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Soil Fertility Assessment of Guimaras' Mango Plantations

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Abstract: Sustainable mango (*Mangifera indica* L.) production depends on balanced soil fertility and adequate nutrient availability. However, information on the integrated soil fertility status of mango plantations in Guimaras Province, Philippines, remains limited. This study provides the first province-wide assessment of soil physical and chemical fertility across sixteen mango plantations in five municipalities to identify key constraints affecting nutrient availability. Surface soils (0–30 cm) were analyzed for texture, pH, organic matter (OM), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and their plant-available fractions. The soils were predominantly sandy loam and strongly acidic (pH 4.14–5.82), with generally low organic matter (0.47–2.57%) and total nitrogen (0.06–0.22%). Although total phosphorus and potassium reserves were moderate to high in several plantations, plant-available phosphorus remained consistently low (6–14 ppm), indicating widespread phosphorus limitation associated with soil acidity, low organic matter, and nutrient leaching. Exchangeable potassium, calcium, and magnesium varied considerably among plantations, reflecting differences in parent material and management practices. The disparity between total nutrient reserves and plant-available fractions indicates hidden hunger, where nutrients are present but poorly available for plant uptake. These findings highlight that soil fertility constraints in Guimaras mango orchards arise primarily from limited nutrient availability rather than nutrient depletion. Integrated soil management, including liming, organic matter enhancement, and soil test-based fertilization, is therefore recommended to improve orchard productivity.

Keywords: mango; soil acidity; nutrient availability; hidden hunger; soil fertility assessment; site-specific nutrient management

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1. Introduction

Soil fertility is a fundamental determinant of productivity and sustainability in perennial cropping systems such as mango (*Mangifera indica* L.), where long-term nutrient dynamics directly influence vegetative growth, flowering, fruit set, and fruit quality. In tropical environments, soil fertility is governed not only by total nutrient reserves but more critically by nutrient availability, which is strongly regulated by soil physicochemical properties (Lira et al., 2021; Razi et al., 2022). However, many tropical soils are highly weathered, acidic, and structurally fragile, conditions that inherently limit nutrient retention and plant accessibility (Saentho et al., 2022; Hartemink and Barrow, 2023).

In addition to phosphorus dynamics, the availability of base cations such as potassium (K), calcium (Ca), and magnesium (Mg) is strongly influenced by soil texture, mineralogy, and organic matter content, which together determine cation exchange capacity (CEC) and nutrient retention. In tropical sandy soils, limited CEC reduces the ability of soils to retain exchangeable cations, increasing their susceptibility to leaching under high rainfall conditions (White, 2005; Senbayram et al., 2015; Zhang et al., 2015; Ouyang et al., 2023). These processes further contribute to imbalances between total nutrient reserves and plant-available fractions.

In such systems, nutrient availability rather than total nutrient content is the primary determinant of crop performance. Acidic soils promote phosphorus fixation through interactions with iron and aluminum oxides, reducing its solubility despite substantial total phosphorus reserves (Saentho et al., 2022; Hartemink & Barrow, 2023). Similarly, sandy soil textures and low organic matter reduce cation exchange capacity (CEC), limiting the retention of essential base cations such as potassium (K), calcium (Ca), and magnesium (Mg), and increasing their susceptibility to leaching under high rainfall conditions (White, 2005; Senbayram et al., 2015). These interacting constraints highlight the need to evaluate soil fertility beyond total nutrient concentrations.

This discrepancy between nutrient reserves and plant-available fractions is commonly described as 'hidden hunger,' a condition in which soils contain adequate nutrient stocks but fail to supply sufficient nutrients in plant-accessible forms, resulting in suboptimal crop performance (Gayar, 2021). Hidden hunger is often associated with soil acidity, nutrient fixation, low organic matter, and imbalanced fertilization, all of which reduce nutrient use efficiency and limit crop productivity. In mango production systems, such constraints have been linked to inconsistent yield responses and reduced nutrient uptake efficiency, particularly under acidic and low-organic-matter conditions (Salehin et al., 2020; Lira et al., 2021). These findings suggest that assessments based solely on total nutrient concentrations may overestimate soil fertility and fail to identify key limitations affecting orchard performance.

