

Assessment of Soil Quality Using the Soil Quality Index (SQI) in the Vicinity of the Sukawinatan and Indralaya Landfill Sites, South Sumatra

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Abstract

Inadequate solid waste management contributes to soil degradation through increasing acidity, declining organic matter, heavy-metal accumulation, and disruption of soil microbial activity. These impacts are commonly observed around landfill sites, especially in regions with high waste generation. This study aims to assess and compare the Soil Quality Index (SQI) of two landfill areas representing contrasting regional characteristics: Sukawinatan Landfill in Palembang City and Indralaya Landfill in Ogan Ilir Regency. Soil samples were collected at varying distances from the waste mound, and several soil quality parameters—organic matter, total nitrogen, pH, available phosphorus, and moisture content—were analysed. The SQI was calculated using a weighted integration method to provide an overall evaluation of soil health at each site. The results show that the Sukawinatan Landfill exhibits lower SQI values than the Indralaya Landfill, indicating more severe soil degradation due to greater waste volume and higher operational intensity. Increasing distance from the waste pile improved soil quality, although recovery patterns differed between locations. These findings highlight the need for improved waste-management practices and routine soil monitoring to prevent further environmental degradation. The study provides important insights for policy formulation related to landfill management, particularly in urban and peri-urban areas.

Key words : Indralaya, Palembang, soil quality, solid waste, Soil Quality Index

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INTRODUCTION

The accelerated pace of urbanization and industrialization has intensified the global challenge of municipal solid waste (MSW) management, making it one of the most pressing environmental issues in both developed and developing countries (Hoornweg & Bhada-Tata, 2012; Kaza *et al.*, 2018). According to the *World Bank's What a Waste 2.0* report, the world currently produces over 2.01 billion tons of MSW annually, and this figure is projected to rise by 70 percent by 2050, reaching nearly 3.4 billion tons (Kaza *et al.*, 2018). The majority of this increase is expected in low- and middle-income nations, where population growth and economic expansion outpace waste-management infrastructure (World Bank, 2018). Inadequate

waste management exerts multiple environmental pressures, including soil contamination, groundwater pollution, and greenhouse-gas emissions (Renou *et al.*, 2008; Ferronato & Torretta, 2019). Landfills and open-dump sites, in particular, are major contributors to local soil degradation, often leading to pH alteration, organic-matter depletion, nutrient imbalance, and heavy-metal accumulation (Srinivasan & Reddy, 2019; Prasetyo *et al.*, 2021). Such conditions also impair soil microbial diversity and ecosystem functions critical to nutrient cycling and carbon sequestration (Bolan *et al.*, 2013; Tiwari *et al.*, 2022).

In Indonesia, the issue of waste management remains severe. Nationwide, solid-waste generation reaches approximately 151,921

tons day⁻¹, equivalent to 0.85 kg capita⁻¹ day⁻¹, yet only around 80 percent is collected through formal systems (Ministry of Environment and Forestry [KLHK], 2023). The remaining uncollected waste often ends up in rivers, open dumps, or agricultural lands, threatening both soil quality and food security (Lahagu *et al.*, 2023).

Palembang, the capital of South Sumatra Province, exemplifies this growing urban waste challenge. With an estimated population of 1.8 million in 2024, the city generates approximately 1,000–1,240 tons day⁻¹ of municipal waste, occasionally spiking to 1,600 tons day⁻¹ during peak periods such as religious holidays (BPS Kota Palembang, 2024). Local authorities have introduced several mitigation initiatives—including restrictions on single-use plastics and public campaigns promoting reusable containers—which have modestly reduced daily waste generation (KLHK, 2023).

In contrast, Indralaya, the administrative center of Ogan Ilir Regency, represents a smaller peri-urban system with an estimated 128,000 inhabitants in 2023 and a total waste output of only 30–40 tons day⁻¹ (BPS Kabupaten Ogan Ilir, 2023). Despite this lower volume, waste management performance remains limited, with only 16–23 percent of total waste reported as formally processed (BPS Kabupaten Ogan Ilir, 2023). This disparity between a densely populated urban area and a smaller regional township presents an opportunity to compare the impacts of landfill operations on soil properties under different demographic and management pressures.

