geometrically capable of accommodating large amounts of leachate.	3.29	0.03	0.09
	Strengths Total		**0.34**	**1.07**
	Weaknesses			
W1	Total effluent nitrogen exceeds quality standards during the dry season (> 60 mg/L).	2.14	0.04	0.09
W2	The denitrification–nitrification unit is unstable (DO and MLSS do not meet criteria).	2.00	0.06	0.11
W3	The anaerobic biofilter is not optimal (media volume is only 32% of the reactor volume).	2.29	0.04	0.10
W4	The BOD loading rate does not meet design criteria (0.008 kg/m^3/day < 0.05 - 0.2 kg/m^3/day) which affects the performance of microorganisms in pollutant removal.	2.00	0.06	0.11
W5	Leachate recycling from the nitrification unit to support denitrification performance is not optimal because the aerator in the nitrification unit is still not functioning.	2.14	0.06	0.12
W6	Ammonia loading in the denitrification unit is too high, inhibiting the denitrification process.	2.14	0.04	0.09
W7	The wetland media has not been replaced/drained for several years, potentially causing saturation and clogging, which can reduce leachate treatment efficiency.	1.57	0.03	0.04
W8	The wetland HRT is higher than the design criteria.	2.57	0.03	0.07
W9	Failure of the aerator or recycle pump can cause the nitrification–denitrification process to fail.	1.71	0.04	0.07
W10	Fluctuations in leachate discharge and characteristics due to seasonal changes have the potential to cause shock loading and decrease the performance of the wastewater	2.00	0.04	0.08

Code	Factor	Rating	Weight	Score
	treatment plant (WTP).			
W11	Increased solids loads due to the rainy season and landfill erosion have the potential to accelerate sedimentation and clogging in wetlands.	2.29	0.04	0.10
W12	Increasing landfill age can cause leachate characteristics to become more complex and difficult to process.	1.86	0.04	0.08
W13	Risk of infrastructure damage due to aging facilities.	1.86	0.04	0.08
W14	Periodic fouling of ultrafiltration (UF) membranes increases the need for cleaning and maintenance, increasing WTP operational costs and reducing effluent quality.	2.14	0.06	0.12
	Weaknesses Total		**0.66**	**1.35**
IFAS Recapitulation Score				
Strengths				**1.07**
Weaknesses				**1.35**
Difference IFAS (S – W) = X Coordinate				**-0.28**

The IFAS analysis indicated that the internal weaknesses of the LTP outweighed its strengths, as reflected by the total strength and weakness scores of 1.07 and 1.35, respectively, resulting in an internal strategic value of −0.28. This finding suggests that the overall technical performance of the LTP is constrained primarily by operational limitations rather than supported by its existing technical advantages. Although the system incorporates advanced treatment technologies, including an integrated membrane bioreactor (MBR), ultrafiltration (UF), and constructed wetland, and the wetland unit generally complies with the recommended design criteria, these strengths have not been sufficient to compensate for the operational deficiencies identified during the technical evaluation. The most critical weaknesses include unstable biological nitrogen removal, elevated Total Nitrogen concentrations in the final effluent during the dry season, and the inadequate filling ratio of the anaerobic biofilter media.

The highest-priority technical constraint was the instability of the nitrification–denitrification process (W2), mainly attributed to malfunctioning aeration equipment that resulted in DO and MLSS concentrations below the recommended operating range. Consequently, biological nitrogen removal was impaired, leading to Total Nitrogen concentrations exceeding the regulatory limit during the dry season (W1). Furthermore, the insufficient recirculation of nitrified leachate from the nitrification unit to the denitrification tank (W5) reduced nitrate availability for denitrification, thereby limiting ammonia conversion and decreasing overall nitrogen removal efficiency (W6) (Deng et al., 2022; Zhou et al., 2023).