In addition, spatial variability in soil properties further complicates nutrient management in perennial orchard systems. Soil fertility parameters can vary substantially within and among mango plantations due to differences in parent material, soil texture, management practices, and microenvironmental conditions (Salehin et al., 2020; Lira et al., 2021). Such variability limits the effectiveness of uniform fertilization strategies and underscores the need for site-specific nutrient management approaches.

Despite these advances, most studies in mango production systems have evaluated either total nutrient reserves or plant-available fractions independently, limiting a comprehensive understanding of functional soil fertility. Integrated assessments that simultaneously examine both nutrient pools remain limited, particularly in the Philippine context. In Guimaras, a major mango-producing province recognized for its high-quality fruit, there is currently no province-scale study that systematically evaluates both total and plant-available nutrients in mango plantation soils.

Therefore, this study represents the first integrated, province-scale assessment of soil fertility in Guimaras mango plantations, combining total nutrient reserves and plant-available fractions within the framework of the hidden hunger concept. Beyond descriptive assessment, the study aims to identify key physicochemical constraints limiting nutrient availability and to evaluate how these constraints contribute to imbalances between nutrient supply and plant uptake. Specifically, it seeks to (1) assess soil physical and chemical properties; (2) determine the dominant limiting factors affecting nutrient availability; and (3) generate site-specific nutrient management implications for improving soil fertility and mango productivity. It is hypothesized that, despite moderate to high total nutrient levels, nutrient availability is constrained by soil acidity, low organic matter, and sandy soil textures, resulting in hidden hunger conditions.

2. Materials and Methods

2.1. Study Area

The study was conducted in the province of Guimaras, Western Visayas, Philippines (10°25′–10°48′ N; 122°28′–122°48′ E) (Figure 1A). The province has a tropical monsoon climate characterized by distinct wet (June–November) and dry (December–May) seasons, with mean annual temperatures of 25–32 °C and average annual rainfall exceeding 2,000 mm. Mango production in the province is predominantly rainfed and represents a major agricultural activity.

Sixteen (16) active mango plantations were selected across five municipalities to ensure province-wide representation: Buenavista (4), Jordan (4), San Lorenzo (3), Sibunag (3), and Nueva Valencia (2) (Figure 1B). The selected plantations were commercially productive and under regular management. Soils in the area are generally derived from sedimentary and limestone parent materials and are predominantly sandy-textured, commonly classified as Inceptisols and Alfisols (USDA Soil Taxonomy).

(a) **(b)**

Figure 1. Location of the study area and sampling sites in Guimaras, Philippines: (**a**) location map of Guimaras within the Philippines; (**b**) spatial distribution of mango plantation sampling sites across the island.

2.2. Soil Sampling

Soil sampling was conducted in sixteen (16) mango (*Mangifera indica* L.) plantations across five municipalities of Guimaras Province, Philippines, during November–December 2024. To capture within-plantation spatial variability, a systematic grid-based sampling approach was employed at each site.

Within each plantation, five (5) sampling points were established at approximately 20–30 m intervals, depending on plantation size and tree spacing, to ensure representative spatial coverage while minimizing sampling bias.

At each sampling point, soil samples were collected from two depth intervals (0–30 cm and 30–60 cm), corresponding to the surface and subsurface layers within the effective rooting zone of mature mango trees. Soil samples were obtained by excavating a vertical soil profile using a spade, and the central portion of the soil slice was retained to avoid contamination from surface litter and underlying layers.

For each plantation and sampling depth, soil samples from the five sampling points were combined to form a composite sample. Composite samples were prepared by thoroughly mixing equal portions of soil from each sampling point, thereby reducing local heterogeneity and providing a representative sample of each plantation. Two composite samples per plantation (one per depth) were initially obtained; however, only the 0–30 cm depth was used for laboratory analysis, as it represents the most biologically active soil layer where nutrient cycling, organic matter dynamics, and root activity are concentrated.

All composite samples were air-dried at room temperature, gently crushed, homogenized, and passed through a 2-mm sieve prior to laboratory analysis.

