A COMPOSITE SOIL QUALITY INDEX INTEGRATING CHEMICAL FERTILITY AND PHYSICAL MATURITY INDICATORS FOR TROPICAL PEAT SOILS IN MAHAKAM TENGAH, EAST KALIMANTAN

Titin Eka Setianingsih*, Bagus Adi Nugroho, Zulkarnain, Raden Mas Nurhartanto

Department of Agroecotechnology, Agriculture Faculty, Mulawarman University, Jl. Pasir Balengkong Gunung Kelua, Samarinda, East Kalimantan, Indonesia

Corresponding author: titineka@faperta.unmul.ac.id

Abstract

Individual soil properties each capture only one dimension of peat condition, so composite soil quality indices (SQI) that integrate multiple chemical and physical indicators are increasingly used to support peatland restoration prioritization. This study developed a composite SQI for tropical peat soils within the Kedangrantau–Sabintulung Peat Hydrological Unit (KHG), Mahakam Tengah, Kutai Kartanegara, East Kalimantan, by combining a Nutrient Fertility Index (NFI: pH, total N, total P, total K, and C:N ratio) and a Physical Maturity Index (PMI: bulk density and porosity) derived from composite peat samples at three villages (Liang Buaya, Tunjungan, and Sabintulung). Each indicator was normalized to a 0–1 scale using min-max scoring and combined with equal weighting, following the additive soil quality index framework. Liang Buaya had the highest NFI (0.600) but the lowest PMI (0.000); Sabintulung showed the reverse pattern (NFI = 0.325, PMI = 1.000); and Tunjungan was intermediate on both axes (NFI = 0.557, PMI = 0.340). The composite SQI (mean of NFI and PMI) was 0.300, 0.449, and 0.662 at Liang Buaya, Tunjungan, and Sabintulung, respectively. This pattern reveals a consistent inverse relationship between chemical nutrient fertility and physical decomposition maturity across the three villages: the least physically decomposed site was chemically most fertile, while the most physically decomposed site was the most nitrogen-constrained despite comparatively higher phosphorus and potassium availability. Because this trade-off is invisible in any single indicator, the composite framework provides a practical, transparent basis for differentiating conservation versus restoration priorities across villages in this degraded KHG, pending validation with a larger, principal-component-weighted sample.

Keywords:

Soil quality index; peat fertility; decomposition; composite indicator; mahakam tengah

1. Introduction

Tropical peatlands are among the most carbon-dense terrestrial ecosystems on Earth, accumulating organic matter over millennia under waterlogged, anaerobic conditions that suppress decomposition (Page et al., 2011). East Kalimantan Province contains approximately 342,089 ha of peat distributed across 16 Peat Hydrological Units (Kesatuan Hidrologis Gambut, KHG), of which nearly 96% lies within the broader Mahakam Tengah landscape along the middle Mahakam River. Within this landscape, the KHG of Sungai Kedangrantau, Sungai Sabintulung (approximately 37,900 ha, Kecamatan Muara Kaman, Kabupaten Kutai Kartanegara) has been classified among the most heavily degraded units in the province, owing to extensive drainage for oil palm cultivation, which now occupies roughly 63% of its land cover.

Peatland conversion of this kind is part of a broader regional pattern: across Peninsular Malaysia, Sumatra, and Borneo, peat swamp forest cover declined from 76% to only 29% between 1990 and 2015 (Miettinen et al., 2016). Drainage-induced aeration accelerates organic matter decomposition and greenhouse-gas emission (Hooijer et al., 2024; Prananto et al., 2020), and comparable geochemical instability has been documented in other West Kalimantan peatlands undergoing lateral degradation (Ivansyah et al., 2025). Beyond its climatic consequences, this degradation directly affects the biogeochemical properties that govern the success of paludiculture-based restoration (Budiman et al., 2020; Hooijer et al., 2024). Landuse driven change in soil chemical and physical properties is not unique to peat within this province: organic carbon content has been shown to track land cover across humid tropical alluvial landscapes elsewhere in East Kalimantan (Setianingsih et al., 2025), pedogenic and carbon-dynamic differentiation has been documented across volcanic landforms in the same province (Mulyadi et al., 2026), and pyrite-driven acidification has been linked to distance from the coast in acid sulfate soils of Paser, East Kalimantan (Setianingsih et al., 2026) together indicating that land use and landscape position are recurring drivers of soil degradation across this region's diverse soil types.

