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Diagnosing Soil Fertility Constraints in Commercial Durian Orchards of Perak, Malaysia: Implications for Sustainable Agroecological Management

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ABSTRACT

Durian (*Durio zibethinus*), revered as the "King of Fruits," is a high-value tropical crop in Southeast Asia. However, declining soil fertility has been implicated in suboptimal durian yields in Malaysia. This study evaluated key soil chemical properties in three commercial durian farms in Perak, Koperasi Perladangan (KPK), Kemasik, and City Plantation (CP). Composite soil samples (0–10 cm depth) were analysed for pH, total nitrogen (N), available phosphorus (P), Cation Exchange Capacity (CEC), organic carbon, and exchangeable cations. Results showed that all sites have strongly acidic soils (pH <6), with Kemasik having the lowest pH at 4.48 ($p < 0.01$). CEC values ranged from low to moderate (5.21–9.72 cmol c/kg), indicating limited nutrient retention capacity. Soil organic carbon was uniformly low (~1.6–1.8%). Critically low levels of available P (0.14–2.32 ppm) and total N (0.08–0.14%) were recorded across all farms. Exchangeable base cations (K, Ca, Mg, Na) and micronutrients (B, Cu, Mn, Zn) were generally deficient, often near or below detection in many samples. Notably, exchangeable aluminium was relatively high (up to ~7 cmol(+)/kg at one KPK site) due to the low pH, and trace levels of potentially toxic metals like cadmium and zinc were detected indicating these elements were not limiting in the soil. These findings underscore severe fertility constraints: strongly acidic, low-organicmatter soils with multiple nutrient deficiencies. There is an urgent need for targeted soil management strategies such as liming to raise pH, organic matter amendments to improve CEC, balanced N–P–K fertilisation, and micronutrient supplementation to rehabilitate soil health and sustain durian productivity. Overall, improving soil pH and fertility through these interventions will help alleviate nutrient stress and support sustainable durian cultivation in the region.

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1. Introduction

Durian is a tropical fruit native to Southeast Asia (notably Malaysia, Indonesia, and Thailand) and is highly prized for its unique taste and aroma. It is rich in fibre, vitamins, and bioactive compounds that confer health benefits [1]. Commercial durian productivity, however, is closely linked to soil fertility conditions. In Malaysian orchards, acidic soils (pH below 5) have been associated with higher incidence of durian stem canker disease, emphasising the importance of pH regulation [2]. Beyond disease risk, nutrient imbalances in soil can directly affect durian growth and fruit quality. Deficiencies in macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as secondary nutrients like calcium (Ca) and magnesium (Mg), are known to significantly impair fruit development, reduce phytochemical content, and weaken overall plant vigour. Under nutrient stress, durian trees exhibit declines in essential compounds (e.g. phenolics, flavonoids, sugars, lipids) alongside reductions in desirable fruit attributes like sweetness and creaminess. Recent research has highlighted these challenges; for example, Ali *et al.,* [3] reported that nutrient-starved durian trees produce fruits with lower nutritional and sensory quality.

To address fertility-related limitations in durian cultivation, various strategies have been explored. The application of organic foliar fertilisers has been found to significantly improve flowering and flushing (vegetative rejuvenation) in mature durian trees, thereby enhancing reproductive performance. For instance, Magbalot-Fernandez *et al.,* [4] demonstrated that durian trees receiving foliar nutrient sprays showed increased flower production and better fruit set compared to conventional soil fertilisation. Similarly, integrated nutrient sources, such as polyhalite fertilisers, which are rich in K, Mg, and Ca, have shown promise. When combined with plastic mulching, polyhalite application improved durian nutrient uptake and significantly enhanced fruit quality by reducing problems such as uneven ripening [5]. These findings suggest that balanced and targeted nutrient management can yield substantial benefits in durian orchards. In addition, spatial variability in soil fertility should be considered. A study in Gua Musang, Malaysia found that soil nutrient availability (particularly potassium) varied significantly with elevation and depth, and several nutrients were below optimal levels for durian indicating a need for site-specific soil amendments [6]. This underscores that even within a region, soil properties can differ and may require tailored management.

Given these challenges and insights, the present study was undertaken to evaluate the soil fertility status of three durian farms in Perak, Malaysia, to identify key nutrient deficiencies and chemical constraints. By analysing soil pH, organic matter, macro- and micronutrient levels at these sites, we aim to diagnose the factors limiting durian production. The findings are used to formulate evidence-based soil management recommendations (e.g. liming, organic amendments, fertilisation regimes) to improve soil health.

