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Comparative Assessment of Soil Quality in Fruit Orchards and an Arboretum Using the Tropical Soil Quality Index (TSQI)

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ABSTRACT
This study assessed soil quality differences between five uniformly aged fruit orchards and an adjacent arboretum reference by applying the Tropical Soil Quality Index (TSQI), which integrates physical, chemical, and biological indicators. The arboretum, which has remained undisturbed relative to orchard management, was used as the benchmark for evaluating current soil condition after long term cultivation in orchard plots. Composite topsoil (0–30 cm) sampling was conducted by dividing each field into nine areas and combining five auger subsamples per area, with separate handling for microbial biomass analysis. Measured soil properties included texture, coarse fragments, bulk density, organic matter proxies (total carbon and total nitrogen), cation exchange capacity, exchangeable bases, available phosphorus, soil pH, exchangeable aluminium, microbial biomass carbon, and microbial biomass nitrogen. These were analysed using Analysis of Variance and TSQI scoring. The results showed clear differences between land uses, with the arboretum exhibiting lower bulk density than orchard soils. Chemical indicators also distinguished the arboretum, where organic matter related fertility indicators were higher (organic matter, total carbon, total nitrogen, cation exchange capacity) than in orchards. The arboretum also had a lower C/N ratio compared to the orchards. Nutrient patterns varied across sites with available phosphorus lowest in the arboretum while all sites remained within a deficient range, and exchangeable magnesium sufficient only in the arboretum but low in most orchards, despite exchangeable potassium being within a sufficient range across plots. Available phosphorus was lowest in the arboretum, although all sites were phosphorus-deficient. Exchangeable magnesium was sufficient only in the arboretum, while potassium levels were adequate across all plots. Soil pH and exchangeable aluminium were similar, with the arboretum showing slightly higher acidity and aluminium content. Biological indicators showed difference from the organic matter pattern, with microbial biomass carbon highest in one orchard soil and lowest in the arboretum, while microbial biomass nitrogen peaked in the arboretum and was lowest in another orchard. Soil quality was further assessed using the TSQI, which integrated multiple indicators into a single comparative framework. The arboretum recorded a higher index score (63.64%) than the fruit orchards (50.00%), primarily due to its greater total carbon, total nitrogen, and exchangeable magnesium, suggesting that rebuilding organic matter linked nutrient retention and alleviating magnesium limitation are central leverage points for improving orchard soil function under sustained management. These findings indicate that long-term conversion of forest land to fruit orchards, combined with intensive management practices, has gradually improved soil quality, with orchard soils approaching the benchmark condition represented by the arboretum. The results also confirm that the TSQI is a sensitive and effective tool for assessing soil condition in tropical agroecosystems and detecting changes driven by management over time.

Keywords: Arboretum, fruit orchard, soil quality, Tropical Soil Quality Index

INTRODUCTION

Soil quality is fundamental to the long-term productivity and environmental performance of perennial fruit orchards, yet it is often the first resource to show cumulative effects from decades of cultivation. In tropical orchards, prolonged management typically leads to reductions in soil organic matter and nutrient reserves as well as degradation of soil physical structure. This includes weakened aggregation and lower porosity, especially under intensive traffic and periodic disturbance, unless organic inputs and soil cover strategies are consistently applied (Manorama *et al.,* 2021; Jin *et al*., 2021). Because these changes occur gradually, managers often lack clear benchmarks to determine when soils have shifted from resilient to constrained conditions or to identify which soil functions most limit orchard performance. (Sharma *et al*., 2023).

Soil quality indices combine multiple indicators into a single metric to support diagnosis and comparison while identifying the properties driving change. Recent reviews emphasize that effective indices should represent key soil functions rather than isolated variables. This typically involves selecting relevant indicators, scoring them on a common scale and aggregating the scores using defined rules to produce a composite value that informs management decisions (Sharma *et al.,* 2023). In tropical perennial systems, this integrative approach is important because physical constraints such as reduced porosity and limited infiltration, often occur alongside biochemical constraints such as declining soil organic matter and altered nutrient pools. The relative importance of these constraints can vary among orchards within the same locality (Jin *et al*., 2021; Trujillo-González *et al*., 2025). Evidence from intensive plantation production shows that organic matter–based interventions such as mulching can mitigate degradation across multiple indicators simultaneously. This supports the use of indices to track multi-dimensional soil responses over extended production cycles (Manorama *et al*., 2021). Adjacent reference ecosystems support interpretation of index values at the landscape scale. In humid tropical Asia, conversions from forest to plantation alter key soil quality indicators such as organic matter declines, nitrogen forms shift, pH changes, and microbial community structure is modified. These variables are widely used to assess soil quality (Lan *et al.,* 2017; Lan *et al*., 2020; Edy *et al.,* 2020). In acidic tropical soils, biochar-based amendments influence microbial properties and nitrogen dynamics. This indicates that soil indices incorporating biological indicators may more effectively capture management impacts over time and across locations in the humid tropics (Halmi *et al*., 2018; Halmi and Simarani, 2021).

Benchmarking orchards against a nearby arboretum helps identify changes in soil functions under perennial fruit production, particularly in humid tropical regions where differences between reference and managed sites often reflect shifts in nutrient cycling and microbial activity. Studies show that root nitrogen uptake and nitrogen turnover pathways differ between rainforest and plantation systems (Edy *et al*., 2020), while in Bornean rainforests, root phosphatase activity responds to nitrogen and phosphorus fertilization, suggesting contrasting phosphorus acquisition strategies between reference and cultivated soils, even on similar parent material (Hirano *et al*., 2022). Orchard-edge practices, such as planting grasses and legumes as hedgerows, can increase organic inputs and support nitrogen uptake, improving fertility-related indicators (Sena *et al.,* 2020; Zang *et al.*, 2025). In addition, litterfall and pruning residues serve as direct nutrient return pathways, helping to maintain soil organic matter and associated indicators (Niscioli *et al.,* 2025). However, orchard-specific evidence remains limited, so localized assessment is required.

In tropical regions such as Kedah, Malaysia, challenges associated with intensive orchard management pose significant risks to soil sustainability. Addressing these region-specific issues requires a targeted analysis of management practices and their direct effects on soil properties, generating essential data to support both orchard productivity and environmental sustainability. This study assesses soil quality in the selected orchards with arboretum and examines the effectiveness of the Tropical Soil Quality Index (TSQI) in representing the condition and variability of these tropical acidic soils for local soil management and planning.

MATERIALS AND METHODS

Description of study sites

This study used a comparative, field-based design to assess soil quality in long-established tropical fruit orchards relative to a nearby, minimally disturbed forest reference within the same agro-climatic zone. The research was conducted at MARDI Sintok, Kedah, Malaysia (6°29′20″ N, 100°29′03″ E), a 345.6 ha tropical fruit research station located in Agro-climatic Zone 1, which experiences a clear drought season lasting up to three to four months (Shaidatul-Azdawiyah *et al.,* 2020). The station's soils are described as tropical acidic soils, which makes it a relevant setting for assessing long-term changes in physical, chemical, and biological indicators under orchard cultivation. An undisturbed arboretum area of approximately 20 ha within the station served as the ecological benchmark because it has not been converted for agricultural use since establishment, thereby providing a reference condition for interpreting orchard-associated changes in soil functioning. To improve comparability and limit confounding from stand age, all selected orchards were 25 years old. Orchard types represented key tropical fruit systems cultivated at the site namely *Artocarpus integer*, *Mangifera indica*, *Averrhoa carambola*, *Durio zibethinus*, and *Garcinia mangostana*.

