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Original Research

Composite Index and Regulatory Assessment of Water-Quality Impairment in the Sedapat River and Shallow Dug Wells near Sukawinatan Landfill, Indonesia

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Abstract

The landfill area can degrade the quality of surface water and shallow groundwater in its vicinity, where leachate collection, treatment, and containment are limited. This cross-sectional study assesses the leachate characteristics and water quality degradation in the Sedapat River and shallow dug wells around the Sukawinatan Landfill, Palembang, Indonesia. The analysis used regulatory compliance at the observation level, Leachate Pollution Index (LPI), Nemerow Pollution Index (NPI), Organic Pollution Index (OPI), Heavy Metal Pollution Index (HPI), and descriptive proximity screening. Leachate shows a high pollution potential, with TSS, BOD, COD, Fe, total coliform, and total nitrogen exceeding their respective standards in 100.0%, 93.3%, 100.0%, 100.0%, 80.0%, and 66.7% of the samples. The average total LPI is 44.2, indicating a substantial pollution potential dominated by the organic sub-index. In the Sedapat River, Fe and total nitrogen exceeded Class II standards in all observations, while BOD exceeded the standards in 5 out of 15 observations. The heavy pollution index based on NPI, moderate organic/nutrient pressure based on OPI, and a low aggregate HPI value, although Fe remains a concern. The shallow wells dug frequently showed non-compliance with total *coliform* (28/30), *Escherichia coli* (19/30), turbidity (21/30), colour (19/30), Fe (14/30), Mn (16/30), and pH (28/30). Proximity screening showed higher multi-parameter violation scores in wells closer to the landfill. However, the direction of groundwater flow, background wells, well depth, soil permeability, and conservative leachate tracers were not studied; the groundwater findings are interpreted as disturbances related to proximity and sanitation relevance rather than confirmed specific landfill contamination. These findings support the improvement of leachate treatment, river monitoring, hydrogeological characterisation, and the protection of shallow dug wells for nearby communities, as well as long-term environmental risk management planning.

Keywords: landfill leachate; surface water; groundwater; leachate pollution index; Nemerow pollution index; heavy metal pollution index;

1. INTRODUCTION

Global municipal solid waste generation is projected to increase from 2.1 billion metric tons in 2023 to 3.8 billion metric tons by 2050, increasing pressure on waste-disposal facilities, particularly in developing countries where open dumping remains common (UNEP, 2024). In landfill systems, waste decomposition produces leachate, a complex wastewater whose composition is influenced by landfill age, waste characteristics, compaction, decomposition stage, rainfall, and temperature(Nanda & Berruti, 2021; J. Wang & Qiao, 2024). Leachate commonly contains elevated concentrations of organic matter, nutrients, heavy metals, and microbial contaminants. In Southeast Asia, chemical oxygen demand (COD) in landfill leachate commonly ranges from 1,000 to 10,000 mg/L, while nitrogenous compounds may substantially impair receiving-water quality (Parvin and Tareq, 2021; Rogers et al., 2021). Diverse microbial communities, including cellulolytic, cidogenic, and sulphate-reducing bacteria, further increase the biological complexity of landfill leachate (Zhao et al., 2021). Leachate-contaminated waters have also been reported to contain bacterial counts exceeding recommended drinking-water safety limits, indicating potential risks to environmental quality and public health (Simon & Adianimovie, 2022). Where liners, leachate collection systems, treatment processes, and containment measures are inadequate, contaminants may pose risks to nearby surface-water and shallow groundwater systems (Gautam et al., 2024; Wijekoon et al., 2022).

Because landfill-related water pollution is multidimensional, single-parameter assessment is often insufficient to describe its magnitude, composition, and spatial distribution. Composite indices, including the Leachate Pollution Index (LPI), Nemerow Pollution Index (NPI), Organic Pollution Index (OPI), and Heavy Metal Pollution Index (HPI), can integrate multiple water-quality variables into interpretable screening measures (Singh & Singh, 2024). However, these indices provide screening-level evidence of pollution intensity, not direct proof of contaminant pathways or source-specific causation. Therefore, index-based assessments should transparently report measured concentrations, reference standards, weights or ratios, sub-index scores, classification thresholds, and the treatment of censored values (Rodriguez-Cardenas et al., 2025; Saghi et al., 2024). Regulatory compliance should also be assessed at the observation level because mean-based interpretation can conceal sample-level exceedances relevant to ecological and public-health risk (Majed & Islam, 2022).

In Indonesia, landfill management remains a critical environmental challenge. In 2024, approximately 68% of Indonesia's 437 landfills operated using open dumping, and more than 90% of nominally sanitary landfill sites functioned as open dumps (National Waste Management Information System, 2024). These conditions are relevant to the Sukawinatan Landfill in Palembang, which is located near the Sedapat River and surrounding residential areas where shallow dug wells are used for daily water needs. Nevertheless, confirming contaminant transport from landfill leachate to river water or groundwater requires hydrological and hydrogeological evidence, including discharge-point identification, upstream–downstream river references, groundwater-flow direction, upgradient or background wells, well depth, hydraulic gradient, soil permeability, and conservative leachate tracers such as chloride and ammonium (Ahmed et al., 2019; Adhikari et al., 2020). Without these supporting data, this study evaluates water-quality impairment, regulatory exceedance, composite-index conditions, and proximity-related spatial patterns, without claiming confirmed landfill-specific transport or direct causality.

Accordingly, this study aimed to: (1) characterize leachate quality and pollution potential using observation-level regulatory compliance and the LPI with its sub-indices; (2) assess Sedapat River water-quality impairment using individual exceedance frequency and reproducible NPI, OPI, and HPI calculations; (3) evaluate shallow dug-well groundwater quality using measured-parameter exceedance and descriptive proximity screening; and (4) formulate management implications while explicitly acknowledging the limits of causal attribution in a tropical landfill setting.

2. MATERIALS AND METHODS

2.1. Study Area

This study was conducted at the Sukawinatan Landfill and its surrounding environment in Palembang City, South Sumatra, Indonesia, at approximately 2°54′40.36″ S and 104°44′53.92″ E. The site represents a tropical urban landfill setting characterized by humid climatic conditions, high rainfall, and relatively stable temperatures, which may support continuous leachate generation. The landfill receives mixed municipal solid waste with limited segregation at source and is located near the Sedapat River and residential areas, where shallow dug wells are used for domestic water needs.The Sedapat River and shallow dug wells were selected as critical environmental media because of their proximity to the landfill and their relevance to local water quality protection. The river represents the main nearby surface-water body, while the shallow dug wells represent community-level groundwater sources that may be vulnerable to surface-derived contamination, poor wellhead protection, sanitation-related inputs, and possible landfill-associated pressure. Therefore, the study area was evaluated as a potential zone of water quality impairment associated with landfill proximity.