2. Methodology

2.1 Study Site

The research was conducted at three durian farms in Perak state, Malaysia which were: (1) Koperasi Perladangan (KPK) and (2) Kemasik, both located in Bagan Datoh district, and (3) City Plantation (CP) in Teluk Intan. The farms represent typical commercial durian orchards in the region. Two premium durian varieties (D197 “Musang King” and D200 “Black Thorn”) are cultivated across these sites under conventional management practices (e.g. regular fertilisation and irrigation schedules). All soils at the sites were classified as clayey in texture, reflecting their alluvial or residual clay-rich parent materials.

2.2 Soil Sampling

A stratified random sampling design was employed to collect soil samples from each farm in 2024. The number of sampling points at each farm was proportional to its size. At KPK (Farm 1) the largest farm, five discrete sampling locations were established; at CP (Farm 3), two locations; and at the smaller Kemasik (Farm 2), one representative location was used. At each location, multiple subsamples were taken and composited. Specifically, at KPK and CP, each designated location was sampled in triplicate (three subsamples per point), while at Kemasik five subsamples were taken (to adequately capture variability at that single point). Soil samples were collected from the topsoil (0–10 cm depth) using a handheld soil auger, focusing on the rooting zone near durian tree bases. The individual subsamples from a location were thoroughly mixed to form a composite sample representing that point.

2.3 Soil Analysis

Composite samples were air-dried, gently crushed, and passed through a 2 mm sieve prior to analysis. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Total nitrogen (N) was determined by the Kjeldahl digestion method, and available phosphorus (P) was extracted (using Bray II for these acidic soils) and measured colorimetrically. Organic carbon content was measured by the Walkley-Black dichromate oxidation method and converted to approximate organic matter percentage. Cation exchange capacity (CEC) was determined by ammonium acetate (pH 7) saturation and subsequent displacement of ammonium, reflecting the soil's capacity to retain exchangeable cations. A suite of exchangeable cations – including macro-nutrients (K, Ca, Mg, Na, P, S) and micronutrients or trace metals (Al, B, Cd, Cu, Fe, Mn, Zn) – were extracted using 1 M ammonium acetate and quantified, typically by atomic absorption spectrometry or ICP-OES. The exchangeable P and S in this context represent the readily available pool of these elements (phosphate and sulphate, respectively) in the soil solution. All analyses followed standard protocols as recommended for tropical soils.

2.4 Data Analysis

Soil data from the farms were compared statistically to discern significant differences among sites. An analysis of variance (ANOVA) was performed for each soil parameter (pH, CEC, N, P, etc.), treating farm/location as the factor. Where ANOVA indicated significant differences ($p < 0.05$), Tukey's post-hoc test was applied to determine which site means differed significantly. Due to the unbalanced sampling design (different number of points per farm), the analysis was weighted by the number of composite samples per farm to avoid bias. All statistical analyses were carried out using Minitab (v12.1) software. Summary data are presented in figures and tables with means and standard deviations. In the tables, an asterisk (*) denotes values that differ significantly (at $p < 0.01$) from other sites for that particular nutrient (based on Tukey's test).

3. Results and Discussion

3.1 Soil Acidity and Aluminium

The soils at all three farms were found to be strongly acidic, with pH values generally below 6.0. Kemasik had the most acidic soil (mean pH ≈ 4.48), which was significantly lower than the other sites (Figure 1). Such a low pH is problematic for durian cultivation, as it can lead to aluminium (Al) toxicity and reduced nutrient availability. Indeed, we observed elevated exchangeable Al levels in these soils, particularly at KPK and Kemasik (Table 1). In tropical soils, pH < 5.5 often coincides with high soluble Al, which can inhibit root growth and bind with phosphate, rendering P less available. Our findings align with Grafu *et al.,* [7], who reported that soil pH below ~5.5 greatly increases exchangeable Al and in turn diminishes P uptake by plants. In this study, available P was extremely low in the most acidic samples (e.g. only 0.14 ppm at site KPK1, Figure 2), suggesting strong P fixation by Al and iron oxides. Prior research in West Africa similarly noted that acidic, highly weathered soils show increased Al release and concurrent P and N deficiency, directly lowering soil fertility [8,9]. Durian trees grown under such acidic conditions are more prone to health issues; for instance, Leng *et al.,* [2] found a negative correlation between soil pH (<5) and durian stem canker incidence, indicating greater disease severity in strongly acidic orchards. Improving soil pH through liming is therefore critical to reduce Al toxicity and disease susceptibility in durian plantations.