Soil sampling

Each field was divided into nine areas to ensure that samples represented the entire site. From each area, five soil cores were collected at a depth of 0–30 cm using an auger in a zigzag pattern to reduce sampling bias (Arshad and Martin, 2002). The five subsamples from each area were thoroughly mixed in a bucket, and the bulk was reduced using the quartering method. Approximately 500 g of the resulting composite sample was retained, placed in a clean plastic bag, and labelled. These samples were then air-dried for 48 hours and stored in polyethylene bags for further analysis. For microbial biomass carbon and microbial biomass nitrogen, fresh soil samples were kept in an ice box at approximately 4 °C and transported to the laboratory for immediate analysis (Gupta, 2007).

Soil analysis

The laboratory analyses involves detailed measurements of soil texture, moisture content, pH, nutrient levels, and microbial biomass, using established scientific methods. These analyses are designed to meet the requirements of the Tropical Soil Quality Index. Bulk density was determined using the disturbed soil sample approach described by Gupta (2007), generating an indicator of compaction and pore-space limitation. Particle size distribution with emphasis on coarse fragment and texture characterization, was measured using the Universal pipette method (Teh and Talib, 2006). Soil acidity was determined using a pH meter following the approach described by Kereen *et al.* (2019). Total carbon and total nitrogen were measured using a CNS analyzer through the dry combustion, enabling determination of soil organic matter proxies and overall nitrogen reserves. Exchangeable base cations (K, Ca, Mg, Na) were extracted using a leaching method with pH 7.0, 1 M ammonium acetate (NH_4OAc) and 0.1 N potassium sulphate (K_2SO_4) (Thomas, 1982). Exchangeable aluminium was determined through 1 M potassium chloride (KCl) extraction (Thomas, 1982). Available phosphorus was determined using the Bray and Kurtz II extraction. Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were estimated using the chloroform fumigation-extraction method reflecting the size of the active microbial pool that mediates decomposition and nutrient mineralization (Vance *et al*., 1987; Wu *et al*., 1990). For MBC, carbon in extracts was determined using dichromate digestion (Vance *et al.,* 1987), whereas MBN was quantified using an Auto Analyzer (SEAL Analytical, AA500).

Tropical Soil Quality Index

The Tropical Soil Quality Index (TSQI) framework by Arifin *et al.* (2012) was used to integrate multiple soil indicators into a single, interpretable measure of soil functioning. Designed for tropical regions like Malaysia, TSQI includes physical, chemical, and biological metrics, allowing direct comparison across land uses and supporting interpretation of constraints and recovery. For each sampling unit, indicators measured were bulk density, pH, total carbon, total nitrogen, exchangeable cations, available phosphorus, and microbial biomass. Each was scored using threshold ranges from the TSQI scoring table, typically assigning ordinal values (0 = limiting, 1 = adequate, 2 = desirable), with exchangeable calcium allowing negative scores in cases of severe depletion. Raw TSQI scores were calculated by summing across all indicators and then standardized to a percentage (TSQI %) by dividing by the maximum score (22) and multiplying by 100. This percentage scale was used to assess relative soil functioning, where low TSQI % indicated multiple constraints (e.g. nutrient depletion, acidity, low microbial activity), moderate values reflected partial recovery, and high values signalled favourable soil conditions with most indicators in non-limiting ranges (Arifin *et al.,* 2012; Bodos *et al.,* 2024).

Statistical analysis

The variables included bulk density, pH, total carbon, total nitrogen, exchangeable bases, exchangeable aluminium, available phosphorus, microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) are analysed using analysis of variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) for mean comparison analysis. All analyses were run in SAS (version 9.4). Correlation analysis was conducted using Prism 10 software. The soil quality scoring was determined using the TSQI scoring (Arifin *et al.,* 2012).

RESULTS AND DISCUSSION

Soil physical degradation across land uses at MARDI Sintok

Across the six land uses evaluated at MARDI Sintok, the results establish a clear gradient in soil condition between the arboretum reference and the uniformly aged fruit orchards (**Table 1**). The arboretum, which had not been used for agriculture since the station was established, consistently showed an undisturbed structure and higher fertility indicators associated with organic matter than the five orchard systems. The physical indicators show that orchard management has caused a lasting structural change compared to the arboretum benchmark, most likely due to compaction and pore alteration from long-term traffic and cultivation. Although bulk density did not differ significantly among orchard species, its consistent elevation above the arboretum level indicates that compaction effects are now widespread across the orchard plots (**Figure 1**). Similar patterns have been observed in other cultivated tropical systems, where the removal of continuous litter cover and repeated mechanical disturbance reduce macroporosity and increase soil density, limiting both water infiltration and root penetration (Lima *et al*., 2018; Pinto *et al*., 2019). The measured orchard bulk densities (1.31–1.35 g cm^{-3}) align with values typical of managed tropical land uses, whereas native benchmarks, often found in well-structured soils under natural vegetation, tend to range from 0.9 to 1.1 Mg m^{-3} (Pinto *et al.*, 2019). This indicates that the structural differences between the arboretum and the orchards represent a long-term equilibrium under management, rather than a temporary condition. Such structural changes are important because they can intensify downstream limitations by restricting water flow, altering oxygen availability and influencing microbial habitats, thereby linking physical degradation to chemical and biological processes over time.

Table 1: Comparison of soil physicochemical and biological properties across the study sites.

No.	Soil properties	Unit	Arboretum	*Artocarpus integer*	*Mangifera indica*	*Averrhoa carambola*	*Durio zibethinus*	*Garcinia mangostana*
1	Bulk Density	g/cm^3	1.19 b	1.35 a	1.31 a	1.32 a	1.33 a	1.35 a
2	Organic matter	%	1.76 a	0.70 bc	0.85 b	0.70 bc	0.77 bc	0.64 c
3	Total carbon	%	1.36 a	0.54 bc	0.65 b	0.54 bc	0.59 bc	0.49 c
4	Total nitrogen	%	0.10 a	0.03 b	0.03 b	0.02 b	0.02 b	0.03 b
5	Cation exchange capacity	$cmol^+/kg$	11.86 a	3.54 d	7.29 b	6.12 bc	4.95 c	5.18 c
6	CN ratio		10.90 c	28.37 a	22.77 ab	22.15 ab	23.55 ab	16.18 bc
7	Soil acidity	pH	4.59 d	5.02 ab	4.88 bc	5.25 a	4.93 bc	4.68 cd
8	Exchangeable potassium	$cmol^+/kg$	1.08 a	0.83 b	0.73 c	0.69 c	0.63 d	0.41 e
9	Exchangeable calcium	$cmol^+/kg$	4.09 a	3.67 a	4.20 a	3.82 a	2.96 b	1.33 c
10	Exchangeable magnesium	$cmol^+/kg$	0.57 a	0.03 c	0.33 b	0.34 b	0.09 c	0.03 c
11	Exchangeable sodium	$cmol^+/kg$	0.09 a	0.05 d	0.05 d	0.08 ab	0.07 b	0.06 c
12	Available phosphorus	mg/kg	1.09 c	2.85 a	2.24 abc	1.83 abc	2.70 ab	1.47 bc
13	Exchangeable aluminium	$cmol^+/kg$	0.92 a	0.28 d	0.57 b	0.48 bc	0.39 c	0.40 c
14	Microbial biomass carbon	µg/g	10152.8 c	17104.3 a	14376.3 b	13866.5 b	15016.9 b	14141.5 b
15	Microbial biomass nitrogen	µg/g	1288.5 a	1017.1 ab	995.3 ab	736.6 ab	913.6 ab	194.2 b

*Means with different letters indicate a significant difference $p<0.05$ between sites using the Duncan's Multiple Range Test (DMRT).

