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Optimization of the Leachate Drainage System and Methane Gas Utilization at the Tamangapa Landfill: An Infrastructure and Energy Engineering Study

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ABSTRACT

This research evaluates the leachate drainage system and methane gas utilization at the Tamangapa Landfill and formulate optimization strategies based on infrastructure and energy engineering. A quantitative descriptive method was employed using field observations, interviews, and primary and secondary data analysis. The evaluation covered drainage hydraulic capacity operational conditions, leachate quality, and methane utilization potential. Results showed that the existing drainage hydraulic capacity was 0.074 m³/s, whereas leachate flow reached 0.090 m³/s, resulting in a 17.8% capacity deficit. BOD concentration exceeded the effluent quality standard of 150 mg/L, while COD exceeded 300 mg/L and TSS exceeded 100 mg/L. Conversely, Total Nitrogen (<60 mg/L) and Cd (<0.1 mg/L) remained within applicable standards at all monitoring points and periods. Using the IPCC FOD method, methane generation potential was estimated at 45,245 m³ CH₄/day, with 27,147 m³ CH₄/day recoverable at 60% collection efficiency. Assuming 35% generator efficiency and 10% parasitic load, net electricity generation potential reached 3.5 MW, equivalent to 30.97 GWh/year. Integrating drainage optimization and LFGTE can improve leachate management, recover energy, and reduce methane emissions. These estimates provide an initial scenario for engineering planning and require field verification, detailed design, and further techno-economic assessment under actual operating conditions and seasonal variations.

1. Introduction

Makassar City, as the capital of South Sulawesi Province and one of the major economic growth centers in Eastern Indonesia, faces increasingly complex challenges in solid waste management. Population growth, urbanization, expanding economic activities, and changes in consumption patterns



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have contributed to a continuous increase in municipal solid waste generation. This phenomenon is a common characteristic of developing cities experiencing economic growth and urban expansion, thereby requiring more effective, efficient, and sustainable waste management systems [1]. In addition to the increasing volume of waste generated, waste management issues in Makassar City are also associated with limited waste management infrastructure and facilities, low public participation in waste segregation, and the insufficient capacity of waste treatment facilities to keep pace with the growing waste volume. These conditions have the potential to degrade environmental quality and adversely affect public health [2].

According to data from the Central Statistic Makassar Municipality (BPS), the population of Makassar City reached 1,485,077 in 2025, making it one of the largest metropolitan cities in Eastern Indonesia [3]. Along with population growth and increasing economic activity, municipal solid waste generation has continued to rise. Based on data from the KLH/BPLH in 2025, the municipal solid waste generation in Makassar City reached 1,034 tons/day, while the planned development of a Waste-to-Energy Facility (PSEL) is designed to process 1,000 tons/day, including 800 tons/day generated within Makassar City [4]. This condition indicates the substantial waste management service burden that must be addressed by the local government. If the increasing waste generation is not accompanied by an adequate waste management system, various adverse impacts may arise, including environmental pollution, public health risks, increased flood risks due to drainage blockage, and growing social and economic losses [5], [6].

In response to these challenges, the Government of Indonesia has established a regulatory framework through Law No. 18 of 2008 on Solid Waste Management and Government Regulation No. 81 of 2012 on the Management of Household Waste and Household-like Waste. These regulations emphasize a paradigm shift in waste management from the conventional collect–transport–dispose approach to an integrated waste management system that prioritizes waste reduction at the source, reuse, recycling, and waste handling that meets technical, environmental, social, and economic requirements. This paradigm shift is consistent with the principles of the circular economy, which promotes resource recovery and minimizes environmental burdens through sustainable waste management practices [7].

Within Makassar City's solid waste management system, the Tamangapa Landfill (TPA Tamangapa) serves as the primary facility responsible for receiving and processing the majority of the city's municipal solid waste. Consequently, its operational performance is a critical factor in determining the overall effectiveness of the city's waste management system. However, the management of the Tamangapa Landfill continues to face several technical challenges, particularly in relation to leachate management and the control and utilization of methane gas (landfill gas). These two aspects are key components of landfill operations, directly affecting environmental quality, operational safety, and the overall efficiency of the waste management system [8].

Anaerobic waste decomposition generates landfill gas, primarily methane (CH_4) and carbon dioxide (CO_2). With a calorific value of approximately 35.8 MJ/m^3 , methane offers significant potential for energy recovery, but its GWP is about 27-30 times that of CO_2 over 100 years, making uncontrolled emissions a major environmental concern. Therefore, landfill gas capture and utilization can enhance energy recovery while reducing greenhouse gas emissions from the waste sector [9], [10], [11].