However, hydrological connectivity between the landfill, river, and shallow dug wells was not assumed. The study did not investigate groundwater flow direction, hydraulic gradient, well depth, soil permeability, or the upgradient and downgradient status of individual wells. Accordingly, the spatial interpretation was limited to descriptive proximity-based screening and regulatory water-quality assessment, rather than confirmation of a direct contaminant pathway or landfill-specific groundwater contribution. The sampling locations, landfill area, Sedapat River, and shallow dug-well distribution are presented in Fig. 1.

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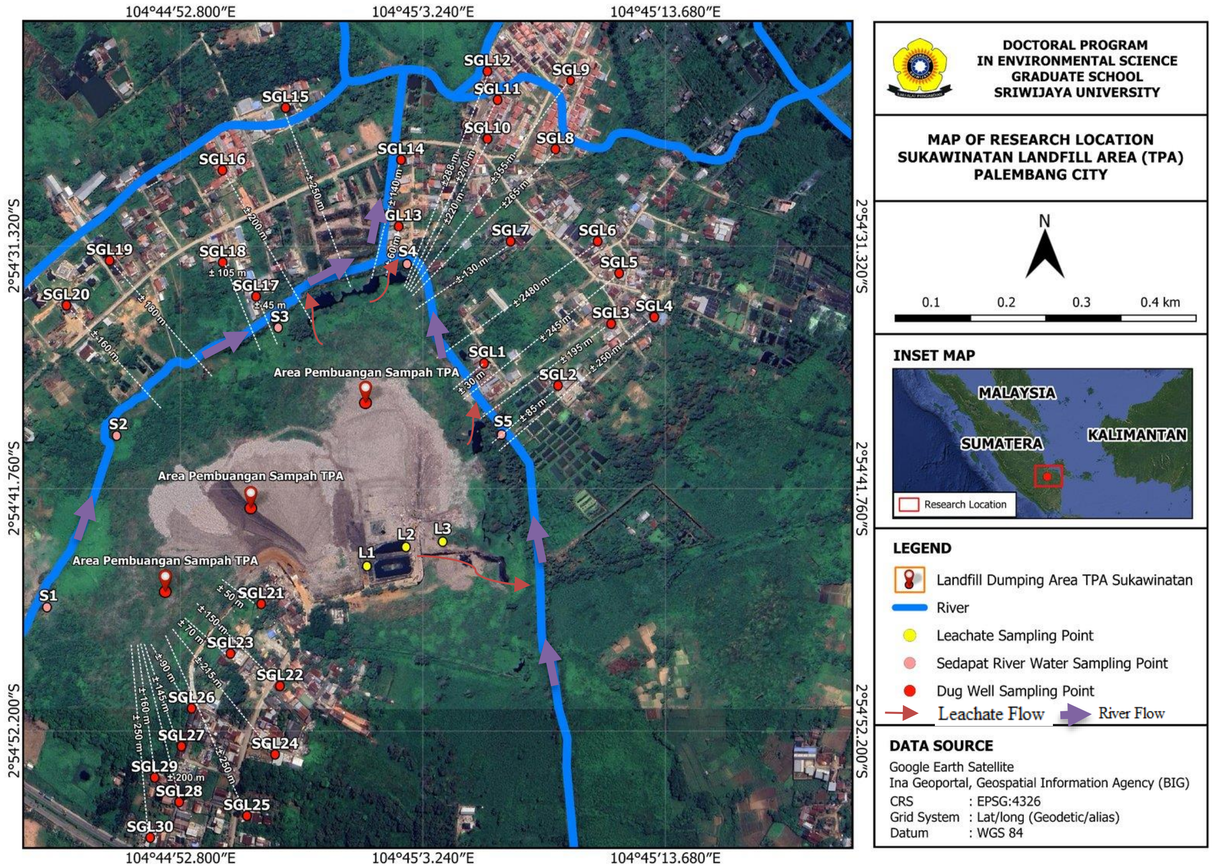

Fig. 1 : Map of the Sukawinatan Landfill study area in Palembang City, Indonesia, showing the landfill dumping area, leachate sampling points, Sedapat River water-sampling points, shallow dug-well sampling points, leachate-flow direction, and river-flow direction.

2.2. Sampling Design

A cross-sectional descriptive-analytical design was used to assess the characteristics of leachate, surface water quality, and shallow groundwater quality around the Sukawinatan Landfill. Sampling was conducted during a single field campaign in June 2025. Leachate samples were collected from three leachate pond stations (L1, L2, and L3) following SNI 8990:2021, with five field sub-samples collected at each station, resulting in 15 leachate observations. Surface water samples were taken from five Sedapat River stations (S1–S5), with three field samples taken at each station, resulting in 15 river observations. Groundwater samples were taken from 30 shallow dug wells (SGL1–SGL30) located approximately 30–355 m from the landfill and grouped into five distance zones: 0–50 m, 51–100 m, 101–150 m, 151–200 m, and >200 m.

Samples are collected and handled to minimise physicochemical and microbiological changes. Water samples are stored in sterile dark bottles, maintained at a temperature of around 4°C, and immediately transported to the laboratory for analysis. Leachate sub-samples and river station samples are treated as field sub-samples or field replicates for descriptive summaries, station-level characterisation, and observation-level regulatory compliance assessment. The three datasets represent different environmental compartments and are not naturally paired based on location, hydrological pathways, sampling units, or temporal sequences. Leachate and river water data were summarised using station averages, ranges, and excess frequencies, while groundwater wells were analysed individually and by distance zone. Statistical interpretation is limited to descriptive associations and screening levels due to the unavailability of temporal replication, groundwater flow direction, flow path verification, upstream/background wells, well depth information, and conservative leachate tracers.

2.3. Laboratory Analysis and Regulatory Compliance Assessment

Laboratory results were summarised using descriptive statistics, including minimum, maximum, average, and standard deviation. The measured values are compared with the applicable Indonesian regulatory standards: Minister of Environment and Forestry Regulation No. P.59/2016 for leachate at landfills, Government Regulation No. 22/2021 for Class II surface water, and Minister of Health Regulation No. 2/2023 for water used for hygiene and sanitation. The parameters for leachate and surface water include TSS, pH, BOD, COD, cadmium (Cd), lead (Pb), iron (Fe), total coliform, mercury (Hg), and total nitrogen (TN). The parameters for groundwater include total *coliform*, *Escherichia coli*, odour, total dissolved solids (TDS), turbidity, temperature, colour, Fe, manganese (Mn), nitrite, and pH. Laboratory analysis follows the relevant Indonesian National Standards (SNI) methods, including SNI 6989.11:2019 for pH, SNI 6989.73:2019 for BOD, SNI 6989.15:2019 for COD, SNI 6989.3:2019 for TSS, SNI 6989.84:2019 for Cd, and SNI 6989.78:2019 for Hg. Analytical quality assurance and quality control include routine instrument calibration, blank analysis, replicate measurements, and the use of certified reference materials if available.