Assessing degradation and guiding restoration, however, requires more than single-parameter measurements. A soil quality index (SQI) integrates multiple chemical, physical, and sometimes biological indicators into one composite score, following an additive framework in which each indicator is scored on a common scale and combined with an explicit weighting scheme (Andrews et al., 2002; Karlen & Stott, 2015). This approach has already been applied to Indonesian tropical peat: (Nusantara et al., 2018) built a peat SQI along a land-use gradient in Kubu Raya, West Kalimantan, finding that secondary peat swamp forest scored highest (0.40) and converted land uses (shrubland, cropland, oil palm) scored lower (0.37); more recently, (Nusantara et al., 2025) applied a principal-component-weighted SQI to canal-blocked peatlands in the same region, finding scores of 0.50–0.64 across sites and identifying organic matter addition and permanent canal blocking as the main levers for improving soil quality. Both studies demonstrate that a composite index can reveal restoration priorities that single indicators cannot.

No soil quality index has yet been developed for the Kedangrantau–Sabintulung KHG, even though existing site-level assessments show that its three main villages differ considerably in both chemical fertility indicators (pH, total N, total P, total K) and physical decomposition indicators (bulk density, porosity). Land evaluation studies elsewhere in the Mahakam Tengah landscape, such as a landform-based assessment of potential rice-field suitability in Makroman, Samarinda, have likewise relied on single-criterion land-suitability classes rather than an integrated, multi-indicator soil quality score (Nugroho et al., 2025), leaving a similar composite-index gap for this KHG's peat soils. The principal-component weighting used by (Nusantara et al., 2025) requires a sample size well beyond the three composite samples available for this KHG, so a transparent, equally weighted alternative is a practical starting point rather than a final validated instrument. This study therefore aimed to (1) construct a Nutrient Fertility Index (NFI) and a Physical Maturity Index (PMI) from chemical and physical peat properties at three villages spanning this KHG, (2) combine them into a composite Soil Quality Index (SQI), and (3) interpret the resulting spatial pattern to inform restoration and conservation prioritization within the KHG.

2. Materials and Methods

This study was conducted within the Peat Hydrological Unit (Kesatuan Hidrologis Gambut, KHG) of Sungai Sabintulung, located at 00°03'07″–00°13'16″ S and 116°45'07″–116°56'52″ E in Kecamatan Muara Kaman, Kabupaten Kutai Kartanegara, East Kalimantan, Indonesia. The KHG covers approximately 37,900 ha and forms part of the wider Mahakam Tengah peat landscape, where peat 3–

13.5 m thick can store on the order of 3,000–6,000 t C ha-1 (Siegert & Jaenicke, 2008). Figure 1 shows the location of the KHG and the three sampled villages within Muara Kaman District.

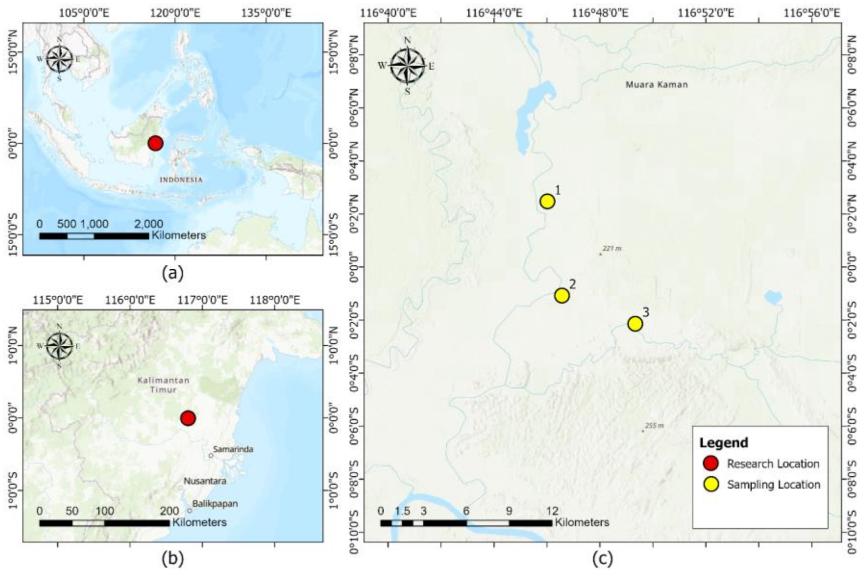

Figure 1. Location of the Kedangrantau Sabintulung, Liang Buaya, and Tunjungan ,Peat Hydrological Unit (KHG), Muara Kaman District, Kutai Kartanegara Regency, East Kalimantan, Indonesia.