Based on regional soil information and field observations, the soils were preliminarily classified as Inceptisols and Alfisols (USDA Soil Taxonomy), corresponding to Cambisols and Luvisols under the FAO World Reference Base (WRB). Detailed soil classification was beyond the scope of this study and would require additional laboratory analyses of diagnostic horizons and base saturation.

Representative soil profile exposures from selected sampling sites are shown in Figure 2 to illustrate field sampling conditions and soil morphological characteristics.

(a) **(b)**

Figure 2. Representative soil profile exposure and sampling conditions in mango plantations in Guimaras, Philippines: (**a**) excavated soil profile showing surface (0–30 cm) and subsurface horizons used for sampling; (**b**) sampling pit illustrating soil structure, texture, and color variability across the study sites.

2.3. Laboratory Analysis

Soil samples were analyzed at the Sugar Regulatory Administration Environmental Laboratory Services, Bacolod City, Negros Occidental, Philippines. The analytical methods used are summarized in Table 1.

Soil texture was determined using the hydrometer method. Soil pH was measured potentiometrically using a glass electrode pH meter. Organic matter was determined using the Walkley and Black wet oxidation method. Total nitrogen was analyzed via the Kjeldahl digestion method.

Total phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) were determined using X-ray fluorescence (XRF) spectrometry. XRF was selected due to its capability for rapid, multi-element analysis of total elemental composition with minimal chemical reagents. However, it is acknowledged that XRF has limitations in detecting light elements, particularly magnesium at low concentrations, which may influence the interpretation of total Mg values.

Table 1. Parameters and methods adopted for the soil analysis at Sugar Regulatory Administration Environmental Laboratory Services, Bacolod City, Negros Occidental, Philippines.

Parameters	Unit	Methods
PHYSICAL		
Soil Texture		Hydrometer
CHEMICAL		
Soil pH		Glass Electrode
Organic matter	%	Walkley and Black
Total N	%	Kjeldahl
Total P	%	X-ray Fluorescence
Total K	%	X-ray Fluorescence
Total Ca	%	X-ray Fluorescence
Total Mg	%	X-ray Fluorescence
Available P	ppm	Truog Method
Available K	ppm	Ammonium Acetate Shaking
Available Ca	ppm	Ammonium Acetate Shaking
Available Mg	ppm	Ammonium Acetate Shaking

Available phosphorus was determined using the Truog method, suitable for acidic soils. Exchangeable potassium, calcium, and magnesium were extracted using ammonium acetate solution and quantified accordingly.

2.4. Statistical Analysis

The study was conducted as a cross-sectional observational assessment of soil fertility across selected mango plantations in Guimaras, Philippines. Each plantation was treated as an independent sampling unit and represented by a single composite soil sample (0–30 cm depth) derived from multiple subsamples within each site.

Descriptive statistics, including minimum, maximum, and range, were used to characterize variability in soil physical and chemical properties across the sixteen (16) plantations. Because each plantation was represented by a single composite sample, statistical measures of within-site variability (e.g., standard deviation and coefficient of variation) were not computed. Instead, variability was interpreted in terms of differences among plantations at the provincial scale.

Soil fertility status was further evaluated using relative categorical rating systems for individual parameters, based on the studies of Ghimire and Bana (2015), Jabborova et al. (2021), Zhan et al. (2016), and classification standards of the Bureau of Soil and Water Management (2024).

To provide an integrated assessment of nutrient status, the nutrient index *(N.I.)* was calculated following the method of Ramamoorthy and Bajaj (1969), as cited by Khadka et al. (2018):

$$Nutrient\ Index\ (N.I.) = (N_L \times 1 + N_M \times 2 + N_H \times 3)/N_T$$

where N_L, N_M, and N_H represent the number of samples in the low, medium, and high fertility categories, respectively, and N_T is the total number of samples. Nutrient index values were interpreted as low (<1.67), medium (1.67–2.33), and high (>2.33).

In addition, Pearson correlation analysis was performed to explore relationships among selected soil properties, including soil pH, organic matter, total nitrogen, available phosphorus, and exchangeable base cations. Given the limited sample size ($n = 16$) and the use of composite samples, correlation results were interpreted as exploratory indicators of association rather than evidence of causal relationships. All analyses were conducted to support pattern identification, spatial comparison, and soil fertility diagnostics, consistent with the observational design of the study.