Compliance with regulations is evaluated at the individual observation level rather than solely based on the overall average value. Each measured value is compared to the relevant regulatory threshold, and non-compliance is reported as the frequency of violations, expressed as n/N, and the percentage of the sample exceeding the standard. The average value is only retained as a descriptive statistic. This approach is used to avoid excessive sample-level closure, especially for parameters with high spatial variability or values close to the regulatory threshold.

2.4. Treatment of Censored Analytical Values

Censored analytical values are treated conservatively before descriptive interpretation and index calculation. Values reported above the laboratory measurement range are treated as right-censored, while values reported below the reporting limit are treated as left-censored. In the descriptive table, censored values are retained using the notation > or < to avoid presenting uncertain concentrations as exact values. For regulatory compliance, censored values are classified based on their relationship to the applicable standards. When numerical input is required for index calculations, right-censored values are entered as a conservative lower bound estimate, while undetected values are replaced using explicitly stated rules, primarily half of the reporting limit. Sensitivity interpretation considers the potential effects of using zero, half of the reporting limit, or the full reporting limit if appropriate.The ratios and indices obtained from the censored parameters are interpreted as conservative or sensitivity-based estimates rather than exact values. Assumptions, substituted inputs, and calculation components are documented in relevant tables or supplementary materials to support transparency and reproducibility.

2.5. Pollution Index and Measured Parameter Screening Assessment

Water quality degradation related to landfills is assessed using pollution indices and filtering measurable parameters according to the characteristics of each environmental compartment. The potential leachate pollution is evaluated using the Leachate Pollution Index (LPI) and its sub-indices. The surface water quality in the Sedapat River is assessed using the Nemerow Pollution Index (NPI), Organic Pollution Index (OPI), and Heavy Metal Pollution Index (HPI). Groundwater from shallow dug wells is evaluated using individual regulatory exceedance and scores for filtering measurable parameters because the available groundwater parameters do not support the application of standard landfill leachate pollution indices. All indices are interpreted as screening and assessment tools, not as evidence of confirmed contaminant pathways or specific source causes.

2.5.1. Leachate Pollution Index and Sub-LPI

The Leachate Pollution Index (LPI) and its sub-indices were calculated using the method developed by Kumar and Alappat, which integrates multiple leachate quality parameters into a single composite value. This index provides an overall assessment of the pollution potential of landfill leachate by assigning a weight and sub-index value to each selected parameter. The LPI was calculated using the following equation:

$$LPI = \sum_{i=1}^{n} w_i p_i \qquad \dots (1)$$

where:
w_i = normalised weight of parameter *i*
p_i = sub-index value of parameter *i*
n = number of parameters included in the calculation
In this study, 11 leachate parameters were analyzed, however, eight parameters were selected for the LPI calculation based on the standard LPI parameter list. These parameters included pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), iron (Fe), lead (Pb), mercury (Hg), and Total Coliform. Each parameter was assigned its corresponding normalized weight, while the sub-index value was determined according to the appropriate rating curve in the LPI method, including V-shaped, exponential, logarithmic, or toxicity-based curves. The resulting LPI value was used to classify the overall pollution potential of leachate at each sampling station (Singh & Singh, 2024).

2.5.2. Nemerow Pollution Index (NPI)

The Nemerow Pollution Index (NPI) was used to integrate individual pollutant indices into a single composite value that reflects the overall pollution status at each sampling site. This index gives greater emphasis to the most contaminated parameter, thereby allowing the identification of dominant pollutants that strongly influence water quality. First, the single pollution index (P_i) was calculated for each water quality parameter at each sampling site. The average pollution index (P_{avg}) and the maximum pollution index (P_{max}) were then determined from all calculated P_i values. The final NPI value was calculated using the following equation:

$$P_N = \sqrt{\frac{P_{avg}^2 + P_{max}^2}{2}} \qquad \dots(2)$$

where:
P_N = Nemerow Pollution Index at a specific sampling site
P_{avg} = Average value of the single pollution indices
P_{max} = Maximum value of the single pollution indices

2.5.3. Organic Pollution Index (OPI)

The Organic Pollution Index (OPI) was used to evaluate the level of organic pollution in surface water. This index incorporates key organic pollution indicators, including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), and the BOD/COD ratio. Four pollution ratios were calculated, namely R1=BOD/BODstd, R2=COD/CODstd, R3=TN/TNstd, and R4=(BOD/COD)/(BOD/COD)std, where BODstd, CODstd, TNstd, and (BOD/COD)std represent the corresponding standard reference values. The OPI was calculated using the following equation:

$$OPI = \sqrt{\frac{\bar{R}^2 + R_{max}^2}{2}} \quad \ldots(3)$$

where:
$\bar{R}$ = average value of the pollution ratios R1 to R4
Rmax = maximum value among the calculated pollution ratios
The resulting OPI value was used to classify the degree of organic pollution in the surface water samples.

2.5.4. Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) was used to assess the degree of heavy metal contamination in river water. In this study, the HPI was calculated based on selected heavy metal parameters, including cadmium (Cd), lead (Pb), iron (Fe), and mercury (Hg). For each metal, a quality sub-index was calculated to represent the extent to which the measured concentration deviated from the corresponding ideal and standard values. A unit weight was then assigned to each parameter based on the inverse of its standard permissible value, indicating that parameters with lower permissible limits were given greater relative importance. The overall HPI value was obtained by aggregating the weighted quality sub-indices using the following equation:

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{1}^{n} Wi} \quad \ldots(4)$$

where:
HPI = Heavy Metal Pollution Index
Wi = unit weight of the i-th heavy metal parameter
Qi = quality sub-index of the iii-th heavy metal parameter
n = number of heavy metal parameters included in the calculation
The quality sub-index (*Qi*) can be calculated as follows:

$$Qi = \frac{Mi-Ii}{Si-Ii}\, x\, 100 \quad \ldots(5)$$

where:
Mi = measured concentration of the *i*-th heavy metal
Ii = ideal value of the *i*-th heavy metal
Si = standard permissible value of the *i*-th heavy metal
The resulting HPI value was used to classify the level of heavy metal contamination in the river water samples.

2.5.5. Groundwater Assessment

The measured groundwater parameters consist of total *coliform*, *Escherichia coli*, odour, TDS, turbidity, colour, Fe, Mn, nitrite, and pH according to the Ministry of Health regulations. Therefore, groundwater quality is assessed using compliance with individual regulations and scores for the measured parameters.