Peat samples were obtained from three villages within the KHG: Liang Buaya, Tunjungan, and Sabintulung. At each village, a composite topsoil peat sample was collected from a representative peat swamp/agricultural plot and analyzed at the Soil Laboratory, Faculty of Agriculture, Universitas Mulawarman. Because one composite sample was analyzed per village, the resulting index values should be regarded as a site-level, descriptive characterization rather than a spatially replicated, inferentially tested survey; this limitation is addressed further in the Discussion.

Soil pH was determined electrometrically in a 1:5 soil–water suspension. Organic carbon was determined by loss-on-ignition (LOI) and total nitrogen by the Kjeldahl method; the C:N ratio was calculated directly from these values. Total phosphorus and total potassium were extracted using 25% HCl and expressed as P_2O_5 and K_2O, respectively. Bulk density was determined gravimetrically using the core method, and total porosity was calculated from bulk density and particle density. Saturated hydraulic conductivity (Ksat) was measured using a constant head permeameter method but was not included in the composite index because its relationship to decomposition stage is not monotonic in this peat.

The composite Soil Quality Index (SQI) was built following the additive minimum-data-set framework (Karlen & Stott, 1994; Andrews et al., 2002). Two sub-indices were defined as a priori based on the process each indicator reflects. The Nutrient Fertility Index (NFI) combined pH, total N, total P, total K, and the C:N ratio (inverted, since a lower C:N ratio indicates more biologically available nitrogen). The Physical Maturity Index (PMI) combined bulk density and porosity (inverted), following evidence that peat bulk density increases and porosity decreases as decomposition advances (Zulkifley et al., 2013). Each indicator was normalized across the three sites using min-max scoring: score = (x - min)/ (max - min) for a "more is better" indicator, or score = (max - x)/(max - min) for an inverted indicator. NFI and PMI were each calculated as the unweighted mean of their component scores, and the composite SQI was calculated as the mean of NFI and PMI. Equal weighting was used, in contrast to the principal-component-derived weights used by(Nusantara et al., 2025). Given the small number of sampling sites, data were analyzed descriptively; index values are relative to this three-site dataset and are not a validated absolute scale. All calculations and figures were produced in Python 3 using standard scientific computing libraries.

3. Results

The peat soils at all three sites were strongly to very strongly acidic (pH 4.36–4.50) and had uniformly high organic carbon (42.2–43.3%), while total nitrogen, phosphorus, potassium, bulk density, and porosity varied more among sites (Table 1). The C:N ratio increased from 69.9 at Liang Buaya to 76.1 at Tunjungan and 84.4 at Sabintulung, while bulk density increased in the same order (0.11, 0.21, and 0.37 g cm-3) and porosity declined (91.96%, 86.40%, and 73.12%).

A closer look at the individual chemical parameters shows that they did not all decline together (Table 1). pH, organic carbon, and total nitrogen declined in parallel from Liang Buaya to Sabintulung (by 0.14 units, 2.7%, and 19.4%, respectively), whereas total P_2O_5 and total K_2O moved in the opposite direction, increasing by 46.6% and 86.5%, respectively, over the same gradient; total K_2O reached its single highest value at Tunjungan (37.47 mg 100 g-1), which was intermediate on every other chemical parameter. This decoupling between nitrogen and the other two macronutrients is consistent with reported departures from stoichiometric C:N:P balance in decomposing soil organic matter (Cleveland & Liptzin, 2007; Sterner et al., 2017) and with the comparatively greater geochemical retention of phosphorus relative to nitrogen over the course of organic matter turnover(Vitousek et al., 2010).