Although various studies have addressed leachate management and methane gas utilization separately, quantitative studies at the Tamangapa Landfill that integrate the evaluation of the hydraulic capacity of the leachate drainage system with the potential for methane recovery and utilization remain limited. This condition indicates a gap in providing an engineering basis that links the performance of leachate infrastructure with the landfill's energy potential under actual operating conditions. Therefore, this study aims to examine strategies for optimizing the leachate drainage system and methane gas utilization at the Tamangapa Landfill through an infrastructure and energy engineering approach, as an effort to support sustainable and low-emission waste management.

2. Research Method

This study employed a quantitative descriptive approach to evaluate the performance of the leachate drainage system and the potential for methane gas utilization at the Tamangapa Landfill, Makassar City. Data were collected from December 12, 2025, to May 20, 2026, through field observations, technical measurements, sampling, interviews, laboratory analyses, and secondary data. Primary data covered drainage dimensions, slope, sediment thickness, flow rate, leachate ponds, and

pipng networks. Leachate samples from five representative points were analyzed for pH, BOD, COD, TSS, and Cd. Interviews involved landfill managers and operators, while secondary data included operational, waste, rainfall, leachate quality, regulatory, and literature data. These data supported the evaluation of drainage capacity, leachate quality, and methane utilization potential. The hydraulic analysis of the drainage system was conducted based on channel dimensions, bed slope, physical conditions, and flow rate using the Manning equation [12]:

$$Q_c = \frac{1}{n} A R^{2/3} S^{1/2} \dots\dots\dots(1)$$

Where: Q_c = channel capacity (m^3/s), n = Manning's roughness coefficient, A = cross-sectional flow area (m^2), R = hydraulic radius (m), and S = channel bed slope. The calculated capacity was compared with the actual/design flow rate to determine the adequacy of the drainage channel.

Leachate quality was analyzed based on the parameters pH, BOD, COD, TSS, Total Nitrogen (N), and Cadmium (Cd). The test results were compared with the applicable effluent quality standards, while the exceedance level was calculated using the following equation [12]:

$$E = \frac{C - C_{std}}{C_{std}} \times 100\% \dots\dots\dots(2)$$

Where: E = exceedance percentage (%), C = measured concentration, and C_{std} = maximum allowable concentration.

Methane generation potential was estimated using the First-Order Decay (FOD) approach [13]:

$$Q_{CH_4,t} = \sum W_x L_o k e^{-k(t-x)} \dots\dots\dots(3)$$

Where: $Q_{CH_4,t}$ = methane generation in year t , W_x = mass of waste disposed of in year x , L_o = methane generation potential per unit mass of waste, k = decay rate constant ($year^{-1}$), t = calculation year.

Based on the estimated methane generation rate ($Q_{CH_4,t}$), the potential net electrical power (P_{net}) that can be generated through Landfill Gas-to-Energy (LFGTE) technology was subsequently calculated using the following equation [13]:

$$P_{net} = Q_{CH_4,r} \times LHV_{CH_4} \times \eta_g \times (1 - f_p) \dots\dots\dots(4)$$

Where: P_{net} = net electrical power (kW), $Q_{CH_4,r}$ = captured methane flow rate (m^3/s), LHV_{CH_4} = lower heating value of methane (MJ/m^3), η_g = generator efficiency (%), f_p = parasitic load fraction (%)

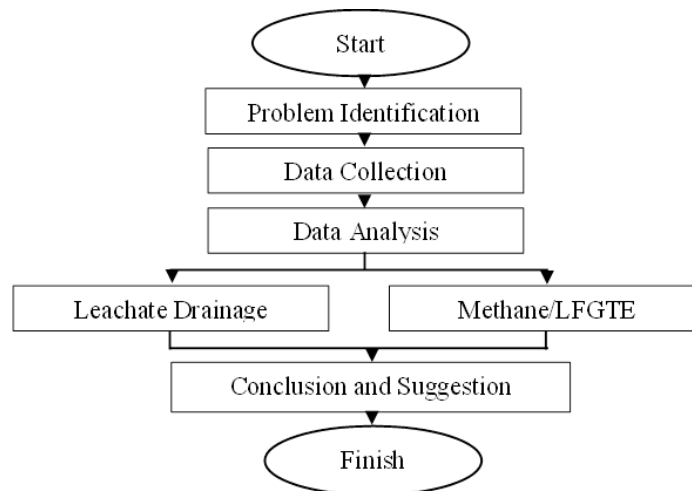
$$Q_{CH_4,r} = Q_{CH_4,t} \times \eta_c \dots\dots\dots(5)$$

Where: η_c = methane gas collection efficiency (%).