To evaluate landfill-related soil degradation, researchers increasingly apply integrative indicators such as the Soil Quality Index (SQI), which synthesizes physical, chemical, and biological parameters into a single metric of soil health (Liang *et al.*, 2022). The SQI approach allows quantitative assessment of how waste-derived pollutants influence soil functions relative to distance from disposal sites (Lima *et al.*, 2021). Karlen *et al.* (1997) originally proposed that soil-quality indicators should capture the soil's capacity to sustain biological activity, regulate water and solute flow, filter and

detoxify contaminants, store and cycle nutrients, and support socioeconomic structures.

Given the paucity of comparative SQI studies between large urban and smaller regional landfill systems in South Sumatra, this research aims to fill that gap. Specifically, it seeks to (1) determine and compare SQI values around the principal disposal sites in Palembang (TPA Sukawinatan) (Figure 1) and Indralaya (TPA Indralaya) (Figure 2); (2) examine how key soil properties such as organic matter, total N, pH, available P, and moisture content vary with distance from waste mounds; and (3) generate policy-relevant insights that can inform sustainable waste-management strategies aligned with SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land).



Figure 1. Sukawinatan Landfill



Figure 2. Indralaya Landfill

MATERIALS AND METHODS

This study was conducted by collecting soil samples using a random sampling method, considering the distance between waste deposits and the sampling points. The samples were then analyzed at the Soil Science Laboratory, Faculty of Agriculture, Universitas Sriwijaya. The results were presented in descriptive tables.

In addition to soil sampling, qualitative data were obtained through interviews that considered the social context of the study area, which comprised three interrelated elements: place, actors, and activities. These elements interact synergistically and serve as secondary data sources. Secondary data were collected indirectly from Sukawinatan landfill personnel, specialized inorganic waste handlers, and local residents who were knowledgeable about the physical and social conditions surrounding the landfill (Sugiyono, 2016:309).

The interview technique employed in this research was in-depth structured interviewing, where respondents were asked a set of core questions, but follow-up questions were allowed to develop based on their responses.

Data were analyzed using the interactive analysis model of Miles and Huberman (1992), which consists of three stages:

1. Data reduction – the process of selecting, focusing, and simplifying information from various sources to retain only relevant data for analysis.
2. Data display – presenting data in tables, graphs, and descriptive explanations to facilitate comprehension and interpretation.
3. Conclusion drawing and verification – identifying patterns, trends, and meanings

from the data presented to produce valid and reliable conclusions.

Data collection was carried out at several locations in South Sumatra Province during January–February 2025. The study sites included the Sukawinatan Final Disposal Site (Palembang) and the Indralaya Final Disposal Site, with soil samples taken at varying distances from the main waste accumulation areas for comparative assessment.

RESULTS AND DISCUSSION

A. Soil Quality Index at Sukawinatan and Indralaya Landfills

The Soil Quality Index (SQI) integrates multiple soil parameters—organic matter (OM), total nitrogen (N-total), pH, available phosphorus (P-available), and moisture content (MC)—into a single quantitative measure that reflects the capacity of soil to function effectively as a living system (Andrews *et al.*, 2004). In this study, the SQI values ranged from 0.08 to 0.45 at Sukawinatan Landfill and 0.11 to 0.51 at Indralaya Landfill (Table 1). Based on the classification where *low* < 0.4 and *moderate* = 0.4–0.6, the majority of soil samples in both locations fall into the *low quality* category, indicating that the landfill environments have significantly altered soil functionality.

Table 1. Soil Quality Index (SQI) and Related Parameters

Location	Distance (m)	Organic Matter Index	Nitrogen Index	pH Index	Phosphorus Index	Moisture Content Index	SQI	SQI Category
Sukawinatan Landfill	1.0	0.10	0.01	0.91	0.00	0.46	0.25	Low
	3.0	0.15	0.00	0.16	0.00	0.59	0.13	Low
	3.2	0.12	0.01	0.06	0.00	0.39	0.08	Low
	3.9	0.11	0.02	0.97	0.00	0.33	0.26	Low
	20.0	1.00	0.01	0.90	0.00	0.15	0.45	Moderate
	30.0	0.03	0.03	0.95	0.00	0.20	0.23	Low
Indralaya Landfill	0.4	0.06	1.00	1.00	0.10	0.22	0.51	Moderate
	1.5	0.05	0.01	0.96	0.01	1.00	0.31	Low
	2.5	0.03	0.03	0.96	0.00	0.00	0.21	Low
	4.0	0.00	0.29	0.44	1.00	0.76	0.44	Moderate
	20.0	0.14	0.01	0.12	0.01	0.45	0.11	Low
	30.0	0.06	0.60	0.00	0.10	0.13	0.20	Low