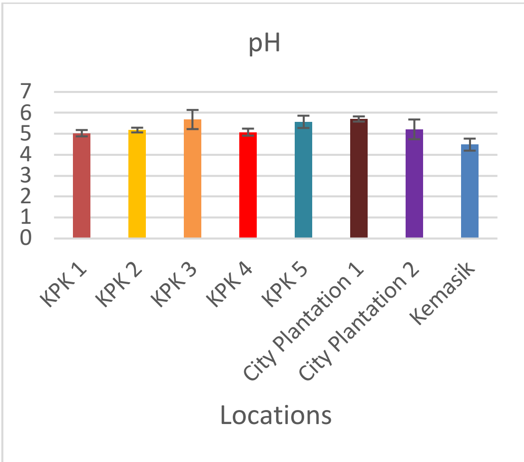

Fig. 1. Mean (± SD) of soil pH in soils from three durian farms in Perak (KPK, Kemasik, City Plantation). (Within each panel, different letters or an asterisk indicate a statistically significant difference between sites for that parameter at p < 0.05.).

Table 1
Exchangeable **Al, B, Ca, Cd, Cu,** and **Fe** (mean ± SD) in soils of the three durian farms.
(KPK 1–5 denote five sampling points at KPK; CP 1–2 denote two points at City Plantation. Values marked with ""* are significantly different from other sites at p < 0.01 for that element.)

Farms	Al	B	Ca	Cd	Cu	Fe
KPK 1	2.15 ± 0.96	0.00* ± 0.00	9.21* ± 3.25	0.0006 ± 0.0005	0.001* ± 0.001	0.12* ± 0.07
KPK 2	2.99 ± 2.54	0.00* ± 0.00	**90.14* ±** 34.57	0.00 ± 0.00	0.003* ± 0.002	0.09* ± 0.03
KPK 3	1.45 ± 1.43	0.00* ± 0.00	**87.629* ±** 30.61	0.00 ± 0.00	0.002* ± 0.00	0.03* ± 0.02
KPK 4	7.63 ± 7.47	0.00* ± 0.00	26.5* ± 27.64	0.00 ± 0.00	0.00* ± 0.002	0.08* ± 0.10
KPK 5	0.8 ± 0.7	0.00* ± 0.00	**112.87* ±** 45.11	0.00 ± 0.00	0.002* ± 0.00	0.00* ± 0.01
Kemasik	3.22 ± 3.99	0.12* ± 0.13	13.03* ± 7.3	0.0003 ± 0.0006	0.01* ± 0.01	0.12* ± 0.08
City Plantation 1	0.16 ± 0.08	0.11* ± 0.15	104.59* ± 34.02	0.0002 ± 0.0005	0.02* ± 0.01	0.08* ± 0.03
City Plantation 2	0.37 ± 0.38	0.15* ± 0.07	76.6* ± 40.05	0.0006 ± 0.0003	0.02* ± 0.00	0.09* ± 0.03

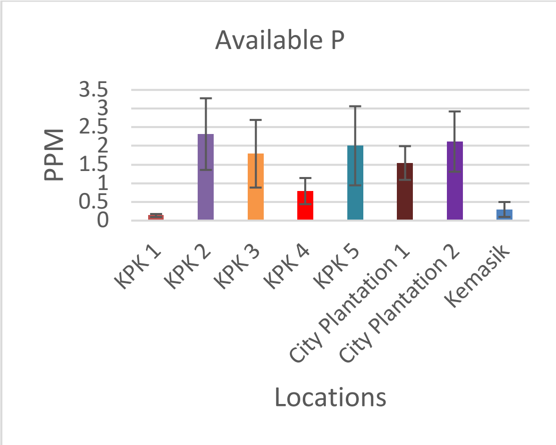

Fig. 2. Mean (± SD) of soil available phosphorus in soils from three durian farms in Perak (KPK, Kemasik, City Plantation). (Within each panel, different letters or an asterisk indicate a statistically significant difference between sites for that parameter at $p < 0.05$.).

