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Efektivitas Pengolahan Lindi Aerob-Anaerob dan Implikasinya terhadap Ekosistem Perairan Penerima di TPA Talumelito, Gorontalo

Effectiveness of Aerobic–Anaerobic Leachate Treatment and Its Implications for the Receiving Aquatic Ecosystem at Talumelito Landfill, Gorontalo

Judul singkat (running title): Leachate treatment and receiving-water implications

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Abstract

Leachate from municipal solid waste landfills threatens receiving aquatic ecosystems when discharged without adequate treatment. This study evaluated the aerobic–anaerobic leachate treatment installation at Talumelito Landfill, Gorontalo Province, Indonesia, operating since 2012, and assessed the implications of its effluent for the receiving stream that drains into Lake Limboto. Grab samples were collected in August 2024 from the inlet and outlet of the installation and analysed for pH, biochemical oxygen demand, chemical oxygen demand, total nitrogen, and heavy metals following APHA and USEPA standard methods. Removal efficiency was calculated for each parameter, and the dilution required for the effluent to meet national river water quality standards was derived from the measured outlet concentrations. Removal efficiency was low for biochemical oxygen demand (7.1%) and chemical oxygen demand (21.4%); outlet concentrations of 1,180 and 2,130 mg/L exceeded the effluent standards of 150 and 300 mg/L. Total nitrogen showed the highest removal (66.5%) yet remained non-compliant at 315 mg/L. All heavy metals complied at the outlet. Meeting the class II river standard would require dilution factors of approximately 393-fold for biochemical oxygen demand and 85-fold for chemical oxygen demand, indicating that the receiving stream cannot assimilate the discharged load and that oxygen depletion and nitrogen enrichment of downstream habitat are likely. Upgrading the installation is therefore urgent for aquatic ecosystem protection.

Keywords: aquatic ecosystem; BOD/COD ratio; dilution factor; Lake Limboto; landfill leachate; removal efficiency

Abstrak

Lindi dari tempat pemrosesan akhir sampah mengancam ekosistem perairan penerima apabila dibuang tanpa pengolahan yang memadai. Penelitian ini mengevaluasi instalasi pengolahan lindi aerob–anaerob di TPA Talumelito, Provinsi Gorontalo, Indonesia, yang beroperasi sejak 2012, serta menilai implikasi efluennya terhadap sungai penerima yang bermuara ke Danau Limboto. Sampel sesaat diambil pada Agustus 2024 dari saluran masuk dan saluran keluar instalasi, lalu dianalisis untuk pH, kebutuhan oksigen biokimia, kebutuhan oksigen kimiawi, nitrogen total, dan logam berat mengikuti metode standar APHA dan USEPA. Efisiensi penyisihan dihitung untuk setiap parameter, dan kebutuhan pengenceran agar efluen memenuhi baku mutu air sungai nasional diturunkan dari konsentrasi saluran keluar terukur. Efisiensi penyisihan rendah untuk kebutuhan oksigen biokimia (7,1%) dan kebutuhan oksigen kimiawi (21,4%); konsentrasi saluran keluar 1.180 dan 2.130 mg/L melampaui baku mutu efluen 150 dan 300 mg/L. Nitrogen total menunjukkan penyisihan tertinggi (66,5%) namun tetap tidak memenuhi standar pada 315 mg/L. Seluruh logam berat memenuhi baku mutu pada saluran keluar. Pemenuhan baku mutu air sungai kelas II memerlukan faktor pengenceran sekitar 393 kali untuk kebutuhan oksigen biokimia dan 85 kali untuk kebutuhan oksigen kimiawi, menunjukkan sungai penerima tidak mampu mengasimilasi beban yang dibuang serta berpotensi mengalami deplesi oksigen dan pengayaan nitrogen pada habitat hilir. Peningkatan kapasitas instalasi karenanya mendesak bagi perlindungan ekosistem perairan.