Furthermore, the analysis results were compared with relevant technical standards, regulations, and scientific literature to identify system performance levels, technical problems, and optimization opportunities from the perspectives of infrastructure and energy engineering [14].

3. Research Framework

The research framework was systematically developed through four main stages: problem identification, data collection, data analysis, and recommendation formulation. Problem identification was conducted to determine the existing conditions of the leachate drainage system and methane gas utilization at the Tamangapa Landfill (Figure 1). Subsequently, primary and secondary data were collected through field observations, interviews, and document reviews [14]. The collected data were then analyzed using a quantitative descriptive approach to evaluate the performance of the leachate drainage system, leachate quality, and the potential for methane gas utilization. The analysis results served as the basis for formulating optimization recommendations based on infrastructure and energy engineering approaches to support more effective, efficient, and sustainable landfill management.



Source: Processed by Researcher, 2026

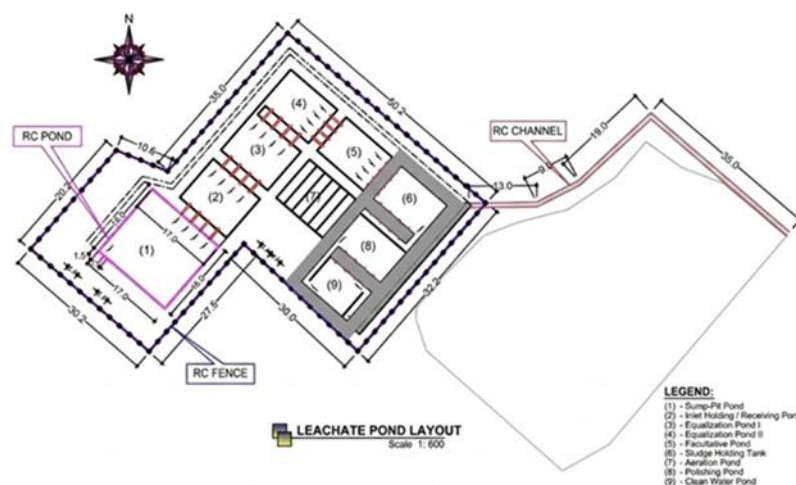
Figure 1. Research Flowchart

4. Results and Discussions

4.1 Existing Conditions of Tamangapa Landfill

The Tamangapa Landfill is the main final waste processing facility in Makassar City, located in Tamangapa Village, Manggala District. The landfill has been in operation since 1993 and covers an area of approximately 19.1 ha, of which around 16.8 ha has been utilized for operational areas and supporting facilities (Figure 2). As one of the key infrastructures in the municipal solid waste management system, Tamangapa Landfill plays a strategic role in ensuring the continuity of waste management services in Makassar City. The increasing generation of municipal solid waste due to population growth and economic activities has made landfill operational capacity a critical factor in determining the success of sustainable waste management systems [15].

According to data from Ministry of Environment/Environmental Control Agency of the Republic of Indonesia 2025, municipal solid waste generation in Makassar City reaches approximately 1,034 tons/day. Meanwhile, the planned waste processing capacity through the development of a Waste-to-Energy (WTE) facility is 1,000 tons/day, including approximately 800 tons/day generated from Makassar City [4]. This substantial waste generation indicates the high service burden that must be managed by the municipal solid waste management system, particularly at the final disposal stage. The continued increase in waste generation driven by population growth and economic activity places additional pressure on landfill capacity and operational performance, making effective capacity management a critical factor in ensuring the sustainability of the urban waste management system (Abdel-Shafy et al., 2024; Kaza et al., 2018).



Source: Tamangapa Landfill Waste Management Master Plan, 2025

Figure 2. Situation Map of the Tamangapa Landfill Leachate Ponds

Geographically, the Tamangapa landfill is bordered by residential areas and productive land. To the north, it is adjacent to the Perumnas Antang residential area (approximately ± 1 km away), to the east it borders agricultural fields and wetlands, to the south it is adjacent to the Kampung Kassi residential area, while to the west, residential settlements are located at a distance of approximately ± 200 m. The proximity of the landfill site to residential areas increases the potential for environmental impacts, particularly due to leachate seepage, landfill gas emissions, groundwater contamination, and deterioration of air quality [16]. Various studies have shown that leachate and landfill gas management are critical aspects of landfill operations, as they directly influence environmental quality and public health conditions in surrounding communities [17], [18].