3.2 Macronutrient Status (N, P, K, Ca, Mg) Soil Acidity and Aluminium

All three farms exhibited very low nitrogen and phosphorus levels. Total N ranged only 0.08–0.14%, falling far below the typical 0.2–0.5% considered moderate for tropical agricultural soils (Figure 3a). Available P was likewise minimal (0.14–2.32 mg/kg), indicating acute P deficiency (Figure 2). Such low N and P availability is likely a major factor limiting durian growth. Nitrogen is essential for foliar development and photosynthesis, so inadequate N can constrain canopy formation and ultimately fruit yield. We observed total N on the order of 0.1%, which is insufficient to meet durian's demand, a finding consistent with the foliar N deficiencies commonly noted in durian. Phosphorus, critical for energy transfer and root development, was virtually absent in some samples (especially KPK1 at 0.14 ppm P). This severe P scarcity will restrict root growth and fruit development; durian trees in such soils often show stunted growth and poor fruit set. Our results corroborate Yoni *et al.,* [8] who reported that strongly acidic cultivated soils tend to have greatly reduced available P and N, contributing to overall low fertility. They noted that by contrast, soils under native forest had higher organic matter and available nutrients, highlighting the impact of land use on nutrient reserves. The present study's orchards, having been cultivated and likely subject to erosion or nutrient mining over time, clearly suffer from depleted N and P pools.

Among secondary macronutrients, Ca and Mg showed variable levels between sites. Exchangeable Ca ranged from ~9 mg/kg at one KPK site up to ~113 mg/kg at another (Table 1), with the highest Ca found in KPK 5 and City Plantation. While some locations (e.g. CP) had moderately higher Ca – possibly due to past liming or naturally calcareous substrata – the majority of samples had very low Ca (often near 0, especially in Kemasik and some KPK subsites). Exchangeable Mg exhibited a similar pattern: a few readings were elevated (e.g. 15–17 mg/kg at KPK 2 and KPK 5, Table 2), but many were ≤ 4 mg/kg. These inconsistencies suggest that fertiliser history or inherent soil differences influenced Ca and Mg levels at specific points, but overall base cation fertility is poor. Importantly, the low CEC of these soils (5–10 cmol c/kg, Figure 3b) means they have limited capacity to retain Ca^{2+} and Mg^{2+} against leaching. Without intervention, rainfall likely washes these nutrients below the root zone.

Table 2
Exchangeable **K, Mg, Mn, Na, P, S** and **Zn** (mean ± SD) in soils of the three durian farms.
(Values with ""* indicate significant differences at p < 0.01 for that nutrient.)

Farms	K	Mg	Mn	Na	P	S	Zn
KPK 1	12.99* ± 3.14	3.18* ± 1.16	0.16* ± 0.07	0.23* ± 0.38	0.00* ± 0.08	3.36* ± 1.61	0.00 ± 0.00
KPK 2	11.25* ± 2.96	15.84* ± 6.48	0.18* ± 0.06	0.63* ± 0.20	0.11* ± 0.15	3.00* ± 0.34	0.00 ± 0.01
KPK 3	8.68* ± 2.24	14.26* ± 0.86	0.14* ± 0.03	0.75* ± 0.58	0.32* ± 0.54	2.82* ± 2.75	0.00 ± 0.00
KPK 4	7.27* ± 6.00	6.40* ± 6.85	0.05* ± 0.05	0.00* ± 1.55	0.00* ± 0.58	2.14* ± 1.63	0.02 ± 0.08
KPK 5	11.5* ± 6.08	16.83* ± 2.98	0.10* ± 0.02	0.89* ± 0.21	0.14* ± 0.07	2.40* ± 1.55	0.00 ± 0.00
Kemasik	5.31* ± 4.33	4.72* ± 2.46	0.09* ± 0.05	1.36* ± 0.60	0.97* ± 0.82	7.09* ± 4.87	0.00 ± 0.03
City Plantation 1	**35.99*** **±** 9.85	14.96* ± 4.18	0.17* ± 0.04	1.68* ± 0.31	2.82* ± 0.39	**16.89*** **±** 7.12	0.01 ± 0.00
City Plantation 2	**37.45*** **±** 12.89	13.2* ± 6.2	0.14* ± 0.04	1.78* ± 0.59	2.23* ± 0.36	**14.42*** **±** 4.03	0.02 ± 0.02