The physical parameters followed a more internally consistent gradient, with one notable exception (Table 1). Bulk density more than tripled from Liang Buaya to Sabintulung (0.11 to 0.37 g cm^{-3}, a 3.4-fold increase) while porosity declined by almost 19 percentage points (91.96% to 73.12%), both consistent with progressively more advanced decomposition and consolidation. Saturated hydraulic conductivity (Ksat), however, did not follow this trend: rather than declining alongside porosity, Ksat at Sabintulung (6.18 cm h^{-1}) was approximately 26 times higher than at Liang Buaya (0.24 cm h^{-1}) and about 77 times higher than at Tunjungan (0.08 cm h^{-1}), which had the lowest Ksat of the three villages despite intermediate bulk density and porosity.

Table 1. Physical and chemical properties of peat soils at three villages in the Kedangrantau–Sabintulung Peat Hydrological Unit, Mahakam Tengah, East Kalimantan.

Parameter	Liang Buaya	Tunjungan	Sabintulung
pH (H2O)	4.50	4.37	4.36
Organic C (%)	43.34	42.63	42.18
Total N (%)	0.62	0.56	0.50
Total P_2O_5 (mg 100 g^{-1})	7.70	10.01	11.29
Total K_2O (mg 100 g^{-1})	15.70	37.47	29.28
C:N ratio (mass)	69.9	76.1	84.4
Bulk density (g cm^{-3})	0.11	0.21	0.37
Porosity (%)	91.96	86.40	73.12
Ksat (cm h^{-1})	0.24	0.08	6.18

After normalization, Liang Buaya scored highest on every Nutrient Fertility Index component except total P and total K, giving it the highest NFI (0.600), while Sabintulung scored highest on total P and total K but lowest on pH, total N, and C:N, giving it the lowest NFI (0.325); Tunjungan was intermediate (NFI = 0.557) (Table 2, Figure 2). The Physical Maturity Index showed the reverse ranking: Liang Buaya had the lowest bulk density and highest porosity and therefore the lowest PMI (0.000), Sabintulung had the highest bulk density and lowest porosity and therefore the highest PMI (1.000), and Tunjungan was again intermediate (PMI = 0.340).

Table 2. Normalized indicator scores (0–1) and composite Nutrient Fertility Index (NFI), Physical Maturity Index (PMI), and Soil Quality Index (SQI) for three villages in the Kedangrantau–Sabintulung Peat Hydrological Unit.

Indicator (score 0–1)	Liang Buaya	Tunjungan	Sabintulung	Direction
pH	1.000	0.071	0.000	higher = better
Total N	1.000	0.500	0.000	higher = better
Total P	0.000	0.643	1.000	higher = better
Total K	0.000	1.000	0.624	higher = better
C:N ratio	1.000	0.572	0.000	inverted (lower = better)
NFI (mean of above 5)	**0.600**	**0.557**	**0.325**	
Bulk density	0.000	0.385	1.000	higher = more mature
Porosity	0.000	0.295	1.000	inverted (lower = more mature)
PMI (mean of above 2)	**0.000**	**0.340**	**1.000**	
SQI (mean of NFI, PMI)	**0.300**	**0.449**	**0.662**	

Note: Scores normalized by min-max across the three villages (see Materials and Methods). NFI = Nutrient Fertility Index; PMI = Physical Maturity Index; SQI = Soil Quality Index.