Another significant limitation was observed in the anaerobic biofilter, where the media occupied only 32% of the reactor volume (W3), substantially lower than the criteria design 50–70%. This condition reduced the available surface area for biofilm development, thereby limiting microbial activity and decreasing the removal efficiency of organic matter and nitrogen. In addition, the extremely low organic loading rate (0.008 kg BOD m^{-2} day^{-1}) (W4) indicates insufficient biodegradable substrate to sustain optimal microbial growth, resulting in suboptimal biological treatment performance. Operational issues were also identified in the polishing units. The constructed wetland has operated with the same filter media for several years (W7), increasing the risk of media saturation and clogging. While the excessively long hydraulic retention time (W8) suggests ineffective hydraulic distribution caused by sediment accumulation or short-circuiting. Therefore, periodic membrane fouling in ultrafiltration unit (W14) further increases maintenance requirements and operational costs and may reduce treatment reliability if not properly controlled.

In addition to these internal constraints, seasonal variations in leachate quantity and composition represent a major operational challenge. Fluctuations in hydraulic and pollutant loading may induce shock loading in the biological treatment units (W10), whereas increased suspended solids during the rainy season accelerate sediment accumulation and clogging within the constructed wetland (W11). Moreover, landfill aging (W12) is expected to increase the proportion of refractory organic compounds and ammonia in the leachate, further reducing the effectiveness of conventional biological treatment processes. These findings indicate that improving process stability, optimizing biological treatment performance, and strengthening operational maintenance should be prioritized to enhance the long-term performance of the LTP.

Table 5. EFAS Assessment

Code	Factor	Rating	Weight	Score
	Opportunities			
O1	Aerator repairs can immediately improve the nitrification process without the need for	3.57	0.17	0.60

Code	Factor	Rating	Weight	Score
	Opportunities			
	new units.			
O2	Optimizing the nitrification-denitrification recycling pathway has the potential to significantly increase total nitrogen removal.	3.14	0.13	0.39
O3	Adding biofilter media to 50–70% of the reactor volume can increase biomass and BOD, COD, and nitrogen removal efficiency.	2.71	0.13	0.34
O4	Vegetation and wetland media rehabilitation can improve polishing and nitrogen removal capabilities.	3.43	0.13	0.43
	Opportunities Total		**0.54**	**1.76**
	Threats			
T1	Increased community waste generation results in greater leachate production.	1.57	0.17	0.26
T2	Heavy rainfall can reduce the effective HRT and disrupt the stability of biological processes.	2.29	0.13	0.29
T3	Leachate quality standards are becoming increasingly stringent, so non-compliance with Total Nitrogen standards can lead to potential environmental sanctions and pollution of receiving water bodies.	2.00	0.17	0.33
	Threats Total		**0.66**	**0.88**
EFAS Recapitulation Score				
Opportunities				**1.76**
Threats				**0.88**
Difference EFAS (O – T) = Y Coordinate				**0.88**

The EFAS analysis indicated that external opportunities outweighed potential threats, with opportunity and threat scores of 1.76 and 0.88, respectively, resulting in an external strategic value of 0.88. This result suggests that, despite several external challenges, the operating environment remains favorable for improving LTP performance. Nevertheless, external threats such as increasing municipal waste generation, which leads to higher leachate production, and high rainfall intensity, which may reduce the effective HRT and destabilize biological treatment processes, should not be overlooked. If not properly managed, these factors could exacerbate existing operational weaknesses and reduce long-term treatment efficiency.

As shown in Table 4, the higher opportunity score suggests that performance improvements can be achieved primarily through optimizing the existing treatment facilities rather than constructing new units. Restoring the aeration system represents a key opportunity, as nitrification efficiency strongly depends on adequate dissolved oxygen availability. Coppini et al. (2018) reported that membrane bioreactor (MBR) systems equipped with effective aeration and recirculation achieved ammonium removal efficiencies of up to 96%. Likewise, optimizing nitrification–denitrification recirculation is expected to enhance Total Nitrogen removal by improving biological nitrogen conversion, which has been recognized as an effective approach for landfill leachate treatment (Mojiri et al., 2021). Additional improvement measures include increasing the biofilter media volume to promote biofilm development and rehabilitating the constructed wetland media and vegetation to strengthen the polishing process. Ntountounakis et al. (2025) demonstrated that constructed wetlands incorporating porous media and healthy vegetation significantly improve the removal of organic matter and nitrogen from landfill leachate. These opportunities support the implementation of a turn-around (WO) strategy, enabling the identified technical weaknesses to be addressed through optimization of the existing treatment system rather than costly infrastructure expansion.