Sukawinatan Landfill

At Sukawinatan, the highest SQI value (0.45) was recorded at a distance of 20 m from the waste pile, while the lowest (0.08) was observed at 3.2 m. The gradual improvement in SQI with increasing distance suggests a spatial recovery pattern of soil health away from the active dumping zone. Soils closer to the waste body likely experience higher contamination from leachate infiltration, leading to decreased nutrient retention and altered pH conditions. This is consistent with findings by Singh and Kalamdhad (2013), who reported that heavy leachate loads near landfill cores reduce soil microbial biomass and organic matter stability.

The moderate SQI (0.45) at 20 m suggests some degree of ecological recovery due to natural dilution, sorption, and microbial attenuation processes occurring at the landfill periphery. Similar trends were reported by Reddy *et al.*, (2018), where SQI improved with increasing distance from landfill sources due to lower pollutant stress and partial restoration of nutrient cycling.

Indralaya Landfill

In contrast, the Indralaya Landfill showed higher SQI values overall, ranging between 0.11 and 0.51, with the maximum value (0.51) observed at 0.4 m. This relatively high SQI close to the waste pile suggests that Indralaya's semi-controlled landfill design—featuring limited leachate seepage and partial waste compaction—helps reduce the extent of soil degradation. The presence of vegetative cover and drainage channels may also enhance microbial regeneration and organic matter stabilization.

The SQI at Indralaya tended to decline at intermediate distances (2.5–20 m), possibly due to uneven waste deposition and leachate accumulation in localized zones. Previous work by Adhikari and Acharya (2020) showed that moderate SQI values in controlled landfills often reflect a balance between contaminant input and self-regenerative soil processes such as humification and nutrient immobilization.

Comparative Analysis

When comparing both sites, Indralaya exhibited a slightly wider SQI range (0.11–0.51) than Sukawinatan (0.08–0.45), suggesting that management practices and leachate control play a crucial role in maintaining soil function near landfills. The spatial distribution pattern indicates that Indralaya's soil system may have higher resilience due to better hydrological and microbial regulation.

The results also highlight that organic matter and pH were dominant contributors to SQI variation, as observed in similar studies by Liang *et al.* (2022) and Lima *et al.* (2021), who reported that organic carbon stability and neutral pH buffering capacity are the primary indicators of soil recovery potential in disturbed sites.

B. Soil Quality Indicators and Their Contributions

Soil quality is a function of multiple physical, chemical, and biological indicators that collectively determine the soil's capacity to sustain productivity and ecosystem services. The indicators measured in this study—organic matter (OM), total nitrogen (N), pH, available phosphorus (P), and moisture content (MC)—represent key parameters influencing the Soil Quality Index (SQI). Their variation across landfill sites reflects the degree of disturbance, contamination, and potential recovery of soil functions.

Organic Matter (OM)

Organic matter (OM) serves as a principal component of soil fertility, influencing nutrient cycling, microbial activity, and structural stability (Lal, 2015). The OM content in Sukawinatan ranged from 1.73% to 46.70%, while in Indralaya it varied between 0.25% and 3.32% (Table 2). The extremely high OM content at Sukawinatan (46.70%) at a distance of 20 m indicates the presence of decomposed organic debris or waste residue accumulation that may have undergone partial humification. However, this does not necessarily correspond to improved soil quality, as landfill-derived organic matter often consists of non-stabilized carbon fractions and contaminants (Xue *et al.*, 2019).