Organic matter patterns across study sites

The chemical indicators show that the most significant differences between the arboretum and the orchards occur in fertility variables associated with organic matter, with the magnitude of these differences indicating long-term depletion of soil organic inputs under orchard management. Organic matter in the arboretum (1.76%) was approximately two to three times higher than in orchard soils (0.64–0.85%) (**Figure 2**). A similar trend appears for total carbon (1.36% vs. 0.49–0.65%) and total nitrogen (0.10% vs. 0.02–0.03%), as shown in **Figures 3** and **Figure 4**, respectively. These patterns are consistent with a mechanistic explanation in which reduced litter return, removal of pruned materials and biomass export through harvesting gradually lower soil organic inputs compared to forest reference systems. Forest studies emphasize that litter production and decomposition regulate the accumulation of soil organic matter and the replenishment of nutrients, while land-use change reduces the organic input pathways that sustain carbon and nitrogen pools (Fetene & Amera, 2018; Giweta, 2020). Orchard systems can maintain or increase organic matter if management includes additional inputs such as intercrops or residue retention. However, intensive systems with residue removal tend to show ongoing declines over time (Zhang *et al*., 2021). After 25 years, orchard plots still cluster at low carbon and nitrogen levels, indicating that organic inputs have not been sufficient to offset losses from decomposition and cultivation.

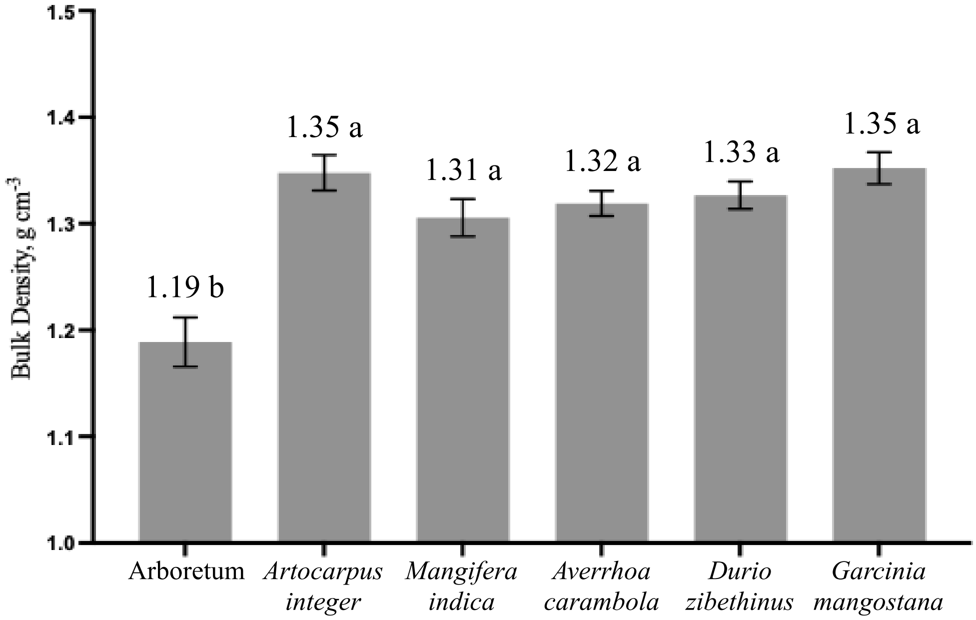

Figure 1: The bulk density values for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

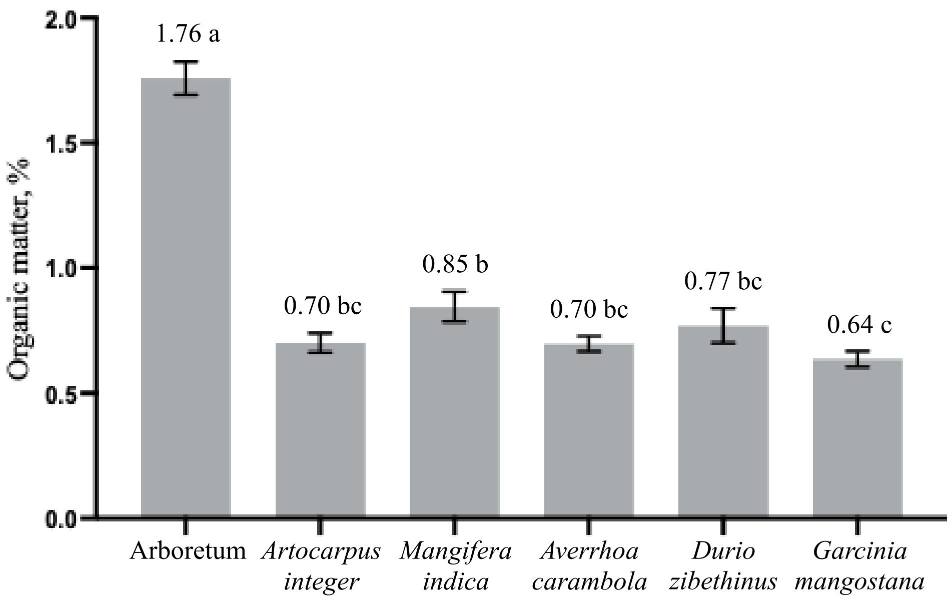

Figure 2: The soil organic matter for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

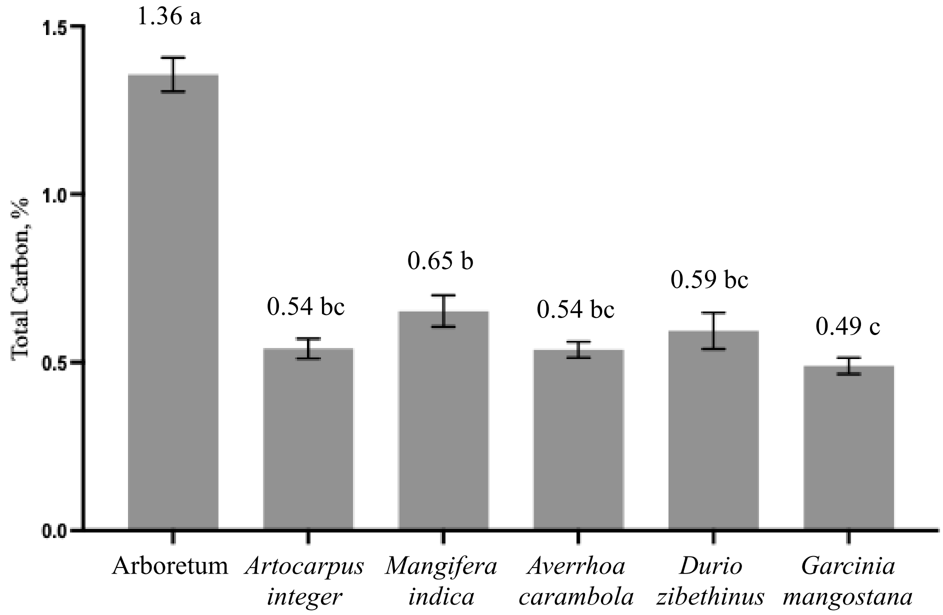

Figure 3: The soil total carbon for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