For each well, the measured parameters are compared with the applicable regulatory standards. The results are reported as the frequency and percentage of violations. The score is calculated as the number of parameters that exceed the applicable standards in each well. This score is only used to describe the relative burden of water quality degradation measured between wells and across distance classes. Because the direction of groundwater flow, upgradient/background wells, well depth, soil permeability, and conservative leachate tracers were not studied, the groundwater findings in this research are interpreted as a decline in water quality around the landfill area. No direct causal conclusion regarding the migration of leachate into groundwater was made.

3. RESULTS

3.1. Leachate Characteristics and Leachate Pollution Index

The leachate dataset showed substantial regulatory non-compliance for several key parameters (Table 1). TSS, COD, and Fe exceeded their respective standards in all 15 observations, while BOD exceeded the standard in 14 of 15 observations (93.3%). Total *coliform* and total nitrogen exceeded their standards in 12 of 15 observations (80.0%) and 10 of 15 observations (66.7%), respectively. In contrast, pH remained within the permissible range, while Cd, Pb, and Hg did not exceed their regulatory limits. This observation-level reporting provides a more robust compliance interpretation than mean-based assessment alone because it identifies the proportion of individual samples exceeding each regulatory threshold.

Table 1. Leachate quality, regulatory standards and observation-level exceedance frequency (n = 15).

Parameter	Unit	Range	Mean ± SD	Standard	Exceed. n/N	Exceed. %
TSS	mg/L	196–1,278	703.0 ± 403.9	100	15/15	100.0
pH	–	8.45–8.66	8.54 ± 0.08	6–9	0/15	0.0
BOD	mg/L	78.2–935.7	723.5 ± 218.7	150	14/15	93.3
COD	mg/L	>1,650	>1,650	300	15/15	100.0
Cd	mg/L	<0.0031	<0.0031	0.1	0/15	0.0
Pb	mg/L	<0.0045–0.03	0.021 ± 0.010	0.1	0/15	0.0
Fe	mg/L	6.07–10.75	8.95 ± 1.19	5.0	15/15	100.0
Total *coliform*	MPN/100 mL	2,641–160,000	37,396 ± 56,503	3,000	12/15	80.0
Hg	mg/L	<0.0004	<0.0004	0.005	0/15	0.0
Total nitrogen	mg/L	25.1–555.9	98.6 ± 128.8	60	10/15	66.7

Note. Standards follow Minister of Environment and Forestry Regulation No. P.59/2016. COD is censored as >1,650 mg/L; the < notation denotes values below the laboratory reporting limit.

The exceedance pattern in Table 1 indicates that the principal leachate concerns were associated with suspended solids, oxygen-demanding organic pollutants, nitrogen, Fe, and microbiological contamination. Although Cd, Pb, and Hg remained below their regulatory limits, the consistent exceedance of TSS, COD, and Fe, together with the high exceedance frequency of BOD and total coliform, indicates that the leachate had substantial pollution potential. The censored COD values also suggest that COD-related interpretation should be treated conservatively. Overall, the observation-level compliance assessment shows that the leachate requires effective treatment and control before any environmental discharge.

The LPI assessment was used to summarize the overall pollution potential of the leachate based on organic, inorganic, and heavy-metal sub-indices. As shown in Table 2, the total LPI values ranged from 42.2 to 47.4, with a mean value of 44.2 across the three leachate stations. The highest total LPI was observed at L1, followed by L3 and L2. Because COD was reported as a right-censored value and was entered as a conservative lower-bound input, the calculated LPI values should be interpreted as conservative lower-bound estimates rather than exact pollution-index values.

Table 2. Leachate Pollution Index (LPI) and sub-indices by station (COD entered at the lower-bound value of 1,650 mg/L).

Station	Organic (LPIor)	Inorganic (LPIin)	Heavy metal (LPIhm)	Total LPI	Interpretation
L1	75.43	14.81	25.19	47.4	Lower-bound (COD censored)
L2	67.31	8.43	27.94	42.2	Lower-bound (COD censored)
L3	68.46	11.38	24.97	42.9	Lower-bound (COD censored)
Mean	70.40	11.54	26.03	44.2	High potential; organic dominant

Note. LPIor = organic pollution index; LPIin = inorganic pollution index; LPIhm = heavy metal pollution index. The LPI table summarizes index-based pollution assessment rather than direct laboratory concentrations.

The sub-index pattern in Table 2 indicates that the organic component was the dominant contributor to the total LPI at all leachate stations. The mean organic sub-index was 70.40, substantially higher than the inorganic sub-index of 11.54 and the heavy-metal sub-index of 26.03. This pattern is consistent with the high exceedance frequency of oxygen-demanding and nutrient-related parameters, particularly BOD, COD, and total nitrogen, as reported in Table 1. The heavy-metal sub-index was lower than the organic sub-index, reflecting the limited exceedance of Cd, Pb, and Hg, although Fe remained consistently above its regulatory threshold. Overall, the LPI results support the observation-level compliance findings by showing that the leachate had substantial pollution potential, mainly driven by organic and nutrient-related loads. Since COD was censored, the actual pollution potential may be higher than the calculated lower-bound LPI values.

3.2. Surface Water Quality and Reproducible Index Results

Surface water quality in the Sedapat River was evaluated using descriptive statistics and observation-level regulatory compliance against the applicable Class II water-quality standards. Table 3 presents the measured concentration range, mean value, standard deviation, regulatory threshold, and exceedance frequency for each assessed parameter. This observation-level approach was used to avoid relying solely on mean values, particularly for parameters that showed spatial variability or values close to the regulatory threshold.

Table 3. Observation-level Sedapat River water quality and Class II regulatory exceedance

Parameter	Unit	Range	Mean ± SD	Class II std	Exceed. n/N	Exceed. %
TSS	mg/L	28–38	31.8 ± 3.1	50	0/15	0.0
pH	–	7.65–8.04	7.85 ± 0.12	6–9	0/15	0.0
BOD	mg/L	2.31–3.34	2.80 ± 0.33	3	5/15	33.3
COD	mg/L	7–11	8.67 ± 1.33	25	0/15	0.0
Cd	mg/L	<0.0025	<0.0025	0.01	0/15	0.0
Pb	mg/L	0.004–0.010	0.0048 ± 0.0016	0.03	0/15	0.0
Fe	mg/L	2.31–3.49	2.88 ± 0.35	0.3	15/15	100.0
Total *coliform*	MPN/100 mL	1,702–4,934	2,707 ± 918	10,000	0/15	0.0
Hg	mg/L	<0.0004	<0.0004	0.002	0/15	0.0
Total nitrogen	mg/L	37.1–67.2	45.67 ± 9.78	15	15/15	100.0

Note. Surface-water standards refer to Government Regulation No. 22/2021 Class II values used in this assessment.