Source: Researcher's Documentation, 2025

Figure 3. Actual Conditions of the Tamangapa Landfill Leachate Ponds

4.1.1 Condition of the Leachate Drainage System

The observation results indicate that the leachate drainage system at Tamangapa Landfill is functioning to convey leachate to the storage and treatment ponds (Figure 3). However, its performance remains suboptimal due to limited channel capacity, sediment accumulation, and inadequate operation and maintenance, which may hinder leachate conveyance during high-rainfall periods.

The hydraulic analysis using the Manning equation showed that the existing channel capacity is $0.074 \text{ m}^3/\text{s}$, while the actual leachate flow rate reaches $0.090 \text{ m}^3/\text{s}$. This difference results in a capacity deficit of $0.016 \text{ m}^3/\text{s}$, equivalent to 17.8%, indicating that the existing drainage channel can accommodate only approximately 82.2% of the actual leachate flow. Therefore, the existing channel does not have sufficient capacity to convey the leachate flow optimally.

From an infrastructure engineering perspective, inadequate drainage capacity can cause waterlogging, leachate overflow, seepage, and groundwater contamination, while unstable flows may reduce treatment efficiency [8]. Therefore, evaluating channel dimensions, slope, conveyance capacity, and operation and maintenance is essential to improve drainage reliability and treatment performance [19], [20].

4.1.2 Condition of Methane Gas Utilization

The anaerobic decomposition process of waste at the Tamangapa Landfill generates landfill gas, which is predominantly composed of methane (CH_4) and carbon dioxide (CO_2). Based on field observations, the landfill has been equipped with a gas piping network as a facility for landfill gas collection and conveyance. However, methane gas utilization remains limited, indicating that the available energy potential has not yet been optimally utilized.

This limitation is influenced by the suboptimal performance of the landfill gas collection system, limited supporting infrastructure, and the absence of adequate energy conversion facilities. Consequently, a portion of the methane gas is still released into the atmosphere as a greenhouse gas emission. In fact, methane has a global warming potential approximately 27-30 times greater than carbon dioxide over a 100-year period, making emission control a crucial strategy for climate change mitigation [11]. Various studies have demonstrated that optimizing landfill gas collection systems and utilizing the captured gas through LFGTE technology can improve energy efficiency while significantly reducing greenhouse gas emissions [9], [21].

4.1.3 Implications for System Optimization

The evaluation results indicate that leachate management and methane gas utilization at the Tamangapa Landfill still face several technical challenges that affect overall operational performance. In the leachate drainage system, the main issues are related to hydraulic capacity, sedimentation, and the effectiveness of operation and maintenance activities. Meanwhile, in the methane gas utilization system, the primary constraints are associated with the efficiency of the gas collection system and the limited utilization of methane as an energy source.

These findings reveal a gap between existing conditions and system potential, requiring an integrated infrastructure and energy engineering approach to improve leachate drainage, strengthen operation and maintenance, and optimize landfill gas collection through LFGTE [22]. This integration can enhance landfill performance, reduce pollution and greenhouse gas emissions, and support sustainable waste management and circular economy principles [5], [9].

4.2 Evaluation of the Leachate Drainage System

The evaluation showed that the Tamangapa Landfill leachate drainage system has not yet adequately accommodated leachate flows. Key problems include limited channel capacity, sedimentation reducing the effective cross-sectional area, and uneven flow distribution which may cause ponding and leachate seepage and increase soil and water pollution risks [10], [23]. Technically, the system uses collector channels along the waste mass and relies on gravity flow to convey leachate to the treatment unit based on elevation differences, improving operational and energy efficiency [24], [25].

To ensure effective conveyance, the capacity and hydraulic conditions of the drainage channels must comply with the applicable design criteria. The analysis using the Manning equation showed that the existing channel capacity is 0.074 m³/s, which is lower than the actual leachate flow rate of 0.090 m³/s, resulting in a capacity deficit of 0.016 m³/s (17.8%). According to Minister of Public Works Regulation No. 3/PRT/M/2013, the required flow velocity ranges from 0.6–3.0 m/s, while for circular pipes, the maximum flow depth is specified as $d/D \leq 0.80$ [26]. Therefore, the existing drainage system can convey only 82.2% of the actual leachate flow and does not yet provide the required hydraulic capacity. This condition is further exacerbated by sedimentation, accumulation of solid materials, and suboptimal operation and maintenance, which may reduce conveyance efficiency and increase the risk of leachate overflow and seepage into the surrounding environment [19], [27].