The strategic coordinates of the LTP were calculated as (−0.28, +0.88), placing the system in Quadrant III (WO) of the SWOT (Figure 2). This strategic position indicates that internal weaknesses outweigh existing strengths, while the external environment continues to provide favorable opportunities for improvement. According to Muliyadi et al. (2023), organizations positioned in this quadrant should adopt a turn-around (WO) strategy, which emphasizes minimizing internal weaknesses by leveraging available external opportunities.

The Quadrant III position reflects that the current performance of the LTP is constrained primarily by internal operational and technical deficiencies rather than by external conditions. The technical evaluation identified several critical issues, including unstable nitrification–denitrification processes, inadequate biofilter media, membrane fouling, and the declining performance of the constructed wetland. Nevertheless, the positive external conditions indicate considerable potential for performance enhancement through optimization of the existing treatment system. If these internal limitations are not addressed, however, the available opportunities may not be fully utilized, and external pressures such as increasing leachate generation and seasonal hydraulic

fluctuations could further compromise treatment performance. Therefore, the strategic priority should focus on strengthening the reliability and efficiency of the existing treatment units through targeted operational improvements rather than expanding treatment capacity. This approach is consistent with the role of SWOT analysis as a strategic decision-making tool for improving the sustainability and effectiveness of environmental management systems (Muliyadi et al., 2023).

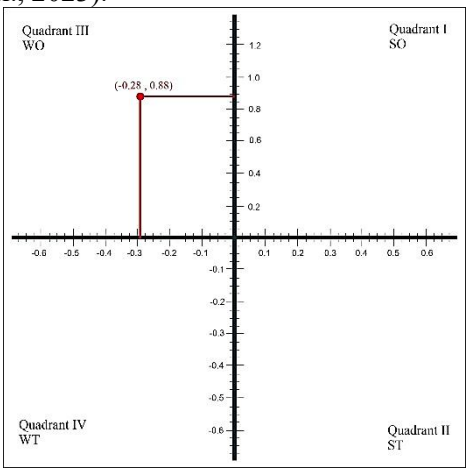


Figure 2. Diagram Analysis of SWOT

3.2.2. LTP Improvement Strategies Based on SWOT Matrix

Based on the identified internal and external factors, the dominance of internal weaknesses, and the significant external opportunities, the appropriate strategy to implement is a turn-around (WO) strategy, aimed at improving internal weaknesses by exploiting available external opportunities. The primary improvement priority is the rehabilitation and technical optimization of the biological treatment units. Repairing the aerator in the nitrification unit as an urgent measure that can immediately increase the efficiency of the nitrification-denitrification process without requiring the construction of a new unit (O1). Repairing the aerator will optimize the leachate recycling pathway from nitrification to denitrification (O2), thereby reducing the ammonia load in the denitrification unit and increasing the Total Nitrogen removal process to meet quality standards. Simultaneously, adding biofilter media to fill 50–70% of the reactor volume is necessary to increase the active biomass density (O3). In addition, rehabilitation of the constructed wetland, including replacement of saturated media, sediment removal, and vegetation restoration, is required to recover its polishing and nitrogen removal functions.

To facilitate implementation, the formulated strategies are further organized based on their urgency, resource requirements, and potential impact on improving WWTP performance. However, a shift toward Quadrant I (SO) is still very possible if the turn-around strategy is implemented consistently and measurably (Bhakti & Herumurti, 2016). Implementation priorities are presented in **Table 6**.