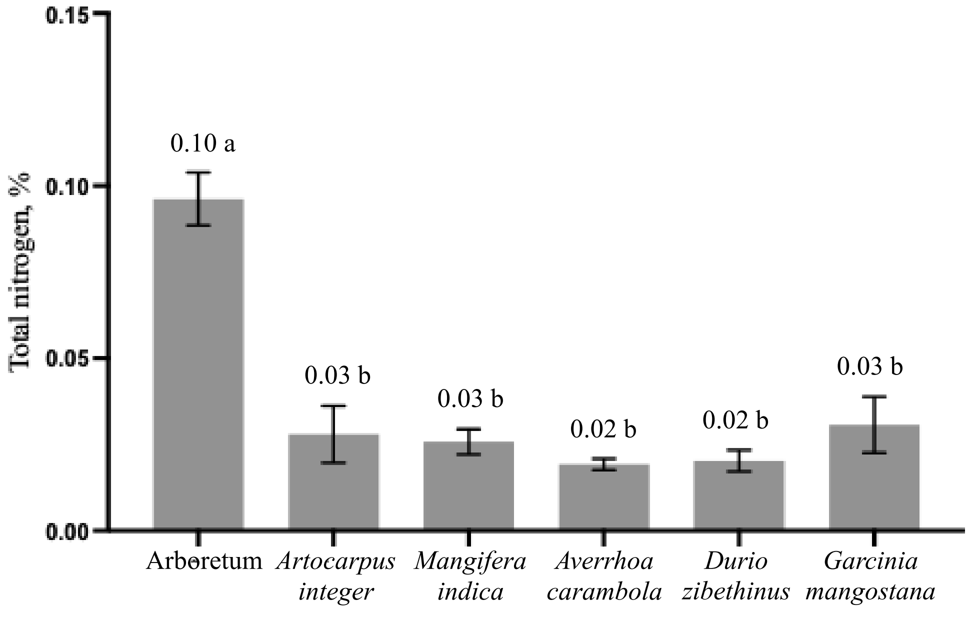

Figure 4: The soil total nitrogen for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

Cation exchange capacity (CEC) pattern across sites

CEC patterns closely mirror organic matter and carbon levels, indicating that organic matter loss is a primary cause of reduced nutrient retention in orchard soils. The arboretum, with 42.71% clay, had the highest CEC (11.86 $cmol^+ kg^{-1}$), while orchard values ranged from 3.54 to 7.29, with *Artocarpus integer* lowest due to its high sand content and low organic matter as shown in **Table 2** and **Figure 5**. Strong correlations among organic matter with CEC (**Figure 6**) confirm the role of organic matter in nutrient retention, particularly in tropical soils with low-activity clays and acidic conditions, where CEC relies heavily on organic contributions

(Fetene & Amera, 2018; Zhou *et al*., 2019). Soil texture further reinforces this relationship: clay-rich soils retain more carbon and support higher CEC, whereas sandy soils are more susceptible to leaching and depend more on organic matter for nutrient retention (Khaledian *et al*., 2017; Costa *et al*., 2020). Variations in soil texture and series help explain differences among orchards with similar TSQI scores, indicating that soil quality at MARDI Sintok reflects both management practices and texture-related constraints on nutrient.

Table 2: Soil texture analysis for the six sampled determined by USDA soil texture classification standards.

	Total particle size distribution (microns)				Soil Texture Class (USDA)
Treatment	**Clay**	**Silt**	**Sand**	**Coarse fragment**	
	< 2	2 - 50	> 50	> 500	
Arboretum	42.71	23.45	33.82	12.85	clay
Artocarpus integer	14.31	9.60	76.08	1.88	sandy loam
Mangifera indica	26.11	18.98	54.91	1.92	sandy clay loam
Averrhoa carambola	20.50	20.14	59.32	0.84	sandy clay loam
Durio zibethinus	9.04	18.24	72.70	1.59	sandy loam
Garcinia mangostana	13.28	39.02	47.70	1.76	loam

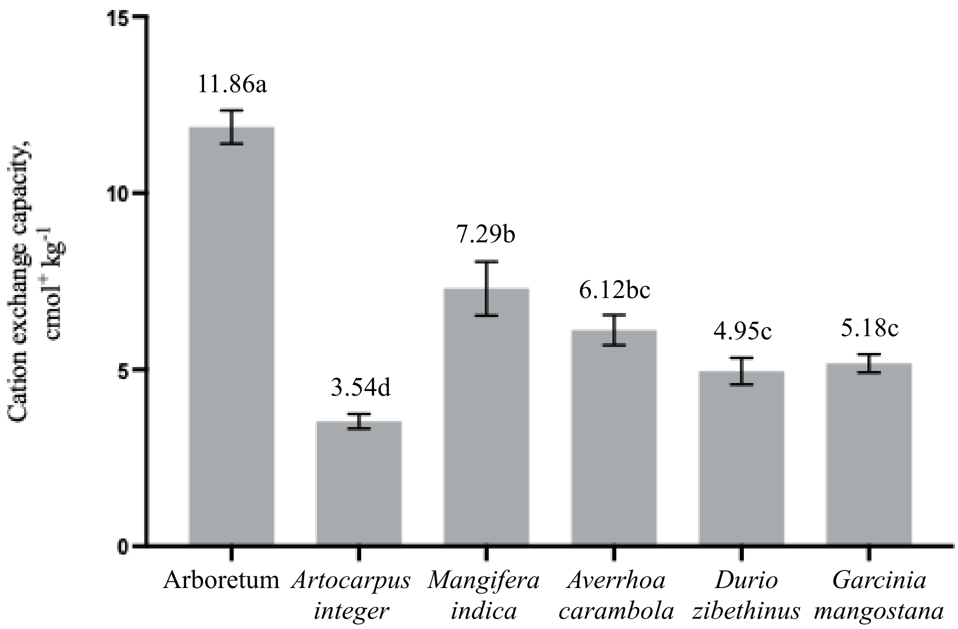

Figure 5: The soil cation exchange capacity (CEC) for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

Soil C/N ratio patterns across arboretum and orchard soils

The C/N ratio results further demonstrate that nutrient cycling dynamics differ markedly between the arboretum and orchard soils, and that orchard soils vary by species in ways that may reflect differences in substrate quality, microbial activity or nitrogen limitation. The arboretum recorded the lowest C/N ratio (10.90), indicating relatively nitrogen-rich organic matter with active cycling (**Figure 7**). In contrast, orchard soils showed higher C/N ratios, with *Artocarpus integer* highest (28.37) and *Garcinia mangostana* lowest among orchards (16.18).