4.2.1 Evaluation of the Leachate Treatment System

Leachate treatment at Tamangapa Landfill is carried out through three main stages, namely physical, biological, and chemical treatment. The combination of these three processes represents a commonly applied approach in leachate treatment, as it is capable of reducing suspended solids, organic matter, nutrients, and pathogenic microorganisms before the effluent is discharged into the receiving water body.

a. Physical Treatment

The initial stage is carried out through a screening process at the inlet channel of the leachate pond to separate large-sized materials such as plastics, wood, and other floating debris. This stage aims to reduce the solids load entering the subsequent treatment units, prevent clogging, and improve the efficiency of further treatment processes [27], [28].

b. Biological Treatment

The existing biological treatment system comprises sedimentation ponds, bioball media, paddle-wheel aerators, and eco-enzyme addition. As operational parameters such as HRT, pond volume, aeration rate, DO, media volume, dosage, temperature, and pH were not directly measured, treatment performance was evaluated based on monitored BOD, COD, and TSS concentrations against applicable effluent standards [1], [28].

c. Chemical Treatment

The final stage is conducted through a chlorination disinfection process to reduce the number of pathogenic microorganisms before the effluent is discharged into the environment. In addition to its function as a disinfectant, chlorine also assists in oxidizing some residual odor-causing compounds that remain after the biological treatment process [6], [29].

4.2.2 Implications for Leachate Drainage System Optimization

The evaluation results indicate that the performance of the leachate drainage system is influenced not only by the capacity of the drainage network but also by the effectiveness of the leachate treatment units as an integrated system. Sedimentation, limited channel capacity, and uneven flow distribution reduce the effectiveness of leachate collection and conveyance to the treatment facility. These conditions may decrease treatment efficiency and increase the potential for environmental contamination if not addressed promptly [6], [8],

Optimization of landfill management should be implemented through improvements in the hydraulic capacity of the leachate drainage system, sedimentation removal and channel normalization, enhancement of channel slope conditions, strengthening of operation and maintenance practices, and integration of leachate collection and treatment systems. This approach is consistent with the concept of integrated landfill management, which aims to improve operational reliability and minimize pollution risks [1], [24], [25]. Therefore, leachate drainage optimization should focus on increasing channel hydraulic capacity, regular sediment removal and normalization, improving channel slopes, strengthening operation and maintenance, and integrating collection and treatment systems to enhance pollution control, operational reliability, and sustainable landfill management [7].

4.3 Leachate Quality Monitoring Results

The leachate quality monitoring results around Tamangapa Landfill (Table 1) indicate that several key parameters still exceed the quality standards stipulated in Minister of Environment and Forestry Regulation No. P.59/Menlhk/Setjen/Kum.1/7/2016. The parameters exceeding the permissible limits include BOD, COD, and TSS, while Total Nitrogen and Cd concentrations remain below the required threshold values [30].

Table 1. Leachate Quality Monitoring Results Around the Tamangapa Landfill Site

No	Parameter	Unit	Quality Stand.	Monitoring Results		Monitoring Results	
				Semester I 2025		Semester II 2025	
				A1	A2	A1	A2
1	pH	–	6-9	8.1	8.2	8.1	8.3
2	BOD	mg/L	150	465.9	257.8	449.5	239.8
3	COD	mg/L	300	1,549.28	861.92	1,472.51	836.60
4	TSS	mg/L	100	817.5	425.7	797.0	402.7
5	N Total	mg/L	60	30.46	23.65	29.95	22.88
6	Cadmium (Cd)	mg/L	0.1	<0.09	<0.09	<0.09	<0.09

Source: Wastewater Laboratory Analysis Results, 2025

Note: A1 (Leachate Inlet Pond) = S: 05°10' 26.624" E: 119°29' 31.17"

A2 (Leachate Outlet Pond) = S: 05°10' 27.336" E: 119°29' 32.554"