Table 6. Priority Improvement Strategies

Priority	Strategy	Implementation Timeline	Success Indicator
1 (High Priority)	WO-1: Repair the aeration system and optimize the nitrification–denitrification process	Short-term (0–1 year)	Final effluent Total Nitrogen complies with the regulatory standard
2 (Medium Priority)	WO-2: Rehabilitate the constructed wetland and strengthen the monitoring system	Medium-term (1–2 year)	Nitrogen removal efficiency of the constructed wetland improves, with no clogging observed

The first prioritized strategy is WO-1, which involves the rehabilitation and technical optimization of the biological treatment unit, specifically through aerator repair and optimization of the nitrification–denitrification process. This strategy is considered an urgent priority because the main problems identified in the technical evaluation relate to suboptimal nitrogen removal, as indicated by effluent total nitrogen concentrations that still exceed quality standards and the instability of the nitrification–denitrification process. Furthermore, aerator repair scored the highest in the IFAS analysis, making its implementation potentially significant in improving effluent quality in a relatively short time without requiring significant investment in the construction of a new unit.

The second priority is WO-2, which involves the rehabilitation of the wetland unit and strengthening the monitoring system. This strategy is considered a medium priority because wetland rehabilitation requires more

technical planning and resources than aerator repair. Nevertheless, this effort remains crucial for improving polishing and nitrogen removal capabilities and reducing the risk of performance degradation due to media saturation and clogging.

4. CONCLUSSION

The technical evaluation showed that the Leachate Treatment Plant (LTP) at Banjardowo Landfill has not yet operated optimally, particularly in biological nitrogen removal. During the dry season, the final effluent met the standards for BOD, COD, TSS, TSS, Cd, and Hg are 77.63 mg/L, 178.9 mg/L, 3.5 mg/L, 0.00031 mg/L, and <0.0013 mg/L, respectively. However, TN remained high at 281 mg/L, exceeding the regulatory limit of 60 mg/L. In contrast, during the rainy season, all parameters complied with the standards, including TN. Several technical deficiencies were identified, including low DO (0.53–0.65 mg/L) at nitrification, low MLSS at nitrification (680–1,590 mg/L) and denitrification (680 – 880 mg/L), insufficient anaerobic biofilter media (32% of reactor volume), aerator malfunction, prolonged wetland HRT, and periodic membrane fouling. Nevertheless, the ultrafiltration and constructed wetland units performed effectively as polishing processes. SWOT analysis placed the system in Quadrant III (WO) with coordinates of (−0.28, +0.88**)**, indicating that performance improvement should focus on reducing internal weaknesses by utilizing available opportunities. Therefore, the priority strategy is repairing the aeration system and optimizing the nitrification–denitrification process to achieve TN compliance, followed by rehabilitation of the constructed wetland through media replacement, vegetation restoration, and strengthened monitoring.

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APPENDIX

Appendix Table A1. Questionnaire Results for the Strength Factors

Code	Strengths Factor	Rating from Respondents							Number of ratings	Average of Rating	Importance
		R1	R2	R3	R4	R5	R6	R7			
S1	The MBR-based wastewater treatment plant (WWTP) combines biological and membrane technology (MBR + UF + Wetland) with a capacity of 300 m^3/day.	2	2	4	3	3	3	4	21	3,00	4
S2	Most of the wetland unit's design parameters met the design criteria (media, gravel size, BOD loading).	3	2	4	3	3	3	3	21	3,00	2
S3	The UF unit has high TSS and Cadmium removal efficiency.	3	2	4	4	3	3	3	22	3,14	3
S4	The LSP pond volume of 11.423,6 m^3 indicates that the system is geometrically capable of accommodating large amounts of leachate.	2	3	4	4	4	3	3	23	3,29	2
	TOTAL	**23**	**17**	**32**	**29**	**27**	**25**	**24**	**177**		24

Appendix Table A2. Questionnaire Results for the Weakness Factors

Code	Weaknesses Factor	Rating from Respondents							Number of ratings	Average of Rating	Importance
		R1	R2	R3	R4	R5	R6	R7			
W1	Total effluent nitrogen exceeds quality standards during the dry season (> 60 mg/L).	2	3	1	4	2	1	2	15	2,14	3
W2	The denitrification–nitrification unit is unstable (DO and MLSS do not meet criteria).	2	3	2	4	1	1	1	14	2,00	4