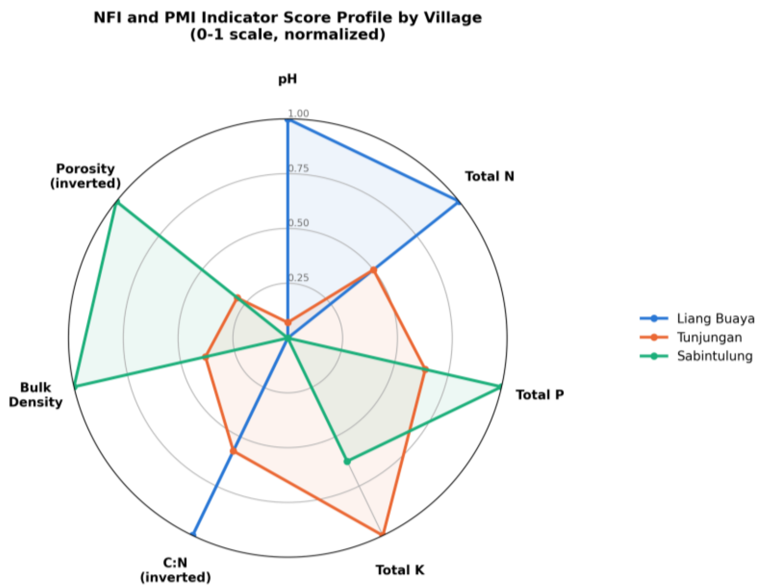

Figure 2. Radar profile of the seven normalized indicator scores underlying the Nutrient Fertility Index and Physical Maturity Index at each village

Plotting NFI against PMI places the three villages along a clear negative diagonal rather than in a single quadrant (Figure 3): Liang Buaya falls in the "less decomposed, more fertile" region, Sabintulung falls in the "more decomposed, less fertile" region, and Tunjungan lies close to the midpoint of both axes. The composite SQI (mean of NFI and PMI) was 0.300 at Liang Buaya, 0.449 at Tunjungan, and 0.662 at Sabintulung an ordering opposite to that of the NFI alone, because Sabintulung's very high PMI outweighed its low NFI when the two sub-indices were averaged.

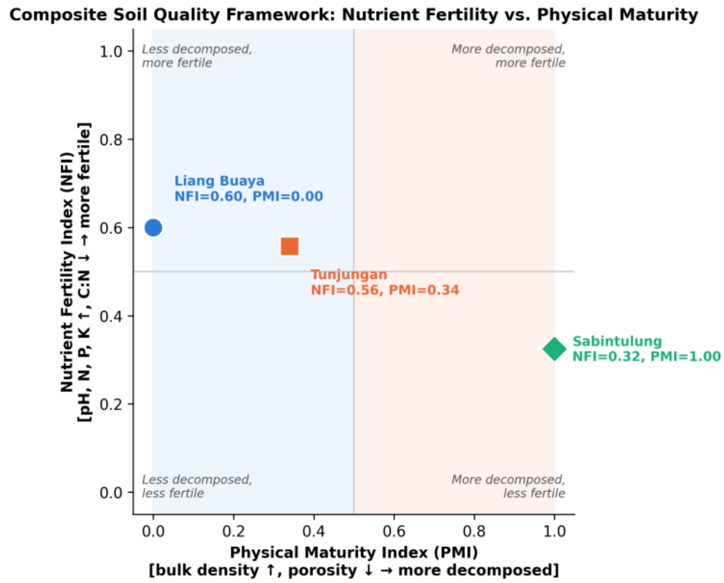

Figure 3. Nutrient Fertility Index (NFI) versus Physical Maturity Index (PMI) for three villages in the Sabintulung Peat Hydrological Unit, showing a negative diagonal (trade off) pattern rather than clustering in a single quadrant.

4. Discussion

The clearest finding of this composite index analysis is not any single site's score, but the consistent inverse relationship between the Nutrient Fertility Index and the Physical Maturity Index across the three villages (Figure 3). The village with the least physically decomposed peat (Liang Buaya: lowest bulk density, highest porosity) was also the most chemically fertile by this index (highest pH, total N, and lowest C:N), while the most physically decomposed village (Sabintulung: highest bulk density, lowest porosity) was the least chemically fertile overall despite having comparatively higher phosphorus and potassium. This trade-off is consistent with, and quantitatively synthesizes, the nitrogen-limitation pattern identified when C:N ratios and bulk density were examined individually for this KHG: the mismatch between conventional "high" total-nitrogen classification and low nitrogen availability was most pronounced at the most physically decomposed site.