3. Results and Discussion

The soil fertility status of the sampling sites was assessed regarding soil texture, pH, organic matter, and total and available primary and secondary nutrients.

3.1. Surface Soil Properties and Total Nutrient Reserves (0–30 cm)

3.1.1. Soil Texture and Structural Context

The surface soils of Guimaras mango plantations were predominantly sandy loam to sandy clay loam, with only one site classified as loam (Table 2). These textures are typical of highly weathered tropical soils derived from sedimentary and limestone parent materials (Srinivasan et al., 2019; Gangopadhyay and Bhattacharyya, 2021). Such soils generally provide adequate drainage and aeration favorable for mango cultivation.

However, their relatively low clay and organic matter content suggests limited cation exchange capacity (CEC), which may constrain the retention of exchangeable nutrients. As a result, these soils are inherently more susceptible to nutrient losses under high rainfall conditions typical of humid tropical environments (White, 2005).

Despite the relatively uniform texture across plantations, substantial differences in nutrient concentrations were observed. This indicates that soil chemical properties and management practices exert a stronger influence on fertility status than texture alone, while texture primarily governs the overall buffering capacity and nutrient retention potential of the soil system.

3.1.2. Soil Acidity as a Province-Wide Constraint

Soil pH across the sampled mango plantations ranged from 4.14 to 5.82, with most sites falling within the strongly acidic category (pH < 5.5). Jordan municipality exhibited consistently low pH values (4.14–4.91) (Table 2), indicating relatively uniform acidity across plantations. In contrast, San Lorenzo showed greater variability, including the least acidic site (Fatima Farms – BPI Adapted, pH 5.82), which may reflect localized differences in parent material, carbonate presence, or liming practices.

The predominance of acidic soils across municipalities suggests that soil acidity is a structural characteristic of Guimaras mango plantations rather than an isolated plantation-specific condition. Such acidity is typical of highly weathered tropical soils, which generally exhibit low base saturation and limited buffering capacity. Under high rainfall conditions, these soils are prone to leaching of base cations such as Ca^{2+}, Mg^{2+}, and K^{+}, which is associated with progressively acidic soil reactions" (Wei et al., 2019; Abure, 2022; Wei et al., 2022).

Management practices may further reinforce this condition. In perennial orchard systems, long-term cultivation without adequate liming or replenishment of base cations can sustain acidic soil reactions, particularly when ammonium-based fertilizers are applied (Sulaiman et al., 2023). At the same time, local variation in soil mineralogy and carbonate content may influence buffering capacity, with carbonate-rich soils maintaining relatively higher pH levels compared with carbonate-poor soils (Hamidi et al., 2021).

From a production perspective, these acidity levels may constrain nutrient availability in mango plantations. Optimal mango growth is generally associated with soil pH values between 5.5 and 7.5 (Salehin et al., 2020), indicating that many plantations in Guimaras operate under suboptimal soil chemical conditions. Strongly acidic environments can enhance phosphorus fixation by iron and aluminum oxides while promoting the leaching of base cations such as Ca^{2+} and Mg^{2+} (Saentho et al., 2022; Hartemink & Barrow, 2023). Consequently, the widespread acidity observed across municipalities likely contributes to the discrepancies between total nutrient reserves and exchangeable nutrient fractions identified in subsequent analyses

3.1.3. Organic Matter and Nitrogen Supply Potential

Organic matter (OM) levels varied considerably among plantations, ranging from 0.47% (Supang Mango Farm) to 2.57% (Kokomojo Farm) (Table 2). Several plantations in Buenavista and Jordan recorded OM values below 1.5%, suggesting limited organic inputs or accelerated decomposition under tropical climatic conditions.

Total nitrogen (0.06–0.22%) closely followed the distribution of OM, reflecting the strong dependence of soil nitrogen reserves on organic matter pools (Brady & Weil, 2016). The highest total N (0.22%) was recorded at Guimaras Wonders (Near Farmhouse), while the lowest value (0.06%) occurred at Baterna Campus Orchard. Despite this variation, overall nitrogen levels remain relatively modest for perennial orchard systems.