Code	Weaknesses Factor	Rating from Respondents							Number of ratings	Average of Rating	Importance
		R1	R2	R3	R4	R5	R6	R7			
W3	The anaerobic biofilter is not optimal (media volume is only 32% of the reactor volume).	2	3	1	4	2	1	3	16	2,29	3
W4	The BOD loading rate does not meet design criteria (0.008 kg/m³/day < 0.05 - 0.2 kg/m³/day) which affects the performance of microorganisms in pollutant removal.	3	2	2	4	1	1	1	14	2,00	4
W5	Leachate recycling from the nitrification unit to support denitrification performance is not optimal because the aerator in the nitrification unit is still not functioning.	2	3	3	4	1	1	1	15	2,14	4
W6	Ammonia loading in the denitrification unit is too high, inhibiting the denitrification process.	2	3	2	4	2	1	1	15	2,14	3
W7	The wetland media has not been replaced/drained for several years, potentially causing saturation and clogging, which can reduce leachate treatment efficiency.	1	1	1	4	2	1	1	11	1,57	2
W8	The wetland HRT is higher than the design criteria.	2	3	3	4	2	2	2	18	2,57	2
W9	Failure of the aerator or recycle pump can cause the nitrification–denitrification process to fail.	1	2	1	4	2	1	1	12	1,71	3
W10	Fluctuations in leachate discharge and characteristics due to seasonal changes have the potential to cause shock loading and decrease the performance of the wastewater treatment plant (WTP).	2	2	1	4	3	1	1	14	2,00	3
W11	Increased solids loads due to the rainy season and landfill erosion have the potential to accelerate sedimentation and clogging in wetlands.	2	2	2	4	3	1	2	16	2,29	3
W12	Increasing landfill age can cause leachate characteristics to become more complex and difficult to process.	1	3	1	3	2	2	1	13	1,86	3
W13	Risk of infrastructure damage due to aging facilities.	1	3	1	4	2	1	1	13	1,86	3
W14	Periodic fouling of ultrafiltration (UF) membranes increases the need for cleaning and maintenance, increasing WTP operational costs and reducing effluent quality.	2	2	1	4	2	3	1	15	2,14	4
TOTAL		**25**	**35**	**22**	**55**	**27**	**18**	**19**	**201**		44

Appendix Table A3. Questionnaire Results for the Opportunity Factors

Code	Opportunities Factor	Rating from Respondents							Number of ratings	Average of Rating	Importance
		R1	R2	R3	R4	R5	R6	R7			
O1	Aerator repairs can immediately improve the nitrification process without the need for new units.	4	2	4	4	4	4	3	25	3,57	4
O2	Optimizing the nitrification-denitrification recycling pathway has the potential to significantly increase total nitrogen removal.	3	2	4	4	3	3	3	22	3,14	3
O3	Adding biofilter media to 50–70% of the reactor volume can increase biomass and BOD, COD, and nitrogen removal efficiency.	3	2	4	3	3	2	2	19	2,71	3
O4	Vegetation and wetland media rehabilitation can improve polishing and nitrogen removal capabilities.	3	2	4	4	4	4	3	24	3,43	3
	TOTAL	**13**	**8**	**16**	**15**	**14**	**13**	**11**	**90**		**13**

Appendix Table A4. Questionnaire Results for the Threat Factors

Code	Threats Factor	Rating from Respondents							Number of ratings	Average of Rating	Importance
		R1	R2	R3	R4	R5	R6	R7			
T1	Increased community waste generation results in greater leachate production.	4	1	1	1	1	2	1	11	1,57	4
T2	Heavy rainfall can reduce the effective HRT and disrupt the stability of biological processes.	3	1	1	1	3	4	3	16	2,29	3
T3	Leachate quality standards are becoming increasingly stringent, so non-compliance with Total Nitrogen standards can lead to potential environmental sanctions and pollution of receiving water bodies.	3	2	1	2	3	2	1	14	2,00	4
	TOTAL	**10**	**4**	**3**	**4**	**7**	**8**	**5**	**41**		**11**