Elevated C/N ratios typically signal slower nitrogen mineralization and reduced nitrogen availability relative to carbon. This condition can result from limited organic inputs, carbon-rich residues, or dominant microbial immobilization.

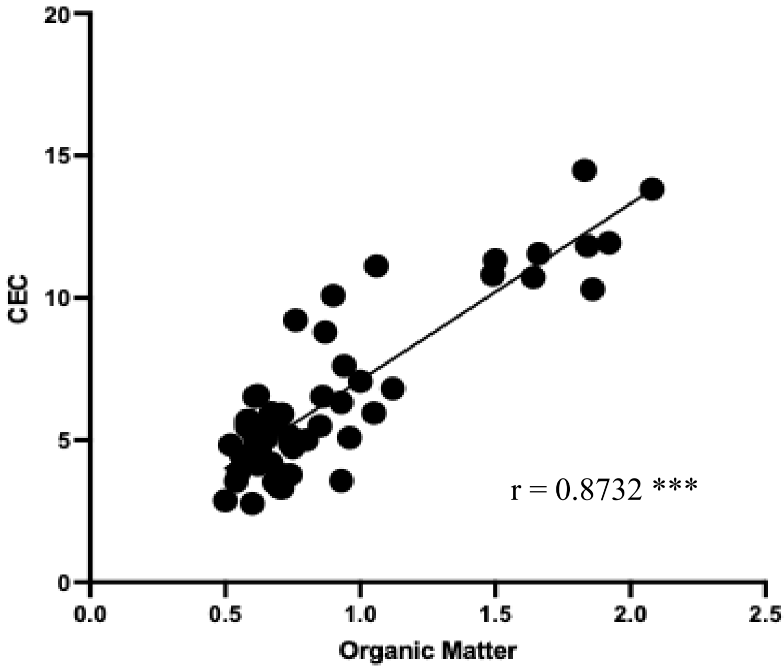

Figure 6: Relationship between organic matter and cation exchange capacity level at 0-30cm depth at study sites. The significant levels are indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$.

Research on orchard systems shows that management can influence C/N ratios through changes in litter quality, residue return and soil microclimate, thereby affecting nitrogen retention and microbial community composition over time (Zhang *et al*., 2021). The results showed that the orchard soils tend toward conditions with limited nitrogen availability and reduced fertility. In this context, the high C/N ratio in *Artocarpus integer* indicates particularly constrained nitrogen inputs or retention, likely compounded by low CEC and sandy texture, which may increase vulnerability to nutrient leaching.

The nutrient results indicate that the arboretum does not consistently outperform the orchards, supporting the interpretation that orchard management leads to selective nutrient shifts rather than uniform enrichment or depletion. Available phosphorus was lowest in the arboretum (1.09 mg kg^{-1}), while *Artocarpus integer* and *Durio zibethinus* recorded the highest levels (2.85 and 2.70 mg kg^{-1}, respectively), though all plots remain phosphorus-deficient (**Figure 8**). This reflects ongoing phosphorus limitation in acidic tropical soils, where phosphorus binds strongly to iron and aluminium oxides. Long-term nitrogen additions can further reduce phosphorus availability by altering soil pH and phosphorus chemistry (Li *et al*., 2016; Chen *et al*., 2020). The slightly higher available phosphorus in orchard soils compared to the arboretum hints that fertilizer application has increased extractable phosphorus, but not enough to overcome overall deficiency. The results support a management context in which inputs are applied yet remain insufficient to fully address persistent phosphorus limitation. In contrast, exchangeable potassium levels are sufficient across all plots as shown in **Figure 9**, but the arboretum remains higher (1.08 $cmol^{+}$ kg^{-1}) than the orchards (0.41–0.83 $cmol^{+}$ kg^{-1}), with *Garcinia mangostana* lowest. This aligns with expectations that forest systems maintain potassium through litter return and deeper rooting, while potassium levels in orchards likely reflect external inputs rather than natural buffering. Lower potassium in *Garcinia mangostana* may result from weaker retention linked to its loam texture, lower organic matter, or management factors.

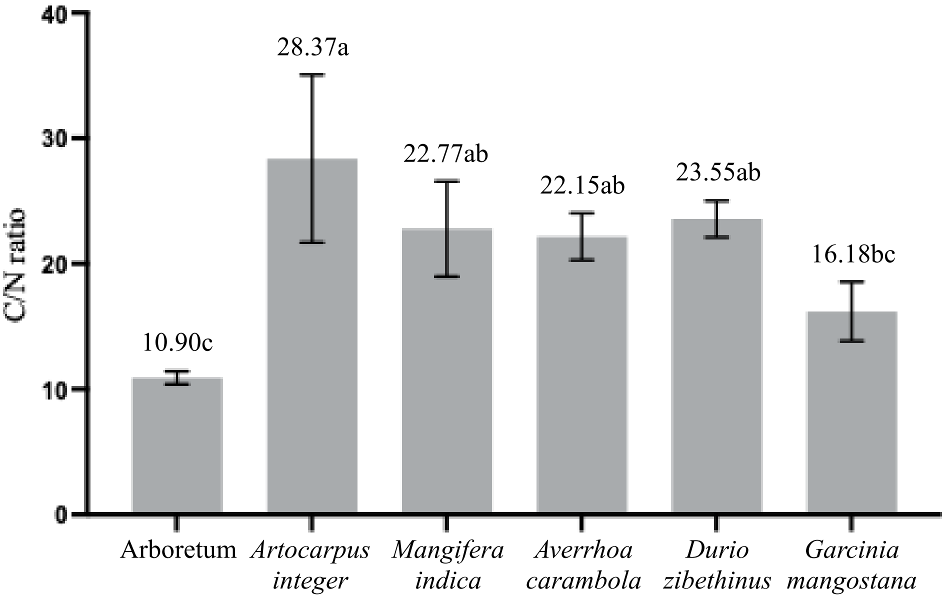

Figure 7: The soil carbon-to-nitrogen (C/N) ratio for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

Therefore, potassium sufficiency in the orchards should be interpreted as a managed state that could become unstable if organic matter and exchange capacity continue to decline (Costa *et al.*, 2020). Calcium and magnesium results show further differentiation. Calcium was sufficient across all plots (1.33–4.20 $cmol^+ kg^{-1}$), with *Mangifera indica* highest and *Garcinia mangostana* lowest (**Figure 10**). In contrast, magnesium was sufficient only in the arboretum (0.57 $cmol^+ kg^{-1}$) and deficient in most orchards (**Figure 11**), particularly in *Artocarpus integer* and *Garcinia mangostana* (both 0.03 $cmol^+ kg^{-1}$). The depletion of magnesium aligns with its higher leaching potential in acidic soils, particularly where sand content is high and CEC is low. Other studies have shown that sandy tropical soils require greater organic inputs or amendments to sustain base cation levels (Costa *et al.*, 2020; Zuza *et al.*, 2023). Acidity and exchangeable aluminium results in **Figure 12** and **Figure 13** respectively show that all sites remain acidic but within an acceptable range (pH 4.59 – 5.25). The arboretum recorded the lowest pH (4.59) and the highest exchangeable aluminium (0.92 $cmol^+ kg^{-1}$), likely reflecting natural acidity maintained by organic acid production and leaching under forest cover. Orchard soils showed slightly higher pH values, possibly due to liming and fertilizer application.