Low OM is associated with reduced soil nutrient buffering capacity and limits the potential for nitrogen mineralization, which serves as a primary source of plant-available nitrogen in many agricultural soils (Johnston et al., 2009). This limitation may be particularly pronounced in sandy-textured soils, where organic matter plays a critical role in stabilizing nutrient pools and improving nutrient retention.

At the municipal level, Sibunag plantations exhibited relatively higher OM values (1.82–2.57%), suggesting comparatively greater nutrient buffering capacity than sites in Buenavista and Jordan, where OM levels were generally lower. These differences indicate that local management practices or organic residue inputs may influence soil organic matter accumulation across plantations.

3.1.4 Total Phosphorus: Adequate Reserves but Limited Functional Relevance

Total phosphorus (TP) reserves in the sampled mango plantation soils were generally high, ranging from 0.369% to 1.365%, with most plantations exceeding 0.9% (Table 2). Buenavista and Nueva Valencia recorded some of the highest TP values, whereas BPI–Guimaras and A. Chan Farm exhibited relatively lower but still moderate reserves. These consistently substantial TP levels indicate that Guimaras soils maintain a considerable phosphorus reservoir within the soil matrix.

High TP reserves may partly reflect inherited soil mineralogy and parent material, which support phosphorus accumulation in relatively stable forms such as Ca-, Fe-, and Al-associated phosphates (Wang et al., 2013; Hospodarenko et al., 2022). In perennial orchard systems, these reserves may also be reinforced through continuous litter deposition and root turnover, which contribute organic phosphorus inputs and stimulate phosphorus cycling through soil enzymatic activity (Li et al., 2021).

Long-term management practices may further sustain these phosphorus stocks. Periodic fertilizer inputs, mulching, and organic residue accumulation can gradually build phosphorus pools in orchard soils, particularly where phosphorus mobility is limited (Song et al., 2017; Liu et al., 2024). Consequently, substantial total phosphorus reserves may persist even when plant-available phosphorus fluctuates.

Despite these considerable reserves, high total phosphorus does not necessarily indicate high phosphorus availability in acidic tropical soils, where phosphorus is readily immobilized through fixation with iron and aluminum oxides. Thus, the relatively uniform presence of high TP across municipalities suggests that phosphorus limitation in Guimaras mango plantations is unlikely due to depletion of total phosphorus but rather due to solubility constraints associated with soil acidity.

Table 2. Soil properties and total nutrient reserves (0–30 cm) of mango plantations in Guimaras, Philippines

Municipality	Plantation	Texture	pH	OM (%)	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)
BUENAVISTA	Getulio Mango Farm	Loam	5.65	1.74	0.08	1.027	0.517	3.521	BDL
	Oro Verde Production Site 1	Sandy Loam	4.89	1.99	0.08	1.337	1.107	2.597	BDL
	Supang Mango Farm	Sandy Loam	5.19	0.47	0.08	1.365	0.651	2.229	BDL
JORDAN	BPI– GNCRDPSC Mango Orchard	Sandy Loam	4.91	1.59	0.086	0.397	0.268	0.566	BDL
	Guimaras Wonders Farm (Organic Site)	Sandy Loam	4.14	2.52	0.14	0.951	2.066	1.529	BDL
	Guimaras Wonders Farm (Conventional Site)	Sandy Clay Loam	4.21	1.28	0.22	1.296	2.789	1.641	BDL
	GSU-Mosqueda Campus Mango Scion Groove	Sandy Loam	4.76	0.50	0.08	1.288	0.576	1.824	BDL
SIBUNAG	Jem Homes Farm	Sandy Clay Loam	4.44	1.82	0.08	0.932	0.394	1.570	BDL
	Kokomojo Farm	Sandy Loam	4.57	2.57	0.14	1.291	0.573	1.643	BDL
	Ramzen Farm	Sandy Clay Loam	4.59	1.99	0.08	0.916	0.658	1.615	0.117
SAN LORENZO	GSU-Baterna Campus Mango Orchard	Sandy Loam	4.91	1.25	0.06	1.199	0.899	3.887	0.217
	Fatima Integrated Farms BPI Adapted Site	Sandy Loam	5.82	1.71	0.08	0.901	0.719	13.713	0.164
	Fatima Integrated Farms Organic Site	Sandy Loam	5.37	2.30	0.08	0.877	0.569	3.049	0.117
	Oro Verde Production Site 2	Sandy Loam	5.52	2.07	0.08	1.142	0.896	2.226	BDL
NUEVA VALENCIA	A. Chan Farm	Sandy Loam	4.97	1.45	0.086	0.369	0.407	0.631	BDL
	Saladan Warden Farm	Sandy Loam	4.40	1.42	0.11	1.343	0.662	2.000	BDL