Kata kunci: Danau Limboto; efisiensi penyisihan; ekosistem perairan; faktor pengenceran; lindi TPA; rasio BOD/COD

1. Introduction

Rapid urbanisation and population growth have intensified municipal solid waste generation in developing countries, placing enormous pressure on waste management infrastructure. Final waste processing sites (FWPS), commonly known as landfills, remain the predominant disposal route in Indonesia despite the environmental burden they impose (Islami et al., 2023). Among these burdens, leachate generation is one of the most serious threats to surrounding environmental quality. Leachate is a complex liquid produced when water percolates through a waste mass, dissolving and transporting organic compounds, inorganic

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salts, and heavy metals from decomposing solid waste (Elvania et al., 2026; Ramadhan et al., 2025; Rizka et al., 2026). Where treatment is inadequate, leachate discharge contaminates groundwater and surface water and degrades the ecological functions of receiving waters (Gunarathne et al., 2024; Rizka et al., 2026). Its composition and pollutant load vary with landfill age, waste composition, climate, and operational practice (Dari & Suhartini, 2024; Lindamulla et al., 2022).

The ecological consequences of poorly treated leachate are transmitted almost entirely through the receiving water body. Elevated organic loading depresses dissolved oxygen and can drive fish kills, while nitrogen enrichment accelerates eutrophication in downstream lakes and reservoirs (Gunarathne et al., 2024; Napitupulu & Putra, 2024). Bioassays using freshwater organisms have confirmed that landfill effluent remains acutely toxic even after conventional treatment (Hasibuan et al., 2025). Evaluating a treatment installation solely against effluent standards therefore captures only part of its environmental performance; the assimilative capacity of the receiving water determines whether compliance at the outfall translates into ecological protection.

Talumelito FWPS is the regional landfill serving Gorontalo Province, Indonesia. It has operated since 2012 using the sanitary landfill method, serves Gorontalo City, Gorontalo Regency, and Bone Bolango Regency (Axmalia & Mulasari, 2020; Royani et al., 2021), and covers 21.05 ha with an active cell area of 4.13 ha. At more than 12 years of operation at the time of sampling, the site sits in its intermediate-to-mature phase, during which leachate shifts toward recalcitrant organic compounds that are less amenable to conventional biological treatment (Emalya et al., 2020; Lasut, 2020; Zhang & Surampalli, 2016). The installed leachate treatment installation (LTI) discharges to a stream that crosses Talumelito, Pentadio Barat, and Pentadio Timur villages and drains into Lake Limboto, the largest lake in Gorontalo. Environmental reporting has documented leachate seepage reaching this stream, exceedance of ambient water quality limits, livestock mortality attributed to the water, and the local disappearance of fish that formerly moved upstream from the lake (Liputan6, 2021; Mongabay Indonesia, 2021).

Despite this documented ecological context, the treatment performance of the Talumelito LTI has not been systematically assessed, and no published study has connected its effluent quality to the assimilative capacity of the receiving stream (Elvania et al., 2026; Yusmartini et al., 2013). Comparable Indonesian landfills persistently fail national leachate standards for organic parameters (Dari & Suhartini, 2024; Islami et al., 2023), yet the resulting pressure on downstream aquatic habitat is rarely quantified. This study therefore aimed to: (1) characterise leachate quality at the inlet and outlet of the Talumelito LTI; (2) evaluate the removal efficiency of the existing aerobic–anaerobic system for key pollutants; and (3) quantify the dilution the effluent would require to satisfy national river water quality standards, as an indicator of the pressure exerted on the receiving aquatic ecosystem.

2. Materials and Methods

2.1. Study area and period

The study was conducted in August 2024 at Talumelito FWPS, Bone Bolango Regency, Gorontalo Province, Indonesia. The facility is a regional sanitary landfill serving three municipalities, with a total land area of 21.05 ha and an active cell area of 4.13 ha. It has operated since 2012, giving a landfill age of approximately 12 years at the time of sampling. Treated effluent leaves the site through a drainage channel that joins a stream flowing westward across Talumelito, Pentadio Barat, and Pentadio Timur villages before entering Lake Limboto (Figure 1).