Variation in Soil Microbial Biomass under Different Vegetation

The microbial biomass results differ from the organic matter pattern, indicating that biological function is shaped by more than total carbon content. *Artocarpus integer* recorded the highest microbial biomass carbon (17,104.3 $\mu g\, g^{-1}$) despite having low organic matter, while the arboretum with the highest organic matter showed the lowest MBC (10,152.8 $\mu g\, g^{-1}$) as shown in **Figure 14**. In contrast, microbial biomass nitrogen (**Figure 15**) was highest in the arboretum (1,288.5 $\mu g\, g^{-1}$) and lowest in *Garcinia mangostana* (194.2 $\mu g\, g^{-1}$), indicating possible nitrogen limitation in that plot. These results indicate that microbial biomass is influenced by substrate quality, disturbance history and nutrient availability, rather than organic matter quantity alone. Studies on orchard systems report that vegetation type and intercropping can reshape microbial communities by modifying rhizosphere inputs and microclimate, which may enhance biomass even in low-carbon soils (Zhang *et al*., 2021). In this case, elevated MBC in *Artocarpus integer* may reflect greater root activity or improved aeration in sandy loam soils, while the lower MBC in the clay-rich arboretum may be due to slower carbon turnover or more stabilized organic matter.

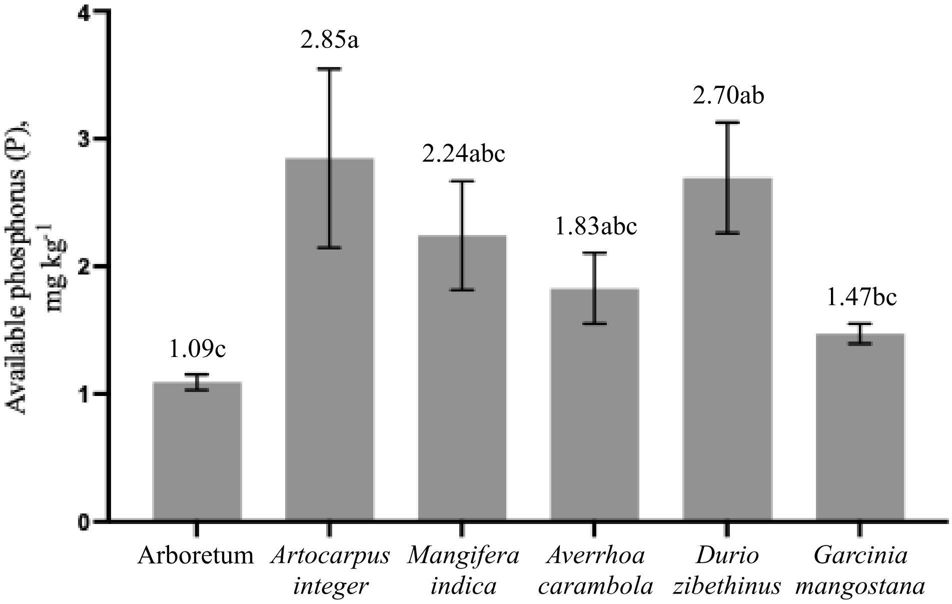

Figure 8: The soil available phosphorus content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

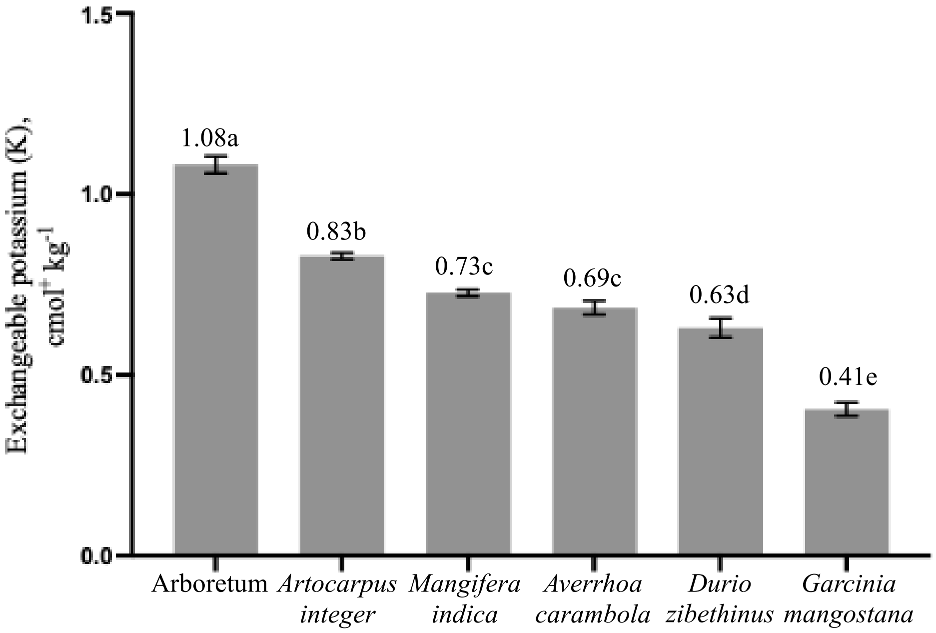

Figure 9: The soil exchangeable potassium (K) content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

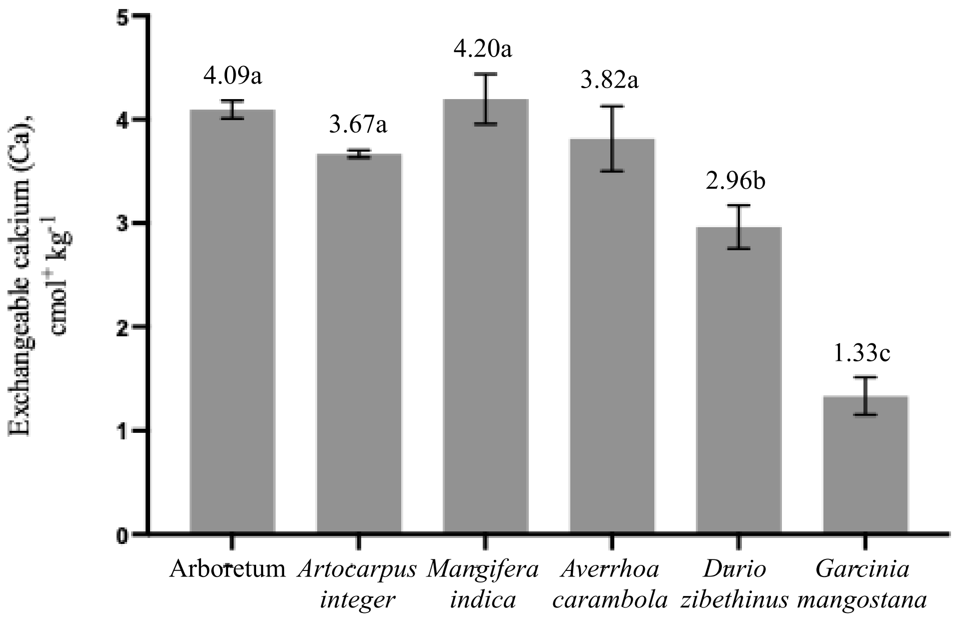

Figure 10: The soil exchangeable calcium (Ca) content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