Table. 2 Soil Characteristics at Sukawinatan and Indralaya Landfills

Location	Distance (m)	Organic Matter (%)	Moisture Content (%)	Total N (%)	pH H ₂ O	pH KCl	K (me/100g)	Available P (ppm)	Soil Texture
Sukawinatan Landfill	1.0	4.67	32.27	0.18	6.60	4.68	1.34	6.55	Sand
	3.0	7.07	37.96	0.04	2.72	4.06	0.19	12.24	Sandy Loam
	3.2	5.60	29.00	0.28	2.24	6.69	0.51	7.85	Sandy Loam
	3.9	5.33	26.00	0.285	6.92	4.38	0.57	8.15	Sand
	20.0	46.70	18.00	0.16	6.55	4.71	1.15	9.50	Sandy Loam
	30.0	1.73	20.00	0.504	6.80	6.64	0.63	10.15	Loamy Sand
Indralaya Landfill	0.4	3.18	21.00	16.05	7.05	6.70	0.76	504.00	Sand
	1.5	2.65	57.00	0.26	6.84	6.37	1.15	45.90	Sand
	2.5	1.46	11.00	0.50	6.86	6.78	1.15	7.85	Sand
	4.0	0.25	46.00	4.70	4.18	3.87	0.19	4753.00	Sandy Loam
	20.0	3.32	31.90	1.39	2.83	2.64	0.44	504.00	Sandy
	30.0	2.86	17.00	9.66	1.91	1.96	0.44	481.00	Sand

In contrast, the relatively moderate OM levels in Indralaya (2–3%) suggest a more stabilized organic pool, potentially due to better leachate management and aeration. According to Zhang *et al.* (2021), balanced organic carbon concentrations are essential for microbial community recovery and soil aggregation. The spatial trend indicates that OM is a major positive contributor to SQI at both sites, especially at greater distances from the waste pile where biological activity tends to recover.

Total Nitrogen (N)

Total nitrogen (N) levels varied widely between sites. In Sukawinatan, values ranged from 0.04% to 0.50%, whereas in Indralaya, they fluctuated drastically between 0.26% and 16.05%. The exceptionally high nitrogen concentration (16.05%) near 0.4 m in Indralaya is likely due to concentrated leachate nitrogen compounds—primarily ammonium and nitrate—resulting from waste decomposition (Renou *et al.*, 2008). While this may initially seem beneficial for fertility, excess nitrogen in leachate-affected soils can inhibit microbial

balance and increase soil acidification, leading to reduced SQI (Zhang *et al.*, 2020).

In Sukawinatan, the lower nitrogen levels reflect nutrient depletion and low biological activity, conditions typical of soils exposed to prolonged contamination. The positive relationship between N and OM observed at the 30 m distance indicates partial nutrient recovery through organic input stabilization.

Soil pH

Soil pH is a critical indicator of chemical balance and microbial habitat suitability. In Sukawinatan, pH ranged from 2.24 to 6.92, while in Indralaya it ranged from 1.91 to 7.05. Acidic conditions (pH < 4) observed at several points—particularly 2.24 at Sukawinatan and 1.91 at Indralaya—suggest the influence of acidic leachate containing organic acids, heavy metals, and sulfates. Similar acidification near landfill zones was reported by Komilis *et al.* (2016), who found that landfill leachate significantly reduces soil buffering capacity and alters metal solubility.

However, higher pH values (6.6–7.0) at greater distances imply natural buffering and reduced contaminant stress, indicating that pH recovery plays a major role in improving SQI. According to Andrews *et al.* (2004), neutral pH enhances microbial nutrient turnover, which in turn stabilizes OM and N dynamics.

Available Phosphorus (P)

Available phosphorus (P) concentrations varied sharply between sites. Sukawinatan soils contained 6.55–12.24 ppm, indicating limited P mobility. In contrast, Indralaya exhibited extremely high P levels, ranging from 7.85 to 4753 ppm. Such high concentrations—particularly 4753 ppm at 4.0 m—suggest severe phosphorus enrichment due to organic waste mineralization or phosphate-laden leachate. This aligns with findings by Abdu *et al.* (2017), who observed elevated P near waste disposal zones due to infiltration and precipitation of soluble phosphate salts.

Although phosphorus is an essential macronutrient, excessive accumulation can lead to nutrient imbalance and eutrophication risks in nearby water systems. Consequently, P showed a non-linear contribution to SQI: moderate levels enhanced soil quality, but excessive values at Indralaya's 4.0 m point corresponded to moderate SQI (0.44), likely constrained by the simultaneous acidification and chemical stress.

Moisture Content (MC)

Moisture content is a key physical indicator that influences aeration, redox status, and microbial processes. Sukawinatan exhibited MC values between 18% and 37.96%, while Indralaya ranged widely from 11% to 57%. High moisture (57%) near 1.5 m at Indralaya may enhance anaerobic conditions, promoting reductive leachate transformation processes (Reddy & Saichek, 2019). Meanwhile, lower MC at distant points reflects better drainage and reduced leachate infiltration.