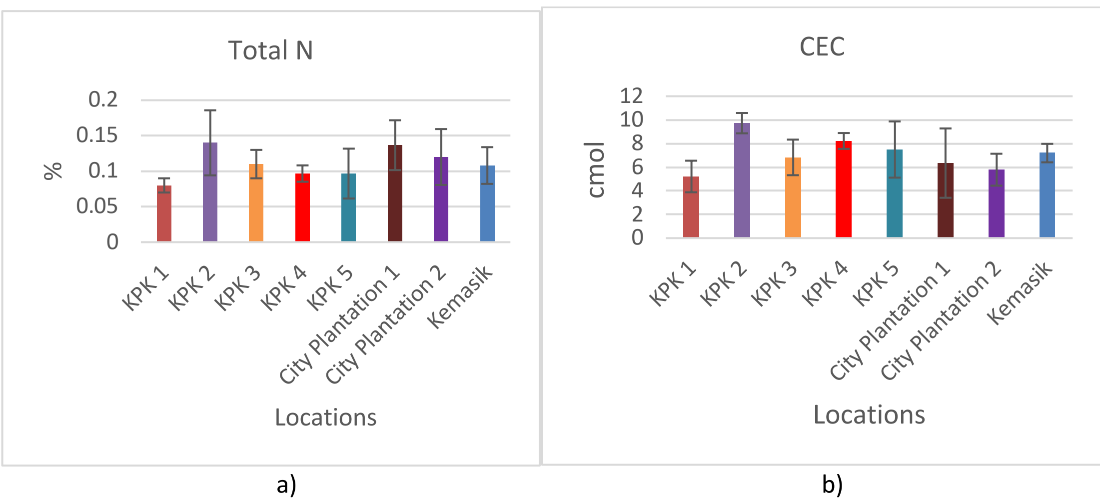

Fig. 3. Mean (± SD) of soil a) total nitrogen and b) cation exchange capacity in soils from three durian farms in Perak (KPK, Kemasik, City Plantation). (Within each panel, different letters or an asterisk indicate a statistically significant difference between sites for that parameter at p < 0.05.).

Potassium (K) was also deficient in most samples, though City Plantation stood out with higher exchangeable K (approximately 36 mg/kg at CP1; Table 2). The CP farm's K was significantly greater than KPK's and Kemasik's (p <0.01), possibly reflecting targeted K fertilisation or different soil parent material at CP. Nonetheless, even ~30–37 mg/kg K is only marginally sufficient – and Kemasik's soil had only ~5 mg/kg K (Table 2, Kemasik row), a critically low value. Durian trees are heavy K feeders (potassium is required in large amounts for fruit development), so the prevalent K shortfall likely contributes to poor fruit yield/quality in these farms. The variation in K and Ca between farms reinforces the need for site-specific fertility management, as highlighted by Amran *et al.,* [6] in their study of durian soils in Kelantan. They found that nutrient levels (especially K) differed with topography and recommended targeted soil amendments – an observation that applies to our Perak sites as well.

3.3 Organic Carbon and CEC

Soil organic carbon content was uniformly low across the farms, ranging only 1.58–1.79% (not significantly different among sites; Figure 4). This corresponds to roughly 2.7–3.1% organic matter, which is considered poor for tropical agricultural soils that ideally should have >5% organic matter for good structure and nutrient supply. The low organic matter is partly responsible for the soils' low CEC. Cation exchange capacity was measured in the "low to moderate" range (approximately 5 to 10 cmol c/kg) far below values seen in more fertile tropical soils or in clay-rich, organic-rich nitisols that can exceed 20–30 cmol c/kg. In our results, KPK 1 had the lowest CEC (~5.21 cmol c/kg), whereas KPK 2 showed a relatively higher CEC (~9.72 cmol c/kg) (Figure 3b). Even the highest value here is modest, suggesting limited clay activity and scant humus content. Low CEC indicates the soil's ability to hold onto cationic nutrients (like K^+, Ca^{2+}, Mg^{2+}, NH_4^+) is weak, nutrients can easily leach out with drainage. This is a concerning characteristic for durian orchards in high-rainfall regions.

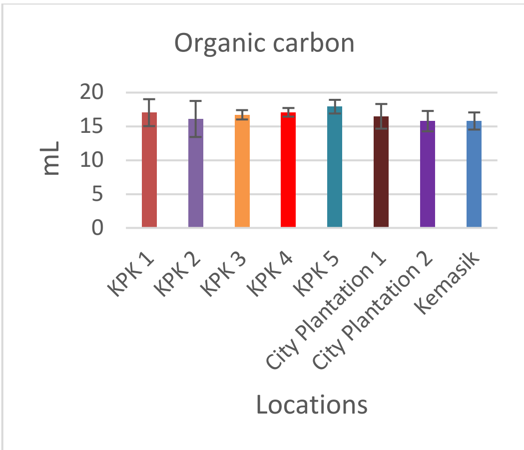

Fig. 4. Mean (± SD) of soil organic carbon in soils from three durian farms in Perak (KPK, Kemasik, City Plantation). (Within each panel, different letters or an asterisk indicate a statistically significant difference between sites for that parameter at $p < 0.05$.).