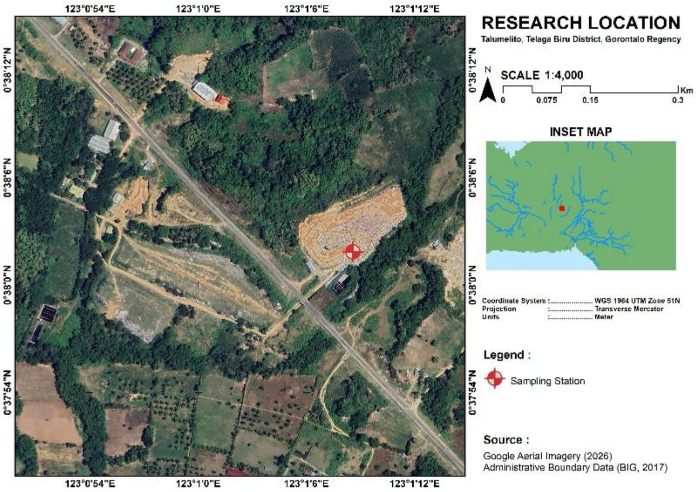

Figure 1. Location of Talumelito FWPS, Bone Bolango Regency, Gorontalo Province, Indonesia, and the drainage direction of treated effluent toward the receiving stream.

2.2. Sample collection

Leachate samples were collected by grab sampling in accordance with SNI 6989.59:2008, the Indonesian national standard for wastewater sampling. Grab sampling was selected as the most widely applied approach for initial characterisation of leachate quality in resource-constrained settings (Al-Hadi et al., 2019; Axmalia & Mulasari, 2020). Samples were taken from two points: the inlet, representing raw leachate entering the equalisation basin before treatment; and the outlet, representing treated effluent after the complete treatment train (equalisation – anaerobic pond – aerobic pond – maturation pond – wetland). Sampling took place between 08:00 and 10:00 local time under dry weather to minimise dilution from precipitation. Samples were collected in polyethylene and borosilicate glass containers of 1,000 mL capacity, pre-rinsed with sample water before filling, preserved in ice boxes at ≤4 °C, and transported to the laboratory within 24 hours to prevent alteration of physicochemical characteristics.

2.2.1. Laboratory analysis

Analytical parameters followed PerMenLHK No. P.59/2016, the national regulation governing leachate quality standards for landfill operations (Kementerian Lingkungan Hidup dan Kehutanan, 2016). Parameters comprised pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), and the heavy metals arsenic (As), cadmium (Cd), iron (Fe), lead (Pb), and mercury (Hg). All analyses were performed by the accredited laboratory PT Water Laboratory Nusantara using the standard methods detailed in Table 1.

Table 1. Analytical parameters, methods, and applicable effluent quality standards.

No	Parameter	Unit	Standard*	Method
1	pH	–	6–9	APHA 4500-H (2017)
2	BOD	mg/L	150	APHA 5210-B (2017)
3	COD	mg/L	300	APHA 5220-D (2017)
4	Total N	mg/L	60	WI-(ID)-[EHS]-LA-306
5	As	mg/L	0.1	APHA 3120-B (2017)
6	Cd	mg/L	0.1	APHA 3120-B (2017)
7	Fe	mg/L	10	APHA 3120-B (2017)
8	Pb	mg/L	0.5	APHA 3120-B (2017)
9	Hg	mg/L	0.005	USEPA 245.7 (2005)

*Note: *Effluent standard under PerMenLHK No. P.59/Menlhk/Setjen/Kum.1/7/2016.*

2.3. Data analysis

Laboratory results were presented descriptively in tabular form and compared with the applicable national standards. Treatment effectiveness was assessed by calculating removal efficiency (RE) for each parameter:

$$RE (\%) = [(C\ inlet - C\ outlet) / C\ inlet] \times 100\%$$

where C inlet is the concentration at the inlet and C outlet the concentration at the outlet. A positive value indicates a reduction in pollutant concentration; a negative value indicates an increase, denoting treatment failure for that parameter. The BOD/COD ratio was calculated at both points as an indicator of leachate biodegradability and stabilisation stage.