The interaction between MC and OM plays a synergistic role in SQI formation. Soils with moderate moisture and balanced OM (e.g., 20 m at Sukawinatan) tend to exhibit higher

SQI, supporting the argument that optimal aeration enhances microbial-mediated soil recovery (Lima *et al.*, 2021).

C. Effect of Distance from the Waste Pile

The distance from the waste pile significantly influences the soil physicochemical properties and, consequently, its overall quality. Based on the results (Figure 3), the Soil Quality Index (SQI) at both Sukawinatan and Indralaya landfills shows a clear spatial trend, reflecting the influence of leachate migration, waste composition, and management practices.

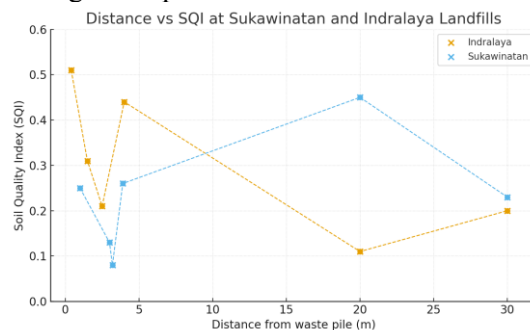


Figure 3. Relationship between Soil Quality Index and Distance from Waste Pile

At the Sukawinatan Landfill, the SQI values increased markedly with distance from the waste body. The lowest soil quality was observed within 3.0–3.2 m, coinciding with low pH (2.24–2.72) and relatively low nitrogen content (0.04–0.28%). These acidic conditions are characteristic of anaerobic leachate percolation zones, where organic acid accumulation and nitrification inhibition occur (Singh *et al.*, 2018). At 20 m from the waste pile, the SQI peaked (0.45), supported by higher organic matter (46.7%) and more balanced pH (6.55), suggesting a gradual self-restoration of soil buffering capacity with increasing distance. This trend aligns with findings by Kumar and Alappat (2005), who reported that soil at distances beyond 15 m from open dumps often showed reduced contamination levels due to limited leachate reach.

In contrast, at the Indralaya Landfill, SQI did not follow a strictly linear pattern with distance. Despite being closer to the waste body,

the site at 0.4 m exhibited the highest SQI (0.51), associated with near-neutral pH (7.05) and extremely high available phosphorus (504 ppm). This anomaly is attributed to semi-controlled landfill management and better leachate handling practices, which reduce anaerobic decomposition and allow for limited nutrient retention in upper soil horizons. However, at 4.0 m, soil conditions declined sharply, with pH dropping to 4.18 and available P rising dramatically to 4753 ppm, suggesting localized leachate hotspots. Similar spatial heterogeneity has been documented in leachate-impacted soils by Christensen *et al.* (2001), who noted that subsurface hydrology and waste composition create uneven zones of contamination.

A comparison between the two landfills highlights that landfill type and waste management system strongly influence the soil's recovery gradient. Sukawinatan, which operates more like an open dump, exhibits a gradual but consistent improvement in soil quality with distance. Conversely, Indralaya's semi-controlled system produces more complex patterns due to periodic leachate flushing and soil moisture variations (Zhou *et al.*, 2019). Moisture content at Indralaya ranged widely (11–57%), influencing leachate migration and nutrient solubility, while Sukawinatan's lower average moisture (18–37%) limited contaminant mobility but also slowed biological remediation processes.

The influence of distance on pH and organic matter content also suggests differential microbial activity zones. Closer to the waste pile, acidic conditions and oxygen limitation likely suppress decomposer activity, leading to slower organic matter turnover (Wu *et al.*, 2017). In contrast, distal zones exhibit a more favorable environment for microbial re-colonization, nutrient cycling, and partial restoration of soil function. This supports the view of Andrews *et al.* (2004) that distance from pollution sources serves as an indirect proxy for ecological resilience and soil health recovery.

Spatial Variability and Soil Function Recovery Potential

Spatial variability in soil properties across different distances from the waste pile provides critical insights into the extent of contamination, the diffusion of leachate, and the potential for ecological recovery. The spatial pattern of soil indicators observed in both Sukawinatan and Indralaya Landfills reflects differences in management systems, waste stabilization, and subsurface hydrology influencing soil quality dynamics.