The observation-level compliance results in Table 3 show that Fe and total nitrogen were the most persistent water-quality concerns in the Sedapat River, as both parameters exceeded their respective standards in all observations. BOD also exceeded the Class II standard in several observations, indicating the presence of organic pressure at selected river stations. In contrast, TSS, pH, COD, Cd, Pb, total coliform, and Hg remained within their applicable limits across the observed samples. These results indicate that the main surface-water impairment was associated with Fe, nitrogen, and partial organic loading rather than broad exceedance across all measured parameters.

Although the exceedance pattern suggests water-quality pressure within the landfill study area, it should not be interpreted as direct evidence of landfill-specific impact on the river. The absence of confirmed upstream reference conditions, discharge-point verification, rainfall context, and repeated temporal monitoring limits causal attribution. Therefore, the river results are interpreted as regulatory exceedance and water-quality impairment in the study area, while the possible contribution of landfill-associated drainage, urban runoff, domestic wastewater, sediment interaction, and natural geochemical sources requires further investigation. The composite index assessment was used to summarize the overall surface-water condition of the Sedapat River based on general pollution intensity, organic and nutrient-related pressure, and heavy-metal contribution. As presented in Table 4, the NPI, OPI, and HPI values showed different pollution patterns across the five river stations. The NPI values indicated heavy pollution at all stations, whereas the corrected OPI values indicated moderate organic and nutrient-related pressure. In contrast, the HPI values remained within the low category, indicating that the aggregate heavy metal index was relatively low despite parameter-specific Fe exceedance.

Table 4. Composite index assessment ; Nemerow (NPI), Organic (OPI) and Heavy Metal (HPI) Pollution Indices for the Sedapat River stations.

Station	NPI value	NPI class	OPI value	OPI class	HPI value	HPI class
S1	7.13	Heavy pollution	2.27	Moderate	25.95	Low

Station	NPI value	NPI class	OPI value	OPI class	HPI value	HPI class
S2	7.84	Heavy pollution	2.31	Moderate	26.13	Low
S3	6.14	Heavy pollution	3.27	Moderate	24.81	Low
S4	7.12	Heavy pollution	2.52	Moderate	25.65	Low
S5	6.14	Heavy pollution	2.22	Moderate	24.87	Low

Note. NPI was calculated using Class II surface-water thresholds, with pH treated as compliant when values remained within the permissible range. OPI was calculated using BOD, COD, total nitrogen, and the actual BOD/COD ratio. HPI was calculated using normalized inverse-standard weights. Moderate refers to moderate organic and nutrient-related pressure, whereas Low refers to low aggregate heavy-metal pollution. Composite index results should be interpreted together with observation-level exceedance frequencies.

The NPI values ranged from 6.14 to 7.84 and were classified as heavy pollution at all Sedapat River stations. This result was mainly driven by the consistently high pollution ratios of Fe and total nitrogen, which exceeded their respective Class II standards in all observations. The corrected OPI values ranged from 2.22 to 3.27, indicating moderate organic and nutrient-related pressure rather than severe organic pollution. This pattern is consistent with the partial exceedance of BOD and the persistent exceedance of total nitrogen reported in the observation-level compliance results. The HPI values ranged from 24.81 to 26.13 and remained in the low category at all stations. This indicates that the aggregate heavy-metal index was low, largely because Cd, Pb, and Hg were below their regulatory limits. However, the low HPI classification should not be interpreted as the absence of metal-related concern, because Fe exceeded the applicable standard in every river observation. Therefore, the composite index results should be interpreted together with parameter-specific exceedance frequencies. Overall, the index assessment suggests that surface-water impairment in the Sedapat River was primarily associated with Fe, total nitrogen, and moderate organic pressure, rather than broad exceedance across all measured heavy metals.

3.3. Groundwater Quality in Shallow Dug Wells

The groundwater quality in shallow dug wells frequently shows non-compliance with microbiological, aesthetic, metal-related, and acid-base parameters (Table 5). Total coliform exceeded the standard of 0 CFU/100 mL in 28 out of 30 wells (93.3%), while *Escherichia coli* exceeded the standard in 19 wells (63.3%). Turbidity and colour also often do not meet the standards, exceeding the limits in 21 and 19 wells, respectively. Metal-related violations were observed for Fe and Mn in 14 and 16 wells, respectively, while pH was outside the acceptable range in 28 wells. On the other hand, TDS, odour, and nitrite comply with the applicable criteria in the available data.

Table 5. Shallow dug-well groundwater quality, standards, and observation-level exceedance frequency (n = 30).

Parameter	Unit	Range (min-max)	Mean ± SD	Regulatory standard	Compliance status
Total *coliform*	CFU/100 mL	0-200	60.2 ± 58.9	0	Does not meet the standard
Escherichia coli	CFU/100 mL	0-100	18.7 ± 26.1	0	Does not meet the standard
Odor	-	No odor	No odor	No odor	Meets the standard
Total dissolved solids (TDS)	mg/L	62-410	242.2 ± 95.7	<500	Meets the standard
Turbidity	NTU	0.77-21.5	7.73 ± 5.91	<3	Does not meet the standard
Temperature	°C	28	28 ± 0	±3° from air temperature	Meets the standard
Color	TCU	<1-200	50.23 ± 59.4	10	Does not meet the standard
Iron (Fe)	mg/L	0.02-3.50	0.90 ± 0.93	0.3	Does not meet the standard
Manganese (Mn)	mg/L	<0.003-0.60	0.10 ± 0.12	0.1	Meets the standard

Parameter	Unit	Range (min-max)	Mean ± SD	Regulatory standard	Compliance status
Nitrite (NO2-N)	mg/L	0.002-0.120	0.023 ± 0.030	3 (as N)	Meets the standard
pH	-	4.20-6.80	5.59 ± 0.75	6.5-8.5	Does not meet the standard

Note. Regulatory standards follow Ministry of Health Regulation No. 2/2023 for water used for hygiene and sanitation. The < symbol denotes concentrations below the laboratory reporting limit; n.a. = not assessed.

The results in Table 5 indicate that the main groundwater concerns were microbiological contamination, turbidity, colour, acidic pH, and elevated Fe and Mn in several wells. The high frequency of total *coliform* and *Escherichia coli* non-compliance suggests sanitation-relevant water quality impairment, while the recurrent exceedance of turbidity and colour indicates aesthetic and particulate-related deterioration. The groundwater temperature is relatively stable at 28°C, with an average of 28 ± 0°C, and meets regulatory requirements because the measured water temperature remains within ±3°C of the ambient air temperature at the research site, which averages 30°C. This indicates that temperature is not a limiting parameter for the suitability of shallow well water for hygiene and sanitation purposes according to the applied standards. The pH results show that most shallow-dug wells were acidic, which may influence metal mobility and water acceptability for hygiene and sanitation purposes.