This inverse pattern also helps explain why total nitrogen, phosphorus, and potassium did not move together across the gradient. Nitrogen is lost from decomposing organic matter primarily through microbial mineralization followed by leaching and, under the frequently anoxic conditions of tropical peat, denitrification, so its availability tends to decline as decomposition proceeds. Phosphorus and potassium have no equivalent gaseous loss pathway and are largely retained within, or even relatively concentrated in, the residual peat matrix as more mobile carbon and nitrogen fractions are lost a pattern broadly consistent with reported departures from stoichiometric C:N:P balance in decomposing soil organic matter (Cleveland & Liptzin, 2007; Sterner et al., 2017) and with the comparatively greater long-term geochemical retention of phosphorus relative to nitrogen over the course of pedogenesis and organic matter turnover (Vitousek et al., 2010). The elevated total P_2O_5 and K_2O observed at the most decomposed site (Sabintulung) should therefore not be read as an indicator of greater overall soil fertility: nitrogen remained the more limiting macronutrient there by every measure in this study.

The composite SQI itself, however, tells a different story from the NFI alone: because SQI averages NFI and PMI, Sabintulung's very high physical maturity score raised its overall SQI (0.662) above that of the chemically more fertile Liang Buaya (0.300). This illustrates a general caution about composite indices noted in the soil quality literature (Andrews et al., 2002): collapsing indicators that move in different directions into a single number can mask the underlying trade-off that matters most for management decisions. For this KHG, the composite SQI is best interpreted alongside, not instead of, its two component sub-indices and the quadrant pattern in Figure 3.

Comparing these results with other Indonesian applications of peat SQI frameworks highlights both consistencies and methodological differences. Nusantara et al. (2018) found a comparatively narrow SQI range (0.37–0.40) across land-use types in Kubu Raya, West Kalimantan, using a wider minimum data set with correlation-based indicator reduction; (Nusantara et al. (2025) reported a higher range (0.50–0.64, "moderate" to "good") for canal-blocked peatlands using principal-component-derived weights across 13 indicators. The considerably wider range obtained here (0.300–0.662) likely reflects the smaller, unweighted two-domain indicator set used in this study rather than a genuinely more extreme degradation gradient, and the values from the three frameworks are not directly comparable on an absolute scale. What is consistent across all three studies, including this one, is that land-use and hydrological condition are the dominant drivers structuring peat soil quality, and that a composite, multi-indicator approach reveals spatial patterns that a single parameter would not.

The anomalously high saturated hydraulic conductivity at Sabintulung, despite that site having the highest bulk density and lowest porosity of the three villages, is a notable exception to the otherwise consistent physical decomposition gradient and warrants separate comment. Bulk density and porosity measure the proportion and packing of solid material within the peat matrix, whereas Ksat depends strongly on the size, continuity, and connectivity of macropores and any residual root or fiber channels; a peat can therefore be more decomposed and more compact in bulk terms while still retaining preferential flow pathways that dominate its saturated flow rate, a distinction consistent with reported changes in pore structure and hydraulic behavior with peat decomposition (Zulkifley et al., 2013). Because Ksat was measured on a single core per village in this study, this result should be treated as indicative rather than conclusive, and it should be verified with replicate cores before it is used to infer site-scale drainage or rewetting behavior. If confirmed, however, it has a direct practical implication: canal-blocking or water-table-management designs at Sabintulung cannot be based on bulk density or porosity alone, since actual water movement through the peat may be governed by macropore structure that these two indices do not capture.

These findings suggest differentiated priorities for restoration and conservation within this KHG. Liang Buaya, with the least decomposed peat and the highest nutrient fertility index, most closely resembles an undegraded peat swamp and should be prioritized for protection from further drainage, consistent with the KHG's designated protection function in areas of thick, less-disturbed peat. Sabintulung, with the most physically decomposed peat and the lowest nitrogen fertility, is the strongest candidate for hydrological restoration (water-table control and canal blocking, following site-specific designs such as those described byUrzainki et al. (2020) combined with nitrogen-aware management for any paludiculture species introduced there (Hartanto et al., 2024), but at Sabintulung any such amendment would need to specifically target nitrogen availability rather than bulk organic matter alone: phosphorus-only or generic organic amendment is unlikely to resolve its nitrogen constraint, and given its anomalously high saturated hydraulic conductivity relative to its bulk density and porosity, canal-blocking design at this site should be preceded by a targeted hydrological pre-assessment rather than assuming standard decomposition-based flow behavior. Tunjungan, intermediate on both axes, may be an appropriate site for monitoring the trajectory of change under current land use. This prioritization logic using the position of a site within the fertility-maturity quadrant rather than a single combined score is, in the authors' view, the more actionable output of this analysis than the SQI value itself.