2.4. Assessment of implications for the receiving water body

Because compliance with an effluent standard does not by itself demonstrate protection of the receiving water, the pressure exerted on the downstream aquatic environment was expressed as the dilution factor (DF) required for the measured effluent to satisfy the ambient river water quality standards set out in Government Regulation No. 22 of 2021, Appendix VI (Pemerintah Republik Indonesia, 2021):

$$DF = C\ outlet / C\ standard$$

where C outlet is the measured outlet concentration and C standard is the ambient limit for the water class concerned. Class II applies to water designated for recreation, freshwater aquaculture, livestock watering, and irrigation, and class III to freshwater aquaculture, livestock watering, and irrigation; both therefore represent designated uses that depend on a functioning aquatic community. DF expresses how many volumes of clean receiving water each volume of effluent requires before the ambient limit is met, and thus indicates whether the receiving stream can plausibly assimilate the discharged load. The approach uses measured effluent concentrations and published ambient limits only; it does not substitute for direct measurement of ambient water quality or biota, which is identified below as a priority for follow-up work.

A recognised limitation of this study is that sampling comprised a single grab event, so the results reflect conditions at the time of sampling and may not represent temporal variability in leachate quality. Ambient water quality and biological assemblages in the receiving stream were not measured directly; the receiving-water assessment is therefore indicative rather than a substitute for in-stream monitoring. Future studies should combine repeated effluent sampling with in-stream physicochemical and biological sampling across seasons.

3. Results

3.1. Leachate quality at the inlet

Laboratory results for inlet samples are presented in Table 2. Nearly all organic and nutrient parameters exceeded the standards stipulated in PerMenLHK No. P.59/2016.

Table 2. Leachate quality at the inlet prior to treatment, Talumelito FWPS.

No	Parameter	Unit	Inlet	Standard	Status
1	pH	–	7.78	6–9	Compliant
2	BOD	mg/L	1,270	150	Exceeds (8.5×)
3	COD	mg/L	2,710	300	Exceeds (9.0×)
4	Total N	mg/L	940	60	Exceeds (15.7×)
5	As	mg/L	0.041	0.1	Compliant
6	Cd	mg/L	0.0006	0.1	Compliant
7	Fe	mg/L	2.12	10	Compliant
8	Pb	mg/L	0.007	0.5	Compliant
9	Hg	mg/L	0.00194	0.005	Compliant

Note: Primary data, August 2024. Standard under PerMenLHK No. P.59/2016.

The inlet pH was 7.78, within the permitted range. BOD and COD reached 1,270 mg/L and 2,710 mg/L respectively, and total nitrogen 940 mg/L. Heavy metals were detected at low concentrations: As 0.041 mg/L, Cd 0.0006 mg/L, Fe 2.12 mg/L, Pb 0.007 mg/L, and Hg 0.00194 mg/L, all below their respective limits. The inlet BOD/COD ratio was 0.47.

3.2. Leachate quality at the outlet and removal efficiency

Outlet concentrations and the calculated removal efficiencies are presented in Table 3.

Table 3. Leachate quality at the outlet and removal efficiency of the aerobic–anaerobic treatment system, Talumelito FWPS.

No	Parameter	Unit	Inlet	Outlet	Standard	RE (%)	Status
1	pH	–	7.78	7.78	6–9	–	Compliant
2	BOD	mg/L	1,270	1,180	150	7.1	Non-compliant
3	COD	mg/L	2,710	2,130	300	21.4	Non-compliant
4	Total N	mg/L	940	315	60	66.5	Non-compliant
5	As	mg/L	0.041	0.033	0.1	19.5	Compliant
6	Cd	mg/L	0.0006	0.0005	0.1	16.7	Compliant
7	Fe	mg/L	2.12	1.25	10	41.0	Compliant
8	Pb	mg/L	0.007	0.006	0.5	14.3	Compliant
9	Hg	mg/L	0.00194	0.00038	0.005	80.4	Compliant

Note: RE = removal efficiency. Standard under PerMenLHK No. P.59/2016.