The parameter-specific exceedance pattern also shows why compliance cannot be inferred from mean values alone. For example, Mn exceeded the standard in more than half of the wells, although the mean value was close to the regulatory threshold. Similarly, Fe showed substantial spatial variability, with some wells exceeding the standard by a large margin. However, these groundwater results should not be interpreted as evidence of a single contamination source. Microbiological indicators may be influenced by septic systems, poor wellhead protection, surface runoff, or household sanitation practices, while Fe, Mn, and acidic pH may also reflect local geogenic or hydrochemical conditions. Therefore, the groundwater findings are best interpreted as shallow dug-well water-quality impairment around the landfill study area, requiring improved well protection, sanitation control, and further hydrogeological investigation.

3.4. Distance-Based Screening of Groundwater Impairment

Distance-based screening was conducted to examine whether shallow-dug wells located closer to the landfill showed higher multi-parameter non-compliance than wells located farther away. The exceedance score was calculated as the number of non-compliant parameters among the assessable groundwater-quality variables for each well and then summarized by distance zone. As shown in Table 6, the mean exceedance score tended to be higher in wells located within 100 m of the landfill and lower in the outer distance zones. This analysis was used only as a descriptive spatial screening tool to identify proximity-related patterns of groundwater impairment.

Table 6. Groundwater exceedance score and selected mean parameter values by distance zone from the landfill.

Distance zone	n	Mean score	*Coliform*	*E. coli*	Turbidity	Colour	Fe	Mn	pH
0–50 m	3	6.33	83.67	13.33	10.19	183.67	3.12	0.19	5.35
51–100 m	4	6.50	88.00	33.75	7.74	79.75	1.62	0.32	5.56
101–150 m	5	5.40	43.60	30.00	6.92	74.80	1.21	0.08	6.00
151–200 m	6	4.50	36.83	3.33	9.73	35.00	0.64	0.15	5.38
>200 m	12	3.83	65.33	19.25	6.30	8.25	0.11	0.11	5.60

Note. The exceedance score represents the number of non-compliant parameters among total coliform, *Escherichia coli*, TDS, turbidity, colour, Fe, Mn, nitrite, and pH. The score is used only as a transparent descriptive screening indicator; it is not a standardized pollution index and should not be interpreted as evidence of landfill-specific contribution.

The distance-zone results in Table 6 show a decreasing trend in mean exceedance scores from the nearest zones to the farthest zone. Wells located within 0–50 m and 51–100 m had mean scores of 6.33 and 6.50, respectively, whereas wells located more than 200 m from the landfill had a lower mean score of 3.83. Higher mean colour and Fe values were also observed in the nearer zones, particularly within 0–50 m, suggesting that several groundwater-quality indicators were more pronounced in wells closer to the landfill. However, microbiological indicators and acidic pH were not limited to the nearest wells, indicating that groundwater impairment was spatially heterogeneous.

This proximity-related pattern should be interpreted cautiously. The distance-zone screening suggests an association between landfill proximity and higher multi-parameter exceedance scores, but it does not confirm landfill-specific leachate migration. Groundwater-flow direction, hydraulic gradient, well depth, soil permeability, upgradient or background wells, and conservative leachate tracers were not available in this study. Therefore, the results are best interpreted as descriptive evidence of proximity-related shallow dug-well impairment, requiring further hydrogeological investigation before any contaminant pathway or source-specific contribution can be confirmed.

4. DISCUSSION

The results of this study indicate that the degradation of water quality around the Sukawinatan Landfill is characterised by different patterns in leachate, river water, and shallow well groundwater. The leachate assessment shows a high pollution potential dominated by organic load, particulates, nitrogen, microbiological factors, and Fe-related elements. The river water assessment indicates damage primarily related to Fe, total nitrogen, and moderate organic stress. Meanwhile, the shallow dug well results show groundwater damage relevant to sanitation, particularly for microbiological indicators, turbidity, colour, Fe, Mn, and acidic pH. These findings should be interpreted as regulatory violations, index-based screening, and a decline in water quality related to proximity rather than direct evidence of confirmed contaminant pathways.

4.1. Leachate Characteristics and Pollution Potential

The leachate from Sukawinatan Landfill showed substantial pollution potential, mainly associated with suspended solids, oxygen-demanding organic matter, nitrogen compounds, Fe, and microbiological contamination. Although the pH was slightly alkaline, ranging from 8.45 to 8.66, this condition does not indicate low pollution risk. Frequent exceedances of BOD, COD, TSS, Fe, total nitrogen, and total coliform confirm that the leachate still contained high organic, particulate, nitrogenous, metal-related, and microbial loads. The BOD/COD ratio should be interpreted cautiously because COD was reported as a right-censored value above the laboratory reporting limit. Based on the censored COD threshold, the estimated BOD/COD ratio was ≤0.44, suggesting the presence of both biodegradable and refractory organic fractions. This indicates that biological treatment may reduce part of the organic load, but additional physicochemical or advanced treatment is likely required to remove persistent compounds before discharge or environmental release (Wang et al., 2018; Wdowczyk et al., 2020; Lindamulla et al., 2022).

The LPI results reinforce the concentration-based assessment. Total LPI values ranged from 42.2 to 47.4, with a mean value of 44.2, substantially exceeding the commonly cited treated-leachate disposal benchmark of LPI ≤7.4–7.5 (Kumar & Alappat, 2005; Rodriguez-Cardenas et al., 2025; Saghi et al., 2024). The organic sub-index was the dominant contributor, indicating that oxygen-demanding pollutants, nitrogen compounds, and microbiological indicators were the main drivers of leachate pollution potential. Because COD was entered as a conservative lower-bound input, the calculated LPI should be considered a lower-bound estimate, meaning that the actual pollution potential may be higher. This profile is consistent with studies showing that landfill leachate in tropical and developing-country settings commonly contains high organic, nutrient, and microbial loads that require integrated treatment systems (Lindamulla et al., 2022; Teng et al., 2021; J. Wang & Qiao, 2024). Elevated organic and nitrogen loads may increase oxygen demand and contribute to nutrient enrichment if inadequately treated leachate reaches receiving waters. High COD may also create operational problems in treatment and drainage systems, including clogging and reduced treatment efficiency if not properly managed (Teng et al., 2021). In addition, high total coliform levels indicate microbiological risk and reinforce the need for effective containment and disinfection control before any environmental discharge sources (Bouraada et al., 2023; Daniel et al., 2023; Mherzi et al., 2020). Although the heavy-metal sub-index was lower than the organic sub-index, Fe exceeded the regulatory threshold at all leachate stations and should therefore remain a management concern. Elevated Fe may contribute to discolouration, sediment deposition, turbidity formation, and secondary oxygen demand in receiving environments if discharged without adequate control (Abdel-Shafy et al., 2023; Essien et al., 2022). Thus, the relatively lower heavy-metal sub-index should not be interpreted as the absence of metal-related concern, particularly because Fe showed consistent exceedance.