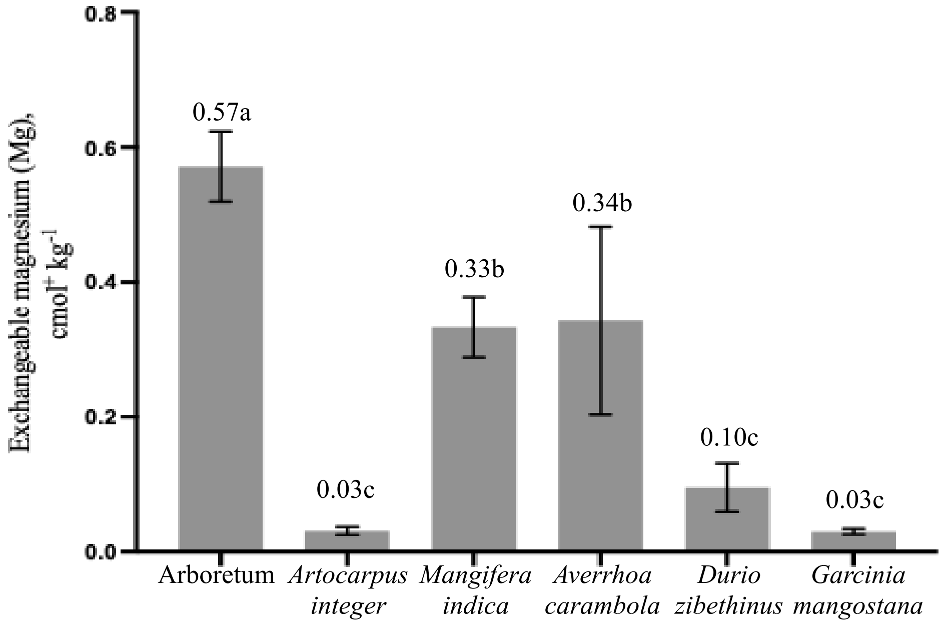

Figure 11: The soil exchangeable magnesium (Mg) content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

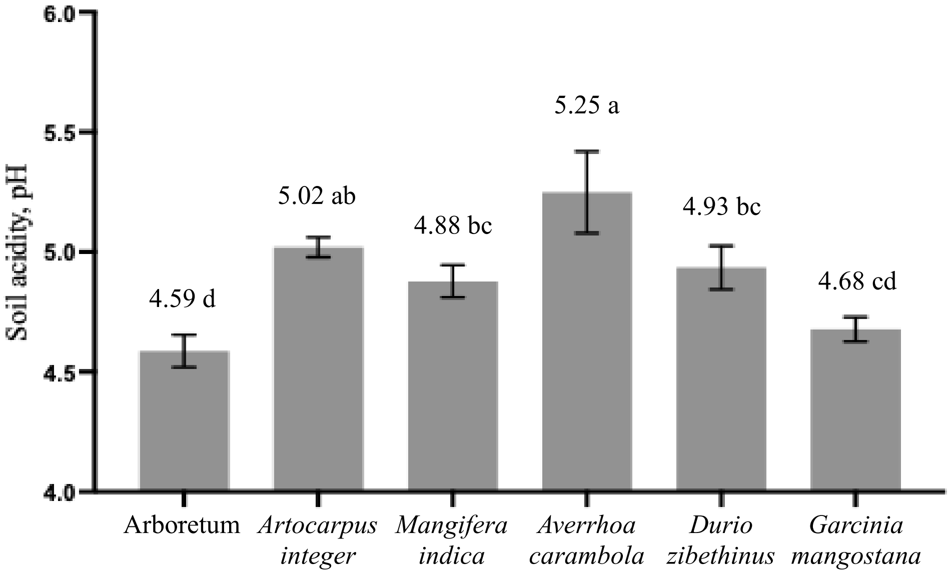

Figure 12: The soil acidity levels for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

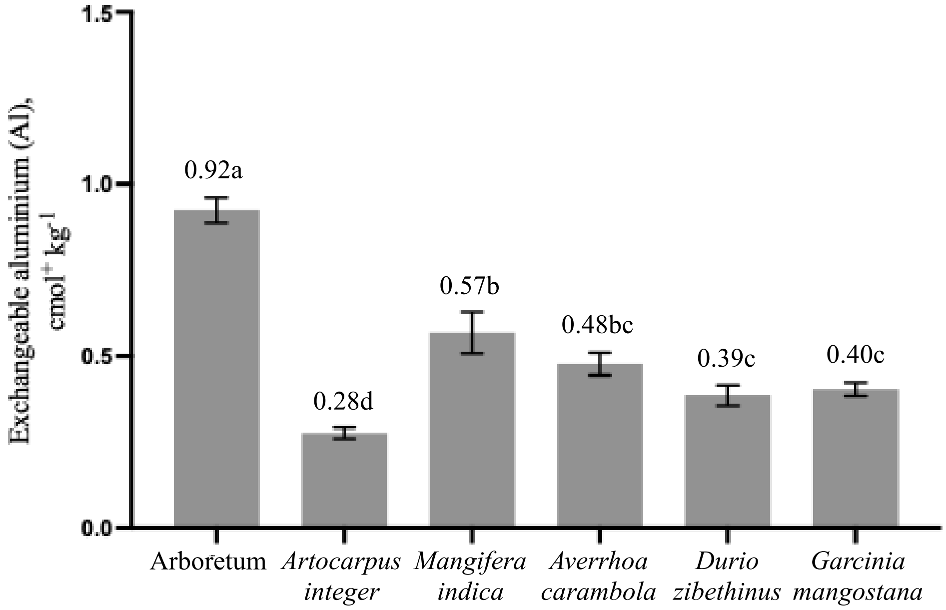

Figure 13: The soil exchangeable aluminium (Al) content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference p<0.05 between plots using Duncan's Multiple Range Test (DMRT).

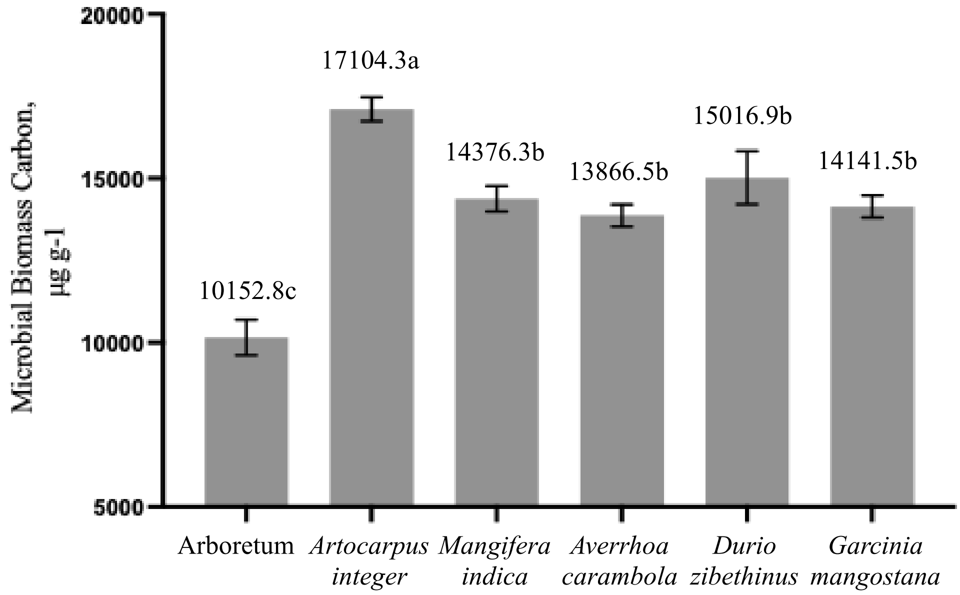

Figure 14: The soil microbial biomass carbon content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