The system complied with the effluent standards for pH and for all five heavy metals, with mercury showing the highest removal efficiency (80.4%), followed by iron (41.0%), arsenic (19.5%), cadmium (16.7%), and lead (14.3%). It did not comply for the organic parameters or for nitrogen: BOD 1,180 mg/L against a limit of 150 mg/L (RE 7.1%), COD 2,130 mg/L against 300 mg/L (RE 21.4%), and total nitrogen 315 mg/L against 60 mg/L (RE 66.5%). The BOD/COD ratio rose from 0.47 at the inlet to 0.55 at the outlet.

3.3. Dilution required by the receiving stream

Table 4 presents the dilution factors derived from the outlet concentrations against the ambient river water quality standards of Government Regulation No. 22 of 2021.

Table 4. Dilution factors required for the treated effluent to meet ambient river water quality standards (Government Regulation No. 22 of 2021, Appendix VI).

Parameter	Outlet	Class II	DF II	Class III	DF III
BOD	1,180	3	393	6	197
COD	2,130	25	85	40	53

Note: all concentrations in mg/L. DF = dilution factor, calculated as the outlet concentration divided by the ambient limit; values rounded to the nearest whole number. Class II covers recreation, freshwater aquaculture, livestock watering, and irrigation; class III covers freshwater aquaculture, livestock watering, and irrigation.

Meeting the class II standard would require approximately 393 volumes of clean receiving water per volume of effluent for BOD and 85 volumes for COD. Even against the less stringent class III standard, the corresponding factors remain 197 and 53.

4. Discussion

4.1. BOD and COD removal performance

The removal efficiencies recorded for BOD (7.1%) and COD (21.4%) are critically low for a treatment train that includes both anaerobic and aerobic stages. Two explanations are consistent with the data. First, the inlet BOD/COD ratio of 0.47 places Talumelito leachate in the intermediate stabilisation stage, in which a substantial fraction of the organic load consists of recalcitrant, humic-type compounds that resist biological degradation; conventional biological treatment performs well on young leachate with a ratio above 0.5 but loses effectiveness as the ratio declines (Emalya et al., 2020; Lindamulla et al., 2022; Zhang & Surampalli, 2016). That the ratio rose to 0.55 at the outlet, rather than falling as it would under effective biological degradation, indicates that the ponds removed a modest fraction of chemically oxidisable material while leaving the readily biodegradable fraction largely untouched — a signature of hydraulic passage rather than biological treatment.

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Second, the treatment train appears to function largely as a series of passive sedimentation ponds rather than as managed biological reactors. Under such conditions the aerobic stage cannot supply the oxygen transfer that degradation of a 2,710 mg/L COD load requires. Comparable findings have been reported at Piyungan Regional Landfill in Yogyakarta, where the leachate treatment system likewise failed to reduce BOD and COD below the limits set by PerMenLHK No. P.59/2016 (Dari & Suhartini, 2024), and the pattern recurs across Indonesian landfill management (Islami et al., 2023). As Lindamulla et al. (2022) emphasise, leachate from tropical landfills generally carries a higher organic burden than temperate counterparts and requires correspondingly more intensive treatment, so open-pond aerobic–anaerobic systems are structurally inadequate for intermediate-stage tropical leachate.

4.2. Total nitrogen removal performance

Total nitrogen achieved the highest removal efficiency of any parameter (66.5%), which suggests that the maturation pond supports partial nitrification–denitrification. The residual concentration of 315 mg/L nevertheless exceeds the effluent limit by 5.3-fold. Ammonium nitrogen is the most persistent long-term pollutant in landfill leachate: it does not decline with landfill age and accumulates through the degradation of organic nitrogen compounds (de Almeida et al., 2023). Achieving compliance would require controlled nitrification–denitrification or advanced processes such as anaerobic ammonium oxidation (Dari & Suhartini, 2024).

4.3. Heavy metal parameters

All five heavy metals complied with the effluent standard at the outlet, and partial removal was observed for each, indicating that adsorption and sedimentation within the ponds attenuate metals even where organic removal fails. Low metal concentrations in leachate from tropical landfills are commonly attributed to sorption and precipitation within the waste mass itself, which retains metals before they reach the collection system (Gunarathne et al., 2024; Yusmartini et al., 2013). Compliance at the outfall should not be read as an absence of risk: metals attenuated by sedimentation accumulate in pond sediments, from which hydrological disturbance can remobilise them, so periodic monitoring of both effluent and pond sediment remains warranted.