The strong influence of organic matter on CEC is well documented. Adding organic residues or amendments can markedly increase the soil's cation-holding capacity by providing negatively charged sites on humus. Studies have shown that incorporating organic materials (e.g. compost, manure, crop residues) enhances CEC and improves nutrient retention in tropical soils. For instance, Goda *et al.,* [10] found that applying feather hydrolysate (an organic N-rich amendment) and poultry manure significantly raised the CEC of a calcareous soil, outperforming equivalent synthetic fertilisers in sustaining soil fertility. Similarly, Hashimi *et al.,* [11] reported that continuous organic fertilisation improved the soil CEC and yield of maize in a tropical Alfisol, whereas mineral fertilisers alone had a lesser effect. The implication for our durian farms is clear: organic matter enrichment is needed to build soil CEC and fertility. The low carbon content here likely results from years of cultivation with insufficient residue return or groundcover, leading to organic matter depletion. Also, tropical conditions favour rapid decomposition, so maintaining soil carbon requires regular inputs. Notably, in natural ecosystems (e.g. secondary forests or savannas), soils often exhibit higher CEC and more moderate pH due to continuous organic inputs and vegetative cover. Yoni *et al.,* [12] observed that uncultivated forest soils had improved CEC and pH relative to adjacent cultivated plots, precisely because of greater organic matter accumulation. This contrast underscores how current management has likely degraded soil structure and nutrient reservoirs in the studied orchards. Incorporating organic amendments (compost, peat, green manures) would not only supply nutrients but also enhance soil physical properties and microbial activity, leading to more resilient soil fertility.

3.4 Exchangeable Cations and Micronutrients

Tables 1 and 2 summarize the mean exchangeable cation concentrations at each site. Consistent with the low CEC and organic matter, most nutrient cations are at deficiency levels. Calcium (Ca), crucial for cell wall formation and fruit integrity, was deficient especially at Kemasik (~13 mg/kg) and KPK (many sites <30 mg/kg). Only City Plantation had notably higher Ca (~105 mg/kg at CP1, 76 mg/kg at CP2; Table 1), likely due to either liming history or inherently richer parent material. Magnesium (Mg), needed for chlorophyll and enzyme function, followed a similar trend: extremely low at Kemasik (~4.7 mg/kg) and some KPK points, but higher at KPK 2 and KPK 5 (~15–17 mg/kg) and at CP (~13–15 mg/kg). The peaks in Ca and Mg at certain points (e.g. KPK 5 had Ca ~113 and Mg ~16 mg/kg) might indicate spots where coral limestone or dolomitic materials were present or applied. However, even these “high” values may not be truly sufficient for durian’s demands, and the majority of sampled area is well below optimum. Potassium (K) was discussed above – aside from CP (33–37 mg/kg K), values were low (often <13 mg/kg). Exchangeable sulphur (as sulphate) was generally low at KPK (approx. 2–3 mg/kg S) and moderate at Kemasik (~7 mg/kg) and CP (~14–16 mg/kg) (Table 2). While plants typically require less S than N or K, durian can suffer if S is lacking (it is vital for protein synthesis and aroma compound formation). Our data suggests KPK’s soil is sulphur-poor, and even CP’s ~15 mg/kg might be only marginally adequate. This aligns with foliar analyses in other durian studies that frequently find S deficiency in durian leaves. Ngoc *et al.,* [13] using the DRIS diagnostic method in Vietnam, identified S and Mg as the most frequently limiting nutrients in durian leaf tissue, reinforcing that soil S and Mg shortages are widespread issues. Our soil measurements mirror those concerns, particularly for Mg at Kemasik and S at KPK.

Turning to micronutrients, the soils are severely impoverished in available zinc (Zn), copper (Cu), boron (B), and manganese (Mn). In most samples, these elements were barely detectable. For example, exchangeable Zn was ~0.00 mg/kg in KPK and Kemasik soils, and only ~0.01–0.02 mg/kg at CP (Table 2) – far below typical critical levels (~1–2 mg/kg for Zn). Similarly, exchangeable Cu averaged ~0.001 mg/kg at KPK and ~0.01 mg/kg at Kemasik (Table 1), indicating an acute Cu deficiency. Manganese was slightly higher (0.05–0.18 mg/kg across sites, Table 2) but still very low in absolute terms. Boron was effectively zero in KPK (0.00 mg/kg) and low in Kemasik (~0.12 mg/kg) and CP (~0.11–0.15 mg/kg) (Table 1). These micronutrients are essential for durian: Zn and Mn are involved in photosynthetic enzyme systems and hormone production, Cu is needed for reproductive growth and disease resistance, and B is critical for flowering and fruit set. Micronutrient deficiencies are likely contributing to subtle disorders in these orchards, such as leaf chlorosis (Zn, Fe deficiency), dieback (Cu deficiency), or poor floral development (B deficiency). Indeed, common symptoms in under-fertilised durian include pale young leaves and reduced flowering, consistent with Zn and B shortages. Scientific observations support this: insufficient Zn and Mn can disturb chlorophyll synthesis and stunt root growth, while low Cu impairs pollen formation and disease defence. Our findings concord with these known impacts, the extremely low Zn, Mn, and Cu availability in soil explains why supplemental micronutrients are often required in durian cultivation.