Overall, the leachate findings show that Sukawinatan Landfill continues to generate polluted effluent despite pH conditions that may suggest a relatively stabilised or methanogenic phase. Leachate management should therefore prioritise suspended-solids removal, reduction of biodegradable and refractory organic loads, nitrogen control, microbial risk reduction, Fe removal, and strengthened containment. These measures are necessary to improve compliance with leachate standards and to reduce potential pressure on nearby environmental media.

4.2. Surface Water Pollution Dynamics in the Sedapat River

The Sedapat River showed selective water-quality impairment rather than broad contamination across all measured parameters. Observation-level compliance indicated that Fe and total nitrogen exceeded Class II surface-water standards in all river observations, while BOD exceeded the standard in one-third of the samples. In contrast, TSS, pH, COD, Cd, Pb, total coliform, and Hg remained within the applicable standards. This pattern confirms the importance of reporting exceedance frequency in addition to mean values, because average-based interpretation may obscure sample-level non-compliance, particularly for parameters close to regulatory thresholds. The composite indices provided a clearer screening of river impairment. The Nemerow Pollution Index classified the river in the heavy-pollution category, mainly due to high pollution ratios for Fe and total nitrogen. This indicates that a few dominant parameters can strongly influence aggregate pollution status, even when several conventional parameters remain compliant. Similar index-based approaches have been used to identify ecological risks driven by dominant pollutants that may not be fully captured through single-parameter assessment (Majed & Islam, 2022; Su et al., 2022). Based on the actual BOD/COD ratio, the OPI indicated moderate organic and nutrient-related pressure, which is consistent with partial BOD exceedance and compliant COD values. This differs from leachate-affected waters near the Cipayung landfill, where elevated BOD and COD were associated with dissolved oxygen depletion (Noerfitriyani et al., 2018).

The HPI showed a low aggregate heavy-metal index because Cd, Pb, and Hg were low or below reporting limits. However, this result should not be interpreted as the absence of metal-related concern, because Fe exceeded the regulatory threshold in every river observation. Elevated Fe may cause discoloration, turbidity formation, sediment staining, benthic habitat disturbance, and longer-term sediment degradation if pollutant inputs are not controlled (Badeenezhad et al., 2023; Essien et al., 2022; Jiang et al., 2018). The consistent exceedance of total nitrogen is also environmentally important because nitrogen enrichment can promote eutrophication, alter dissolved-oxygen dynamics, and reduce aquatic habitat suitability (Gobler et al., 2024; Jian et al., 2020). The selective behaviour of BOD and COD may reflect dilution, biodegradation, sediment adsorption, photochemical transformation, and hydrodynamic transport within the river system (Luan et al., 2024; J. Wang & Qiao, 2024). These processes can modify pollutant concentration, persistence, toxicity, and spatial distribution after pollutants enter receiving waters. Nevertheless, the consistent exceedance of Fe and total nitrogen indicates continuing pressure on the Sedapat River that is not fully represented by conventional oxygen-demand indicators alone.

Although Fe and total nitrogen may be related to landfill-associated pressure, the available data do not establish direct landfill causality. The study did not fully document upstream reference conditions, confirmed discharge points, river-flow direction, rainfall conditions during sampling, or a structured upstream–discharge–downstream comparison. Therefore, the observed impairment should be interpreted as water-quality deterioration in the landfill-adjacent river reach, not as definitive proof of a single landfill source. Other plausible contributors include urban runoff, domestic wastewater, local drainage, sediment–water interaction, and natural geochemical processes. Elevated Fe may also occur under reducing or anaerobic conditions, as reported in other Indonesian water-quality settings (Iresha et al., 2024). In contrast, Cd, Hg, and Pb remained low or below reporting limits in the present study, which differs from seasonal metal fluctuations reported near the Wukirsari landfill (Siswoyo & Habibi, 2018). Overall, the laboratory results and composite indices indicate that the Sedapat River was impaired mainly by Fe and total nitrogen, with moderate organic and nutrient-related pressure. These findings support improved leachate control, nitrogen reduction, Fe management, sediment monitoring, and continued river-water surveillance. Future monitoring should apply a structured upstream–discharge–downstream design, document rainfall and flow conditions, identify potential discharge points, and include repeated seasonal sampling to strengthen source attribution and management decisions.

4.3. Groundwater Impairment and Source Attribution Limits

Groundwater around the Sukawinatan Landfill showed clear impairment in shallow dug wells, mainly indicated by microbiological contamination, elevated turbidity and colour, Fe and Mn enrichment, and acidic pH. Frequent non-compliance for total coliform, *Escherichia coli*, turbidity, colour, Fe, Mn, and pH is relevant for public health because these parameters affect the suitability of groundwater for hygiene and sanitation. The presence of total coliform and *E. coli* indicates vulnerability to faecal or surface-derived contamination, which is common in shallow dug wells with inadequate wellhead protection, sanitary sealing, or construction quality (Adekanmbi et al., 2024). The physicochemical pattern suggests that hydrogeochemical processes may also influence groundwater quality. Acidic pH and elevated Fe and Mn can result from reducing subsurface conditions, metal mobilization, local soil and geological characteristics, poor well construction, or interaction with contaminated shallow groundwater. Organic-rich and reducing environments may promote Fe and Mn release and lower pH, as reported in leachate-affected groundwater systems where organic matter degradation and weak hydraulic protection alter groundwater chemistry (Dagwar & Dutta, 2024; Islam & Mostafa, 2024). However, these indicators are not specific to landfill leachate because similar responses may also arise from geogenic Fe/Mn release, sanitation systems, surface runoff, animal waste, and unsanitary water handling.