4.4. Implications for the receiving aquatic ecosystem

The dilution factors in Table 4 make the ecological significance of the organic loading explicit. A discharge requiring 393-fold dilution for BOD to reach the class II ambient limit cannot be assimilated by a small tropical stream, whose dry-season flow is unlikely to exceed the effluent flow by anything approaching that margin. The practical consequence is a reach immediately downstream of the outfall in which oxygen demand exceeds reaeration capacity. Dissolved oxygen depletion is the mechanism through which organic pollution translates into biological loss, since sustained hypoxia eliminates oxygen-sensitive taxa and, at severity, produces fish mortality (Napitupulu & Putra, 2024). This is consistent with reports from the Talumelito receiving stream, where residents recorded the disappearance of fish that formerly moved upstream from Lake Limboto after the landfill began operating, and where livestock mortality was attributed to the water following documented leachate seepage into the channel (Liputan6, 2021; Mongabay Indonesia, 2021).

Nitrogen presents a second, spatially broader pathway. An outlet concentration of 315 mg/L total nitrogen represents a continuous nutrient subsidy to a stream that terminates in Lake Limboto. Unlike organic matter, which is progressively oxidised along the watercourse, nitrogen is conserved and delivered to the lake, where it contributes to the eutrophication pressure to which shallow tropical lakes are particularly vulnerable. The ecological endpoint of nitrogen loading is therefore displaced from the discharge point to the lake basin, and is not captured by outfall monitoring at all. Ammonium is additionally toxic to fish in its un-ionised form, with toxicity increasing at the alkaline pH recorded here (de Almeida et al., 2023; Gunarathne et al., 2024).

Two implications follow. First, effluent standards and ambient standards answer different questions, and compliance with the former does not establish protection of the latter: even the heavy metals that complied at the outfall were assessed against an effluent limit, not against the ambient limits that govern aquatic life. Second, the ecological signal at Talumelito is already documented in the receiving stream while the treatment installation continues to operate, which places the burden of evidence on demonstrating that downstream aquatic habitat is protected rather than assuming it. Bioassays with freshwater test organisms such as Cyprinus carpio and Daphnia sp. have shown that landfill effluent can retain acute toxicity after conventional treatment (Hasibuan et al., 2025), and such assays offer a direct and inexpensive route to verifying whether the Talumelito effluent is toxic at environmentally realistic dilutions. Priorities for follow-up work are in-stream physicochemical monitoring above and below the outfall, macroinvertebrate or fish assemblage survey as a biological indicator, and effluent toxicity testing; these would convert the indicative assessment presented here into direct evidence of ecological impact.

5. Conclusion

The aerobic–anaerobic treatment system at Talumelito FWPS did not reduce leachate pollutants to the levels required by PerMenLHK No. P.59/2016. Removal efficiency reached only 7.1% for BOD and 21.4% for COD, leaving outlet concentrations of 1,180 and 2,130 mg/L, while total nitrogen achieved the highest removal (66.5%) yet remained at 315 mg/L. All heavy metals complied at the outlet. The rise in BOD/COD ratio from 0.47 to 0.55 across the installation indicates hydraulic passage rather than effective biological treatment. Expressed as pressure on the receiving water, the effluent would require dilution of approximately 393-fold for BOD and 85-fold for COD to meet the class II ambient standard, a margin no small tropical stream can supply, and the nitrogen load is delivered onward to Lake Limboto. Upgrading the installation is therefore urgent, and monitoring should be extended from the outfall into the receiving stream.

Competing interests

The authors declare no competing interests relevant to this article.

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Authors' contributions

RH: conceptualisation, methodology, investigation, writing — original draft. F: supervision, writing — review and editing. RS: formal analysis, visualisation. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Availability of data and materials

The dataset supporting the findings of this study is available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable. The study analysed leachate samples and did not involve human or animal subjects.

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