It is worth noting that the availability of micronutrients is strongly influenced by soil chemistry and fractions. Fontes *et al.,* [14] demonstrated that exchangeable forms of Zn and Mn in soil are the primary source of those nutrients to plants, whereas Cu availability depends more on organic matter and Fe-oxide bound fractions. In our soils, the negligible exchangeable Zn and Mn pool directly translates to plant deficiency. Copper's fate is tied to organic matter and given the low organic carbon here, the soils likely have minimal Cu- in bioavailable form, with most Cu either inherently low or fixed in recalcitrant minerals. This further underscore how rebuilding soil organic matter (via compost or manure) could improve Cu availability in addition to boosting CEC.

One somewhat contrasting observation in our dataset is the presence of certain heavy metals at measurable levels. Exchangeable aluminium (Al) was discussed above, being high (e.g. ~7.6 cmol c/kg at KPK 4, Table 1) due to low pH, not a nutrient but a stress factor. We also detected trace cadmium (Cd) in a few samples. While most sites had Cd around 0.0000–0.0006 mg/kg (Table 1), KPK 1 showed Cd ~0.0006 and KPK 2 ~0.00 (with a small error), and these values, albeit tiny, were marked as significantly different (perhaps KPK 1's Cd slightly above others, $p<0.01$). Exchangeable iron (Fe) was present in small quantities (~0.08–0.12 mg/kg at KPK and Kemasik; ~0.08–0.09 at CP; Table 1). Although Fe is abundant in soil minerals, low pH increases soluble Fe^{2+} which can contribute to acidity and interfere with other nutrients. However, durian rarely suffers Fe deficiency in such acidic soils; if anything, excess Fe can accumulate. The soils' Fe levels are not alarming, but their Fe:Mn ratio might influence micronutrient uptake (excess Fe can compete with Mn). Given the data, Fe is relatively moderate compared to near-zero Mn, which suggests Mn deficiency could be more pressing despite plenty of total Fe in soil. Exchangeable sodium (Na) was low across all sites (mostly <2 mg/kg, Table 2), which is good from a salinity perspective – no salt build up is evident. Na is not an essential nutrient for durian and low values simply reflect leaching of salts in the humid climate.

In summary, the soil analyses portray a scenario of multi-nutrient deficiency and chemical stress for durian trees. The combination of high acidity, low organic matter, and scarce macro- and micro-nutrients explains the suboptimal orchard performance noted anecdotally by the growers. These results concur with broader findings in durian agro-ecosystems. A recent review by Ali *et al.,* [3] highlights that nutrient deficiencies (N, P, K, Ca, Mg) in durian cultivation led to poor fruit quality and reduced plant health. Our data provide the soil-side evidence for exactly those deficiencies. Additionally, an imbalance in fertiliser use may have aggravated some issues – for example, if growers applied mostly N (urea) without sufficient bases, it could acidify soil and leach Ca/Mg. Experimental studies note that continuous high N application, unaccompanied by lime or other nutrients, can deplete exchangeable Ca and Mg while increasing the availability of Fe, Mn, and Cu in acidic soils. This phenomenon was documented by Niu *et al.,* [15] in a long-term grassland trial: they observed that added N (simulating deposition) lowered soil Ca^{2+} and Mg^{2+} levels and CEC, yet raised soluble Fe, Mn, and Cu via soil acidification. Such dynamics might be at play in our orchards, where historical overuse of ammonium-based fertilisers could have driven down pH and base cations, inadvertently releasing more Fe/Mn (though still insufficient for plants if extreme). The net effect is a vicious cycle of declining fertility.