3.1.5 Total Potassium, Calcium, and Magnesium: Strong Plantation-Level Variability

Total potassium (K), calcium (Ca), and magnesium (Mg) exhibited pronounced variability among mango plantations, indicating strong spatial heterogeneity in base cation reserves (Table 2). Total K ranged from 0.268% (BPI–GNCRDPSC Orchard, Jordan) to 2.789% (Guimaras Wonders Farm – Conventional Site, Jordan). Notably, plantations within the same municipality displayed contrasting K levels; for example, in Jordan, total K varied more than tenfold across sites, suggesting that management practices and localized soil conditions exert stronger control than geographic location alone.

A similar pattern was observed for total Ca, which ranged from 0.566% (BPI–GNCRDPSC Orchard) to 13.713% (Fatima Farms – BPI Adapted Site, San Lorenzo). The exceptionally high Ca levels in San Lorenzo plantations, particularly in both Fatima Farms sites, indicate a strong influence of limestone-derived parent material and/or historical liming practices. In contrast, relatively low Ca values in Jordan and Nueva Valencia plantations suggest base cation depletion under prolonged acidic conditions and leaching environments.

Total Mg was below detection limits (BDL) in most plantations, with measurable concentrations observed only in a few sites such as Ramzen Farm (0.117%) and GSU-Baterna Orchard (0.217%). This uneven distribution suggests limited Mg reserves across the province, with localized enrichment likely associated with specific parent materials or nutrient inputs.

Across municipalities, San Lorenzo consistently exhibited higher Ca and Mg reserves, whereas Jordan and Nueva Valencia tended to show lower base cation levels, reflecting differences in geological origin and soil buffering capacity. The observed variability indicates that base cation distribution is highly site-specific, even within relatively small geographic areas.

These patterns are consistent with findings in tropical soils, where base cation dynamics are strongly influenced by parent material, soil texture, and organic matter content, which collectively regulate cation exchange capacity (CEC) and nutrient retention (Zhang et al., 2015; Hall and Huang, 2017; Ouyang et al., 2023). In sandy soils such as those in Guimaras, limited CEC reduces the ability to retain K^{+}, Ca^{2+}, and Mg^{2+}, increasing their susceptibility to leaching (White, 2005).

Overall, the strong plantation-level variability in total base cations suggests that total nutrient reserves alone are insufficient indicators of soil fertility, reinforcing the need to evaluate plant-available fractions to better understand functional nutrient availability in mango production systems.

3.2. Plant-Accessible Nutrient Fractions and Functional Fertility

A key finding across all macronutrients is the divergence between total nutrient reserves and plant-available fractions. While total concentrations provide an estimate of long-term nutrient stocks, they do not necessarily reflect the fraction accessible for plant uptake under prevailing soil conditions. In Guimaras mango soils, this discrepancy is primarily regulated by soil acidity, organic matter content, and cation exchange processes, which collectively influence nutrient solubility, retention, and mobility. Consequently, evaluating both total and available nutrient pools provides a more functionally relevant assessment of soil fertility and enables identification of constraints associated with hidden hunger, where nutrient reserves exist but remain insufficiently available for crop utilization.

3.2.1. Truog-Extractable Phosphorus: Evidence of Hidden Hunger

Although total phosphorus reserves were consistently high across plantations, Truog-extractable phosphorus remained low (6–14 ppm) (Table 3), indicating limited plant-available P. This contrast suggests that phosphorus in these soils is largely present in stable forms that are not readily accessible for plant uptake. Under strongly acidic conditions, phosphorus is likely immobilized through interactions with iron and aluminum oxides, reducing its solubility despite substantial total reserves.