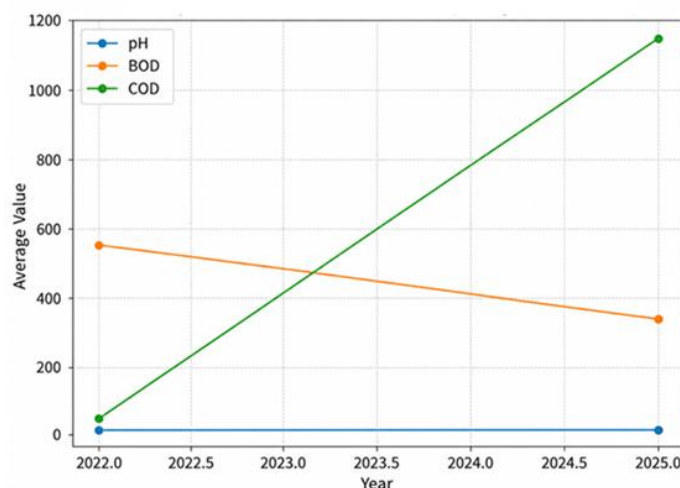
The BOD concentrations at both monitoring points (A1 and A2) were substantially higher than the applicable effluent quality standard of 150 mg/L. In Semester I, the BOD concentrations reached 465.9 mg/L at A1 and 257.8 mg/L at A2, while in Semester II, the concentrations slightly decreased to 449.5 mg/L at A1 and 239.8 mg/L at A2, respectively. The high BOD concentrations indicate that the leachate still contains a substantial amount of biodegradable organic matter, which requires high levels of dissolved oxygen for decomposition. This condition suggests that the biological treatment process has not yet been able to reduce the organic load effectively, potentially causing a depletion of dissolved oxygen if the treated leachate is discharged into the receiving water body [1], [31].

The COD values also showed very high concentrations compared with the quality standard limit of 300 mg/L. In Semester I, COD concentrations were recorded at 1,549.28 mg/L (A1) and 861.92 mg/L (A2), while in Semester II, the values decreased to 1,472.51 mg/L (A1) and 836.60 mg/L (A2). The high COD concentrations indicate the presence of chemically oxidizable organic and inorganic compounds, including refractory organic compounds that are difficult to degrade by microorganisms. Biological treatment alone is often insufficient to meet regulatory standards, particularly for mature leachate containing high levels of humic substances, fulvic acids, and complex organic compounds. Therefore, biological treatment should be optimized in combination with advanced processes, such as advanced oxidation processes (AOPs), adsorption, coagulation-flocculation, or membrane technologies, to improve COD removal and achieve compliant effluent quality [32].

The TSS concentrations at both monitoring points consistently exceeded the applicable effluent quality standard of 100 mg/L. In Semester I, TSS concentrations reached 817.5 mg/L at A1 and 425.7 mg/L at A2, corresponding to 8.18 and 4.26 times the standard, or 717.5% and 325.7% above the standard, respectively. In Semester II, the concentrations slightly decreased to 797.0 mg/L at A1 and 402.7 mg/L at A2, but remained 7.97 and 4.03 times the standard, or 697.0% and 302.7% above the standard, respectively. The high TSS concentrations indicate that the leachate still contains substantial amounts of suspended particles that have not been adequately removed. This condition may contribute to increased sedimentation, reduce the hydraulic capacity of drainage channels, and decrease the efficiency of subsequent treatment units [24], [31].

The Total Nitrogen concentrations in both monitoring periods remained below the quality standard limit of 60 mg/L, with values of 30.46 mg/L (A1) and 23.65 mg/L (A2) in Semester I, and 29.95 mg/L (A1) and 22.88 mg/L (A2) in Semester II. These results indicate that the total nitrogen content still complies with the required quality standards. Nevertheless, periodic monitoring remains necessary, considering that nitrogen compounds, particularly ammonia, may increase over time due to landfill aging and changes in leachate characteristics [20].

The monitoring results showed that Cd concentrations at all monitoring points and during both observation periods remained below the applicable effluent quality standard of 0.1 mg/L. In both Semester I and Semester II, the Cd concentration was recorded at 0.09 mg/L, indicating compliance with the applicable standard, although the value was relatively close to the specified threshold. This condition indicates that the Cd concentration in leachate from Tamangapa Landfill has not exceeded the applicable effluent quality standard. Nevertheless, periodic monitoring of heavy metals remains necessary because the composition of waste entering the landfill is dynamic and may influence leachate characteristics over time [10].