3.5 Contrasts with Fertile Durian Soils

It is informative to contrast these results with durian orchards on inherently fertile soils. For instance, in parts of Thailand's Sisaket Province, durian is grown on basaltic-origin soils that are rich in clay minerals. Singtuen & Phajan, [16] reported that highly weathered basaltic soils (classified as nitisols) in that area have very high CEC and naturally abundant base cations (K, Ca, Mg) due to the mineralogy of the basalt parent material. These "lava" durian orchards benefit from a steady nutrient supply and near-neutral pH, creating an ideal environment for durian cultivation. In our study, however, the soils appear to be derived from less fertile parent material (possibly sedimentary or alluvial) and have undergone intensive leaching and cultivation-induced degradation. As a result, they lack the buffered fertility of Sisaket's nitisols. This stark difference emphasizes that management strategies must compensate for what the native soil does not provide. Where geology does not endow the soil with nutrients, human intervention in the form of amendments and inputs is essential. In practice, this means applying lime to neutralize acidity, adding organic matter to improve CEC, and supplying a full spectrum of nutrients via fertilisers.

3.6 Implications for Durian Productivity

The collective deficiencies observed are likely manifesting as yield limitations in the studied farms. Critically low N and P will limit vegetative growth and fruit set; deficient K can reduce fruit size and pulp quality (since K affects sugar transport and rind development); lack of Ca can lead to weak stems and increased disease incidence; low Mg and Zn can cause leaf chlorosis and reduce photosynthetic rates; and inadequate B can result in poor flowering and fruit abortion. The high Al and low pH further exacerbate nutrient inefficiency and predispose trees to diseases like Phytophthora stem canker [2]. Farmers may have already noticed some of these issues for example, yellowing leaves (suggesting N, S, or micronutrient shortage) or low fruit counts per tree (possibly due to P or B deficiency affecting flowering). Our soil data scientifically validate those observations and point to specific remedial actions. In essence, the health of these durian orchards cannot be restored by NPK fertilisers alone; a holistic soil rehabilitation approach is needed. Encouragingly, studies have shown that implementing comprehensive nutrient management can dramatically improve durian performance. Applying organic amendments and a balanced fertiliser regime in previously infertile durian soils led to improved leaf nutrient status and higher yields in trials in Vietnam and the Philippines [5,4]. This suggests that the problems identified in Perak are addressable with proper management.

Finally, beyond soil amendments, integrating advanced technologies could further aid soil fertility management. The use of precision agriculture tools, for instance, IoT-based soil sensors to monitor moisture and nutrient levels can enable real-time adjustments in irrigation and fertilisation. Likewise, near-infrared spectroscopy (NIRS) has emerged as a rapid tool for assessing soil properties and even plant nutrient status on-site [17]. While such technologies were beyond the scope of this study, they represent the next step in sustainable durian agroecology: continuously monitoring soil conditions to optimize resource use. By combining soil science insights (like those from our analyses) with modern monitoring, durian farmers can move toward site-specific, data-driven management that maintains soil fertility and prevents future degradation.

4. Conclusions

In conclusion, the soils of the studied durian farms in Perak are highly acidic and nutrient-depleted, presenting significant challenges to sustainable durian production. Key fertility indicators including CEC, organic matter, and concentrations of N, P, K, Ca, Mg, and essential micronutrients were all at suboptimal levels, explaining the poor growth and yield issues observed. To revitalize these orchard soils and support healthy durian cultivation, a multi-pronged strategy is recommended.

First, liming (application of agricultural lime or dolomite) should be undertaken to raise the soil pH, thereby reducing aluminium toxicity and improving the availability of phosphorus and other nutrients.

Second, organic matter enrichment is crucial: incorporating compost, manure, biochar, or other organic amendments will enhance soil structure, increase microbial activity, and boost the soil's cation exchange capacity, leading to better retention of nutrients.

Third, a balanced fertilisation program must be implemented. Instead of relying on nitrogen alone, customized fertiliser blends containing N, P, K and secondary nutrients (Ca, Mg, S) should be applied according to soil test recommendations to replenish the depleted nutrient pools.

Fourth, targeted micronutrient supplementation is needed; foliar sprays or soil applications of zinc, boron, copper, and manganese (as indicated by deficiencies) will help address the trace element shortfalls and improve leaf nutrition, flowering, and fruit set. Additionally, the use of soil conditioners like zeolite or gypsum can be considered to improve nutrient retention and soil aeration, especially in portions of the orchards prone to leaching or compaction. Improving irrigation management will also complement these efforts by scheduling water supply to meet crop needs can prevent excessive leaching of nutrients from the root zone.

Finally, embracing modern agrotechnology (such as IoT-based soil monitoring and precision nutrient delivery systems) can ensure that amendments are used efficiently and sustainably. By integrating these interventions, the soil health of durian orchards can be progressively restored. This, in turn, will enhance durian tree vigour, increase fruit yields, and promote long-term agroecological resilience for durian farms in Malaysia and similar tropical environments.

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