This study is limited by its reliance on a single composite sample per village (n = 3, no field replication), which precludes the principal-component-based weighting used in more data-rich SQI studies (Andrews et al., 2002; Nusantara et al., 2025) and restricts the index to a descriptive, relative comparison among these three sites rather than a validated, generalizable scale. The saturated hydraulic conductivity values are a particular case in point: measured on a single core per village, they are reported here as indicative field observations rather than validated site means, and the anomalous result at Sabintulung should be confirmed with replicate cores before use in restoration design. The equal weighting adopted here is a transparent but arbitrary simplification; sensitivity analysis with alternative weights, and expansion to more sampling sites to enable objective, data-driven weighting, are needed before this index is used for formal decision-making. Future work should also test whether the inverse fertility-maturity relationship observed here holds at additional sites within this KHG and other Kalimantan peatlands undergoing similar degradation.

5. Conclusion

A composite Soil Quality Index combining a Nutrient Fertility Index (pH, total N, total P, total K, C:N ratio) and a Physical Maturity Index (bulk density, porosity) revealed a consistent inverse relationship between chemical fertility and physical decomposition maturity across three villages in the Sabintulung KHG: Liang Buaya was the least decomposed and most chemically fertile (SQI = 0.300), Sabintulung was the most decomposed and least chemically fertile (SQI = 0.662), and Tunjungan was intermediate (SQI = 0.449). Because the composite SQI, by averaging two indices that move in opposite directions, ranked Sabintulung highest despite its poor nitrogen fertility, the quadrant position of each village not the single SQI value is the more useful basis for restoration planning: Liang Buaya warrants protection from further drainage, Sabintulung warrants hydrological restoration and nitrogen-aware management, and Tunjungan warrants continued monitoring. This equally weighted, two-domain framework offers a transparent starting point for peat soil quality assessment in this KHG pending validation with a larger, principal component weighted sample.

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Conflict of Interest

The authors declare no conflict of interest.

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References

Andrews, S. S., Karlen, D. L., & Mitchell, J. P. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems and Environment*, *90*(1), 25–45. https://doi.org/10.1016/S0167-8809(01)00174-8

Budiman, I., Bastoni, Sari, E. N., Hadi, E. E., Asmaliyah, Siahaan, H., Januar, R., & Hapsari, R. D. (2020). Progress of paludiculture projects in supporting peatland ecosystem restoration in Indonesia. *Global Ecology and Conservation*, *23*, e01084. https://doi.org/10.1016/J.GECCO.2020.E01084

Cleveland, C. C., & Liptzin, D. (2007). C:N:P stoichiometry in soil: Is there a "Redfield ratio" for the microbial biomass? *Biogeochemistry*, *85*(3), 235–252. https://doi.org/10.1007/S10533-007-9132-0/TABLES/4

Hartanto, N., Suriaatmadja, E., & Zulkarnain, Z. (2024). Peningkatan Peran Masyarakat untuk Pengelolaan Ekosistem Gambut di Desa Liang Buaya, Kabupaten Kutai Kartanegara. *Jurnal Abdimas Untag Samarinda*, *2*(1), 1–12. https://doi.org/10.31293/JAUS.V2I1.7648

Hooijer, A., Vernimmen, R., Mulyadi, D., Triantomo, V., Hamdani, Lampela, M., Agusti, R., Page, S. E., Doloksaribu, J., Setiawan, I., Suratmanto, B., & Swarup, S. (2024). Benefits of tropical peatland rewetting for subsidence reduction and forest regrowth: results from a large-scale restoration trial. *Scientific Reports 2024 14:1*, *14*(1). https://doi.org/10.1038/s41598-024-60462-3

Ivansyah, O., Zubair, H., Irfan, U. R., & Widodo, S. (2025). Geochemical behavior of lateral peat degradation in the Kubu Raya Region, West Kalimantan, Indonesia. *Journal of Degraded and Mining Lands Management*, *12*(4), 8405–8419. https://doi.org/10.15243/JDMLM.2025.124.8405