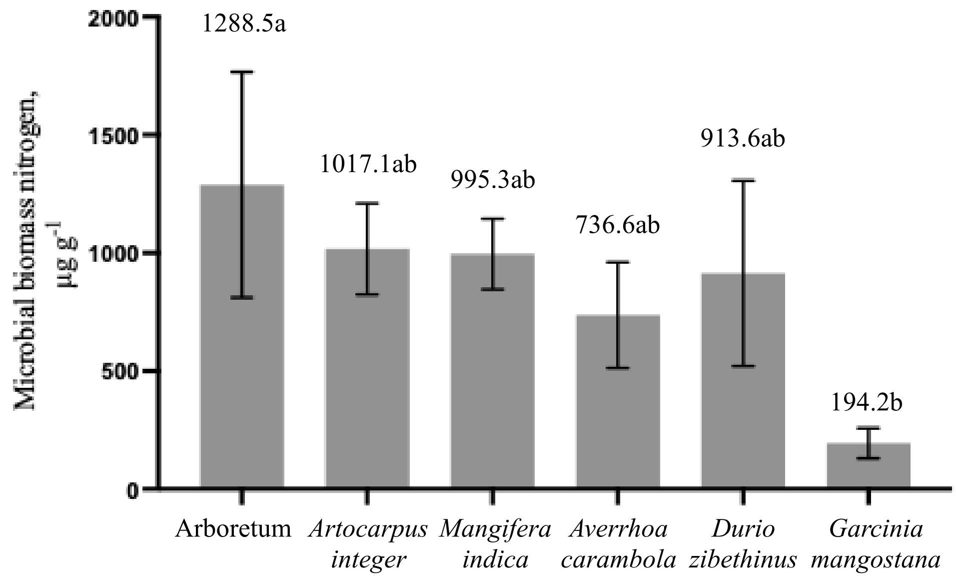

Figure 15: The soil microbial biomass nitrogen content for various sites at MARDI Sintok. Mean values with different letters indicate a significant difference $p<0.05$ between plots using Duncan's Multiple Range Test (DMRT).

Tropical Soil Quality Index (TSQI) scoring

Table 3 summarizes the comparative analysis of soil physicochemical and biological properties across various land-use systems, including an arboretum, *Artocarpus integer, Mangifera indica, Averrhoa carambola, Durio zibethinus*, and *Garcinia mangostana* using the Tropical Soil Quality Index scoring. The evaluation focused on bulk density, soil acidity (pH), total carbon and nitrogen content, available phosphorus, exchangeable cations (K, Ca, Mg, Na, and

Al), coarse fragment content, and microbial biomass carbon (MBC) and nitrogen (MBN). A higher TSQI % indicates better soil quality, as it reflects a greater number of indicators falling within the “adequate” or “excellent” ranges (Bodos *et al*., 2024). The arboretum showed the highest overall performance with a score of 63.64%. This superiority was evident as the arboretum outperformed other land-use types in total carbon, total nitrogen, and exchangeable magnesium content. Other fruit orchards including *Artocarpus integer, Mangifera indica, Averrhoa carambola*, and *Durio zibethinus*, shared similar scores of 50.00% which indicating comparable soil quality among these management systems. The lower TSQI percentages in fruit orchards relative to the arboretum highlight the challenges associated with intensive agricultural practices in tropical environments. Low levels of soil organic matter in orchard systems may compromise long-term soil fertility and resilience (Lal, 2015).

Table 3: Summarizes the scoring of soil physicochemical and biological properties using the Tropical Soil Quality Index (TSQI)

No.	Parameter	Unit	Arboretum	*Artocarpus integer*	*Mangifera indica*	*Averrhoa carambola*	*Durio zibethinus*	*Garcinia mangostana*
1	Bulk density	g cm^{-3}	1	1	1	1	1	1
2	Coarse fragments	%	1	1	1	1	1	1
3	Soil acidity	pH	1	1	1	1	1	1
4	Total carbon in soils	%	1	0	0	0	0	0
5	Total nitrogen in soils	%	1	0	0	0	0	0
6	Exchangeable Na	%	1	1	1	1	1	1
7	Exchangeable K	cmol$^+$ kg^{-1}	1	1	1	1	1	1
8	Exchangeable Mg	cmol$^+$ kg^{-1}	1	0	0	0	0	0
9	Exchangeable Ca	cmol$^+$ kg^{-1}	1	1	1	1	1	1
10	Exchangeable Al	cmol$^+$ kg^{-1}	1	1	1	1	1	1
11	Available P	mg kg^{-1}	0	0	0	0	0	0
12	Microbial biomass C	µg g^{-1}	2	2	2	2	2	2
13	Microbial biomass N	µg g^{-1}	2	2	2	2	2	2
	Total score		**14**	**11**	**11**	**11**	**11**	**11**
	Percentage (%)		**63.64**	**50.00**	**50.00**	**50.00**	**50.00**	**50.00**

CONCLUSION

This study concludes that long-term tropical fruit orchard cultivation at MARDI Sintok has produced measurable and persistent shifts in soil quality relative to the undisturbed arboretum benchmark, and that these shifts are expressed most strongly through linked changes in soil structure, organic matter reserves, and nutrient retention capacity. Across the evaluated indicators, the arboretum consistently maintained superior soil physical condition and higher organic matter associated fertility, including lower bulk density than orchard soils, which clustered at higher bulk density. The arboretum also showed substantially higher organic matter, total carbon, total nitrogen, and cation exchange compared with orchard plots, supporting the interpretation that intensive orchard practices have reduced organic inputs and weakened soil buffering functions over time. Nutrient patterns further show selective change rather than uniform depletion, as available phosphorus remained deficient across all sites and exchangeable potassium and calcium remained within sufficient classes, while exchangeable magnesium was consistently low in orchard soils relative to the arboretum. Microbial indicators showed a more complex response, with microbial biomass carbon highest in *Artocarpus integer* soils and lowest in the arboretum, underscoring that biological function does not always track organic matter levels alone. When these indicators were integrated into TSQI scoring, the arboretum achieved a higher score (63.64%) than all orchards (50.00%), confirming that TSQI effectively distinguishes soil quality status across land uses and that the orchard-to-forest difference is primarily driven by total carbon, total nitrogen, and exchangeable magnesium. The similarity of TSQI scores among the fruit orchards suggests that shared land-use history and management intensity have a greater influence on soil quality. These findings indicate that orchard soils are progressing toward improved fertility levels, approaching those of the arboretum. Collectively, the findings validate the use of TSQI as a practical framework for assessing tropical orchard soil quality at Sintok and demonstrate that improving organic matter and nutrient retention, while protecting soil structure, is central to sustaining long-term soil function in these orchard systems .

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