Source: Researcher Analysis, 2026

Figure 4. Trend Comparison Graph of Leachate Quality from 2022-2025

Overall, the monitoring results show that leachate quality at Tamangapa Landfill is mainly affected by BOD, COD, and TSS concentrations exceeding regulatory limits (Figure 4), indicating the need to optimize drainage capacity, operation and maintenance, and biological and physical treatment efficiency. In contrast, Total Nitrogen and Cadmium meet the applicable standards. These findings support strategies to improve leachate management, reduce environmental risks, and enhance landfill sustainability.

4.4 Methane Gas Potential Analysis

Methane Generation Potential. Based on field observations, Tamangapa Landfill already has a landfill gas collection system to collect gas generated from the waste mass. However, its utilization remains suboptimal because the collection coverage and number of gas wells are still limited, and no gas engine or generator unit is currently available.

In general, landfill gas (LFG) contains approximately 45-60% methane (CH_4) and 40-55% carbon dioxide (CO_2), along with small amounts of other gases [9], [33]. Using an LHV of 35.8 MJ/m³ [11], an initial estimate of CH_4 generation was conducted using the IPCC-FOD model, based on an assumed

waste generation rate of 800 tons/day, equivalent to approximately 292,000 tons/year, with $DOC = 0.15$, $DOC_f = 0.50$, $MCF = 1.0$, CH_4 fraction = 0.50, and decay constant (k) = 0.05 year^{-1} , assuming a constant waste input since 1993. The estimation results indicate that CH_4 generation in 2026 is approximately 45,245 m^3/day . Assuming an LFG collection efficiency of 60%, approximately 27,147 $\text{m}^3 \text{ CH}_4/\text{day}$, or 1,131 m^3/hour , could potentially be recovered. Furthermore, assuming a generator efficiency of 35%, parasitic load of 10%, and 24-hour/day operation, the estimated net electricity generation capacity is approximately 3.54 MW, equivalent to 84.9 MWh/day or 30.97 GWh/year.

These values provide an initial estimate of LFGTE potential based on assumed parameters, not actual measurements or definitive capacity, as field data on LFG flow, CH_4 concentration, pressure, active gas wells, and supply continuity are unavailable. Further development of an integrated gas collection and energy conversion system is therefore required [16]. Environmentally, methane emissions are also significant because its 100-year GWP is approximately 27-30 times that of CO_2 [11]. Thus, methane capture and utilization can support both renewable energy recovery and greenhouse gas mitigation [7], [32].

From an energy engineering perspective, methane utilization at Tamangapa Landfill can be optimized by improving the gas collection system, adding extraction wells in active disposal zones, and developing an integrated LFGTE system for gas collection, purification, and energy conversion. This approach can improve waste management efficiency, generate renewable energy, and reduce methane emissions [33], [34]. Given the substantial waste accumulation at Tamangapa Landfill, LFGTE development offers a promising alternative energy strategy to support landfill sustainability and increase the value of waste resources.

4.5 Optimization Strategies Based on Infrastructure and Energy Engineering Approaches

The evaluation of the leachate drainage system and methane gas utilization indicates that the management of Tamangapa Landfill still faces various technical challenges that affect its operational effectiveness. The high concentrations of BOD, COD, and TSS in the leachate indicate that the drainage system and leachate treatment facilities have not yet been able to control pollutant loads effectively [31], [35]. On the other hand, although a methane gas pipeline network has been installed, it has not been complemented by an adequate gas capture and energy utilization system, resulting in the release of most landfill gas into the atmosphere. Therefore, an optimization strategy that integrates infrastructure engineering and energy engineering is required to improve the overall performance of the landfill management system [19], [27]. Optimization strategies include, among others:

4.5.1 Infrastructure Engineering for the Leachate Drainage System

The evaluation results indicate that the existing leachate drainage system can convey only 82.2% of the actual leachate flow, indicating the need for sediment removal and channel normalization, adjustment of channel dimensions and slope, and evaluation of collector pipe capacity. These improvements should consider flow velocity, the degree of cross-sectional filling, and the use of materials resistant to aggressive environmental conditions, such as coated reinforced concrete or HDPE infrastructure [31]. Increasing drainage capacity should also be accompanied by adjustments to the capacity and hydraulic retention time (HRT) of the leachate treatment units to prevent overloading and support compliance with the applicable BOD, COD, and TSS standards [20], [24]. Therefore, optimization should focus on increasing hydraulic capacity while simultaneously improving the reliability of the integrated leachate management system.