The distance-zone screening showed a proximity-related pattern. Wells closer to the landfill, particularly within the 0–100 m zone, generally had higher exceedance scores than wells in outer zones. Colour and Fe had the strongest negative correlations with distance, suggesting possible attenuation or dilution with increasing distance from the landfill. This pattern is consistent with studies reporting poorer groundwater quality near dumping areas and declining pollutant levels farther from the source (Madhusudhan et al., 2026). Madhusudhan et al. (2026) also showed that LPI, WQI, and cluster-based classification can distinguish groundwater-quality gradients around landfill-affected areas. Nevertheless, the results should be interpreted as proximity-related impairment rather than confirmed landfill-leachate plume migration. Distance alone cannot prove a contaminant pathway. This study did not measure groundwater-flow direction, hydraulic gradient, well depth, soil permeability, background or upgradient groundwater quality, chloride, ammonium, or other conservative leachate tracers. Therefore, landfill-specific contribution cannot be quantified. The absence of upgradient or background wells also prevents the establishment of a natural baseline, and a theoretical constant would not adequately represent local groundwater conditions. This cautious interpretation is consistent with the view that source attribution at unconfined dumpsites requires hydrogeological characterization and tracer-based evidence (Parvin & Tareq, 2021). Overall, the groundwater findings indicate impaired shallow-well quality and a proximity-related public-health concern, but they do not independently prove landfill-specific contamination. Potential co-sources such as septic tanks, poor wellhead protection, surface runoff, animal waste, unsanitary water handling, and geogenic Fe/Mn mobilization remain plausible. Thus, wells near the landfill boundary should receive priority protection through sanitary upgrading, wellhead sealing, routine monitoring, and further hydrogeological investigation.

4.4. Practical Implications for Landfill Management

The findings indicate that Sukawinatan Landfill management should prioritise leachate control, protection of nearby water bodies, and risk reduction for communities using shallow groundwater. Because the main pollutants were suspended solids, organic matter, nitrogen compounds, microbial indicators, and iron, leachate treatment should target TSS, BOD, COD, nitrogen, microbial contamination, and dissolved Fe before environmental discharge. Biological treatment is important for reducing organic matter and nitrogen, but it should be combined with physicochemical processes to improve the removal of suspended solids, refractory organics, iron, and microbial pollutants (Nanda & Berruti, 2021; Teng et al., 2021). Leachate containment should also be strengthened through reliable liner systems, effective collection channels, properly managed storage ponds, and regular inspection of drainage and hydraulic structures. Future COD analysis should use a wider analytical range because censored COD values reduce the precision of treatment evaluation and LPI calculation. Surface-water monitoring in the Sedapat River should apply clearly defined upstream, near-discharge, and downstream stations, supported by records of flow direction, discharge points, rainfall, sampling dates, and river-flow conditions. Monitoring should focus on nitrogen, Fe, BOD, COD, and sediment-associated metals because river impairment in this study was mainly related to nitrogen and iron.

Groundwater protection should focus on shallow dug wells near the landfill, especially those exceeding microbiological or metal standards. Practical measures include wellhead protection, dug-well sealing, prevention of surface runoff entry, water disinfection or treatment before use, alternative safe water supply for high-risk households, and routine groundwater monitoring. Risk communication and community involvement are also needed to help residents identify unsafe wells, report water-quality changes, and adopt safer water-use practices (Mherzi et al., 2020; Rogers et al., 2021). Although the results support preventive management, they do not prove that all groundwater contamination originated from landfill leachate. Stronger source attribution requires hydrogeological data, including groundwater level, flow direction, hydraulic gradient, well depth, soil permeability, upgradient and downgradient monitoring wells, repeated sampling, and conservative tracers such as chloride and ammonium. Overall, Sukawinatan Landfill management should integrate leachate treatment, engineered containment, river and groundwater monitoring, hydrogeological assessment, and community water-safety actions to reduce surface-water impairment and local groundwater risks.

5. CONCLUSION

This study shows that leachate from the Sukawinatan Landfill has high pollution potential, with a mean total LPI of 44.2 dominated by the organic sub-index. The main pollution pressures were associated with suspended solids, organic matter, nitrogen compounds, iron, and microbiological contamination. TSS, COD, and Fe exceeded standards in all leachate observations, while BOD, total coliform, and total nitrogen also showed frequent non-compliance, indicating that untreated or poorly controlled leachate poses a significant risk to surrounding water environments.

The Sedapat River showed water-quality impairment mainly driven by Fe and total nitrogen, which exceeded Class II standards in all observations, together with partial BOD exceedance. Composite indices supported this interpretation: NPI indicated heavy pollution, OPI indicated moderate organic and nutrient pressure, and HPI indicated low overall heavy-metal index values, although Fe remained a consistent parameter of concern. These findings show that observation-level compliance provides a more reliable interpretation than average-based assessment alone, particularly for parameters with high variability or values close to regulatory thresholds. Shallow dug wells near the landfill also showed frequent non-compliance for microbiological indicators, turbidity, colour, Fe, Mn, and pH, with higher exceedance scores generally found in wells closer to the landfill. However, because groundwater-flow direction, background wells, well-depth data, hydrogeological characteristics, and conservative leachate tracers were not investigated, groundwater deterioration should be interpreted as proximity-related impairment rather than confirmed landfill-specific contamination.

Overall, the findings support strengthened leachate treatment and containment, reproducible index reporting, standardized upstream–discharge–downstream river monitoring, follow-up hydrogeological studies, and sanitary protection of shallow community wells. Effective management of the Sukawinatan Landfill should integrate leachate control, surface-water and groundwater monitoring, protective buffer measures, and community water-safety actions to reduce environmental impacts and protect local water sources.

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8. DESCRIPTION OF ABBREVIATIONS

BOD, Biochemical Oxygen Demand; Cd, Cadmium; COD, Chemical Oxygen Demand; Fe, Iron; HPI, Heavy Metal Pollution Index; Hg, Mercury; LPI, Leachate Pollution Index; LPIhm, heavy-metal sub-index of the Leachate Pollution Index; LPIin, inorganic sub-index of the Leachate Pollution Index; LPIor, organic sub-index of the Leachate Pollution Index; LWPI, Landfill Water Pollution Index; Mn, Manganese; MPN, Most Probable Number; NPI, Nemerow Pollution Index; OPI, Organic Pollution Index; Pb, Lead; SGL, dug-well sampling location; SNI, Indonesian National Standard; TDS, Total Dissolved Solids; TN, Total Nitrogen; TSS, Total Suspended Solids;

9. BACKGROUND INFORMATION FOR RECORD (NOT TO BE PRINTED)

Author Contributions

Conceptualization, P; methodology, P.; validation, H.H., F.G. and F.H.; formal analysis, P.,H.H, F.G, F.H.; investigation, N.D, R.F.; resources, P, H.H, F.G, F.H.; data curation, P.; writing original draft preparation, P.; writing review and editing, H.H, F.G, F.H.; visualization, P.; supervision, N.D, R.F.; project administration, P., H.H.; funding acquisition, not **applicable**. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable, as this study did not involve humans or animals

Informed Consent Statement

Ethical review and approval were waived for this study because the research did not involve human or animal experimentation. The study only involved environmental water sampling and did not collect personal, medical, or sensitive information from participants.

Conflicts of Interest

The authors declare no conflicts of interest.