Karlen, D. L., & Stott, D. E. (2015). A Framework for Evaluating Physical and Chemical Indicators of Soil Quality. *Defining Soil Quality for a Sustainable Environment*, 53–72. https://doi.org/10.2136/SSSASPECPUB35.C4

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, *6*, 67–78. https://doi.org/10.1016/J.GECCO.2016.02.004

Mulyadi, M., Nugroho, B. A., Dhonanto, D., & Setianingsih, T. E. (2026). Pedogenic Differentiation Across Volcanic Landforms in Tropical Rainforest: Evidence from Clay Activity and Carbon Dynamics in East Kalimantan, Indonesia. *International Journal of Plant & Soil Science*, *38*(9), 282–293. https://doi.org/10.9734/IJPSS/2026/V38I96290

Nugroho, B. A., Setianingsih, T. E., Salsabila, G., & Dhonanto, D. (2025). Evaluasi Kesesuaian Lahan Sawah Potensial Berdasarkan Bentuk Lahan di Kelurahan Makroman, Samarinda. *Jurnal*

Agroekoteknologi Tropika Lembab, *8*(1), 36–48. https://doi.org/10.30872/JATL.8.1.2025.19472.36-48

Nusantara, R. W., Aspan, A., Alhaddad, A. M., Suryadi, U. E., Makhrawie, Fitria, I., Fakhrudin, J., & Rezekikasari. (2018). Peat soil quality index and its determinants as influenced by land use changes in Kubu Raya District, West Kalimantan, Indonesia. *Biodiversitas Journal of Biological Diversity*, *19*(2), 535–540. https://doi.org/10.13057/BIODIV/D190229

Nusantara, R. W., Gusmayanti, E., & Sudrajat, J. (2025). Soil Quality Index of Tropical Peatlands Affected by Canal Blockages. *Indonesian Journal of Geography*, *57*(2), 385–394. https://doi.org/10.22146/IJG.99247

Page, S. E., Rieley, J. O., & Banks, C. J. (2011). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, *17*(2), 798–818. https://doi.org/10.1111/J.1365-2486.2010.02279.X

Prananto, J. A., Minasny, B., Comeau, L. P., Rudiyanto, R., & Grace, P. (2020). Drainage increases CO2 and N2O emissions from tropical peat soils. *Global Change Biology*, *26*(8), 4583–4600. https://doi.org/10.1111/GCB.15147

Setianingsih, T. E., Nugroho, B. A., Nurhartanto, R. M., & Zulkarnain. (2026). Spatial correlation between coastal distance and pyrite pH in acid sulfate soils of Paser, East Kalimantan. *Journal of Degraded and Mining Lands Management*, *13*(1), 9071–9080. https://doi.org/10.15243/JDMLM.2026.131.9071

Setianingsih, T. E., Prasetyo, R. A., Suryana, Romadhan, P., & Nugroho, B. A. (2025). Hubungan Spasial Antara C-Organik dan Tutupan Lahan di Lanskap Dataran Aluvial Tropika Lembab Kalimantan Timur. *Jurnal Tanah Dan Sumberdaya Lahan*, *12*(2), 395–406. https://doi.org/10.21776/ub.jtsl.2025.012.2.17

Sterner, R. W. ., Elser, J. J. ., & Vitousek, P. M. . (2017). *Ecological Stoichiometry : the Biology of Elements from Molecules to the Biosphere*.

Urzainki, I., Laurén, A., Palviainen, M., Haahti, K., Budiman, A., Basuki, I., Netzer, M., & Hökkä, H. (2020). Canal blocking optimization in restoration of drained peatlands. *Biogeosciences*, *17*(19), 4769–4784. https://doi.org/10.5194/BG-17-4769-2020

Vitousek, P. M., Porder, S., Houlton, B. Z., & Chadwick, O. A. (2010). Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen–phosphorus interactions. *Ecological Applications*, *20*(1), 5–15. https://doi.org/10.1890/08-0127.1

Zulkifley, M. T. M., Ng, T. F., Raj, J. K., Hashim, R., Ghani, A., Shuib, M. K., & Ashraf, M. A. (2013). Definitions and engineering classifications of tropical lowland peats. *Bulletin of Engineering Geology and the Environment*, *72*(3–4), 547–553. https://doi.org/10.1007/S10064-013-0520-5/METRIC