4.5.2 Energy Engineering Through Methane Gas Utilization

From an energy engineering perspective, the development of a methane gas utilization system should focus on improving the efficiency of the landfill gas collection system by increasing the number of gas extraction wells, expanding the gas pipeline network, and optimizing the vacuum system to minimize gas losses. A more effective gas collection system will increase the volume of methane available for utilization while simultaneously reducing greenhouse gas emissions from the landfill area [11], [33].

The captured methane gas can subsequently be utilized as a renewable energy source through the implementation of LFGTE technology. This technology uses methane as fuel for gas engines or generator sets to produce electricity that can be used for landfill operations, including site lighting,

operation of leachate pumps, aerators in the leachate treatment plant, and other supporting electrical facilities. The utilization of internally generated energy can improve operational efficiency while reducing dependence on electricity supplied by the public power grid [9], [31].

4.5.3 Integration of Landfill Infrastructure and Energy Engineering

The integration compared the existing condition with alternative drainage optimization and alternative drainage optimization + LFGTE. The existing hydraulic capacity of 0.074 m³/s is below the 0.090 m³/s leachate flow, indicating a 17.8% capacity deficit. Alternative drainage focuses on sediment removal and channel normalization, while alternative drainage optimization + LFGTE adds LFG utilization, with IPCC-FOD estimating 27,147 m³ CH₄/day and approximately 3.54 MW (84.9 MWh/day) of net electricity. Thus, drainage optimization + LFGTE offers broader benefits through improved leachate management, energy recovery, and methane emission reduction.

This approach supports the eco-landfill concept by integrating pollution control with resource and energy recovery [23]. Infrastructure and energy-based optimization can improve landfill management reliability, reduce leachate pollution and greenhouse gas emissions, and enhance operational efficiency through LFG energy utilization. However, final implementation requires field verification and investment and operational cost analyses. Overall, an integrated strategy at Tamangapa Landfill can promote a more resilient, efficient, and sustainable waste management system aligned with circular economy principles and national emission-reduction targets [7], [11], [15].

5. Conclusion and Suggestion

5.1 Conclusion

Based on the research findings, the leachate drainage system at Tamangapa Landfill is not yet capable of optimally accommodating the leachate flow, with a hydraulic capacity of 0.074 m³/s compared with an actual flow rate of 0.090 m³/s, resulting in a capacity deficit of 17.8%. Leachate quality also showed significant exceedances of the applicable effluent quality standards. BOD concentrations ranged from 239.8-465.9 mg/L, corresponding to 59.9-210.6% above the standard of 150 mg/L, while COD concentrations ranged from 836.60-1,549.28 mg/L, or 178.9-416.4% above the standard of 300 mg/L. TSS concentrations also exceeded the applicable standard of 100 mg/L, whereas Total Nitrogen and Cd remained within the applicable standards of 60 and 0.1 mg/L, respectively. These conditions indicate the need for optimization of drainage capacity, sediment removal and normalization, and improvement of leachate treatment performance.

The IPCC-FOD estimation indicates a methane generation potential of approximately 45,245 m³ CH₄/day, with a potential recovery of 27,147 m³ CH₄/day assuming a collection efficiency of 60%. With a generator efficiency of 35% and a parasitic load of 10%, the estimated net electricity generation potential reaches approximately 3.54 MW, equivalent to 84.9 MWh/day (30.97 GWh/year). Integrating drainage optimization with LFGTE has the potential to improve leachate management, provide an alternative energy source, and reduce potential methane emissions. This LFGTE estimate represents an initial scenario that requires field verification and further technical and economic analysis before implementation.

5.2 Suggestion

Based on the findings of this study, the following recommendations are proposed to improve the performance of waste management at Tamangapa Landfill:

1. The Makassar City Government and the landfill management authority should enhance the capacity of the leachate drainage system through hydraulic design evaluation, regular channel desiltation and normalization, and strengthened operation and maintenance programs to ensure the efficient collection and conveyance of leachate to the treatment facility.
2. The leachate treatment plant should be optimized by improving the efficiency of its physical, biological, and chemical treatment processes, accompanied by regular effluent quality monitoring to ensure that BOD, COD, and TSS comply with the applicable environmental quality standards.
3. The methane gas collection system should be further developed by increasing the number of gas extraction wells, expanding the gas pipeline network, and implementing LFGTE technology so that captured methane can be utilized for electricity generation to support landfill operations while simultaneously reducing greenhouse gas emissions.

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