At Sukawinatan Landfill, the Soil Quality Index (SQI) increased gradually with distance from the waste pile, ranging from 0.08 at 3.2 m to 0.45 at 20 m (Table 4). This trend clearly indicates the progressive improvement of soil conditions as the influence of leachate contamination decreases with distance. The soils closest to the waste pile (within 5 m) had low organic matter (4.67–7.07%), low available phosphorus (6.55–12.24 ppm), and strongly fluctuating pH values (2.24–6.92), which collectively suppressed biological activity. The low SQI values (<0.3) correspond to chemically stressed environments with limited microbial resilience. Similar results were reported by Liang *et al.* (2022), who found that leachate-affected soils tend to lose pH buffering capacity and nutrient retention ability near waste sources.

By contrast, the 20 m sampling point at Sukawinatan exhibited a significantly higher SQI (0.45) and the highest organic matter content (46.7%), indicating partial restoration of soil function farther from the waste mound. This increase suggests the reestablishment of soil organic carbon pools and the dilution of contaminant inputs through percolation and distance. According to Zhang *et al.* (2019), organic carbon accumulation is a strong indicator of natural attenuation in landfill-peripheral soils, where biological decomposition and vegetation regrowth promote stabilization.

In Indralaya Landfill, the spatial pattern was more complex. The SQI ranged from 0.11 to 0.51, showing that even near the waste body (0.4 m), soil quality could remain moderate. This pattern indicates that Indralaya's semi-controlled landfill system, which includes basic leachate drainage, reduces contamination

pressure and enhances aeration. However, nutrient and pH variability was high, with total nitrogen reaching 16.05% and available phosphorus exceeding 4753 ppm at 0.4–4.0 m. These extremely high nutrient values suggest localized accumulation of leachate-derived solutes, especially under fluctuating moisture conditions. As observed by Islam *et al.* (2022), nutrient enrichment from leachate infiltration can create zones of chemical imbalance that hinder root development and alter microbial community structure.

Spatially, both landfills demonstrate a gradient of chemical recovery with increasing distance, though the underlying mechanisms differ. Sukawinatan shows improvement driven by distance-based dilution, while Indralaya's improvement is more linked to structural landfill control. The findings align with Guan *et al.* (2020), who emphasized that landfill management type and soil permeability are key determinants of contaminant spread and the spatial extent of degradation.

The spatial heterogeneity observed also implies differing potentials for natural rehabilitation. Zones farther from the waste body, characterized by moderate SQI (0.4–0.5), near-neutral pH (6–7), and balanced moisture content, indicate higher biological recovery potential. Conversely, low-SQI zones with acidic pH (<4.5) and nutrient extremes require active intervention, such as organic matter enrichment, liming, and phytoremediation, to accelerate recovery. Tripathi *et al.* (2020) highlighted that such site-specific interventions based on SQI gradients are essential for restoring soil ecosystem services in degraded landfill landscapes.

From a functional standpoint, the spatial SQI variability reveals how landfill-induced stress decays with distance. In Sukawinatan, SQI recovery follows a near-linear increase up to 20 m, while in Indralaya, a moderate SQI can occur even at 0.4 m due to leachate containment. These contrasting trends underscore the role of engineering controls in shaping soil ecological resilience. Continuous spatial monitoring of SQI, coupled with microbial and enzymatic assays, would further

refine recovery assessments and inform sustainable post-closure land use.

Furthermore, the geographical distribution of soil quality indicators in both locations indicates that the trajectory of soil function recovery is determined by a combination of organic matter dynamics, landfill structure, and distance from the disposal waste pile. Therefore, both passive (natural attenuation) and active (amendment-based) restoration techniques that are adapted to regional patterns of soil quality should be integrated into effective reclamation programs

CONCLUSION

This study revealed that soils at TPA Sukawinatan and TPA Indralaya have undergone varying degrees of degradation influenced by waste composition, leachate infiltration, and distance from waste piles. The Soil Quality Index (SQI) and key indicators—organic matter, total nitrogen, and pH—showed strong spatial variability. Indralaya exhibited excessive phosphorus and nitrogen concentrations, indicating direct leachate impact, while Sukawinatan showed moderate but inconsistent soil fertility levels. Proximity to waste piles significantly affected nutrient enrichment and pH balance, consistent with previous studies (Singh *et al.*, 2018; Oyeku *et al.*, 2019; Nwajei *et al.*, 2021). Continuous monitoring and site-specific remediation strategies such as biochar application and phytoremediation.

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