This pattern exemplifies hidden hunger, where nutrient availability—not total supply—limits crop nutrition. The relatively uniform distribution of low available P across municipalities further indicates that phosphorus limitation is a province-wide constraint rather than a site-specific issue. Therefore, improving phosphorus availability in Guimaras mango plantations requires management strategies that enhance solubility, particularly through pH correction and organic matter inputs, rather than increasing total phosphorus inputs alone.

3.2.2. Exchangeable Potassium: Site-Specific Imbalance

Exchangeable potassium (K) exhibited substantial variability across mango plantations, ranging from 15 ppm (Guimaras Wonders Organic Site; A. Chan Farm; Saladan Warden Farm) to 102 ppm (Oro Verde Production Site 1) (Table 3). A clear spatial pattern emerged, with Jordan and Nueva Valencia plantations generally exhibiting lower exchangeable K (15–35 ppm), whereas Buenavista and San Lorenzo plantations showed relatively higher values (38–102 ppm).

Within municipalities, variability remained pronounced. For instance, in Buenavista, exchangeable K ranged from 40 ppm (Supang Mango Farm) to 102 ppm (Oro Verde Site 1), indicating that intra-municipal differences can be as significant as inter-municipal variation. Similarly, in Jordan, all plantations consistently recorded low K values, suggesting a systematic limitation in potassium availability across this municipality.

This variability is likely associated with differences in soil texture, organic matter content, and fertilization practices, which collectively influence K retention and mobility. Sandy soils with low organic matter, as observed in many Guimaras plantations, have limited CEC, reducing their capacity to retain exchangeable K and increasing vulnerability to leaching losses under high rainfall conditions (White, 2005).

The divergence between relatively moderate total K reserves (Section 3.1.5) and highly variable exchangeable K further indicates that potassium availability is governed more by soil chemical conditions than by total nutrient stocks. This finding underscores the importance of using exchangeable K as a more reliable indicator of functional fertility in tropical orchard systems.

From a management perspective, the observed spatial heterogeneity suggests that uniform potassium fertilization strategies are unlikely to be effective. Instead, site-specific nutrient management approaches are required to address localized deficiencies and improve nutrient use efficiency.

Table 3. Truog-extractable phosphorus and exchangeable cations (0–30 cm) of mango plantations in Guimaras, Philippines

Municipality	Plantation	Truog-P (ppm)	Exchangeable K (ppm)	Exchangeable Ca (ppm)	Exchangeable Mg (ppm)
BUENAVISTA	Getulio Mango Farm	12	92	1965	241
	Oro Verde Production Site 1	10	102	471	73
	Supang Mango Farm	13	40	134	11
JORDAN	BPI– GNCRDPSC Mango Orchard	7	23	239	31
	Guimaras Wonders Farm (Organic Site)	10	15	160	67
	Guimaras Wonders Farm (Conventional Site)	10	35	34	27
	GSU-Mosqueda Campus Mango Scion Groove	7	23	239	31
SIBUNAG	Jem Homes Farm	11	80	196	91
	Kokomojo Farm	11	23	172	71
	Ramzen Farm	11	28	1027	551
SAN LORENZO	GSU-Baterna Campus Mango Orchard	10	28	393	409
	Fatima Integrated Farms BPI Adapted Site	12	81	1225	323
	Fatima Integrated Farms Organic Site	13	65	1163	659
	Oro Verde Production Site 2	11	38	758	77
NUEVA VALENCIA	A. Chan Farm	6	15	265	53
	Saladan Warden Farm	6	15	265	53

3.2.3. Exchangeable Calcium: Geological Influence and Fruit Quality Implications

Exchangeable calcium (Ca) exhibited the greatest variability among all measured nutrients, ranging from 34 ppm (Guimaras Wonders Conventional Site, Jordan) to 1,965 ppm (Getulio Mango Farm, Buenavista) (Table 3). High Ca levels were consistently observed in San Lorenzo and Buenavista plantations, particularly in Fatima Farms and Getulio Mango Farm, whereas Jordan plantations generally exhibited lower Ca values, with several sites below 250 ppm.

This spatial pattern suggests a strong association with parent material and liming history, with calcium-rich soils likely derived from limestone or carbonate-containing substrates. In contrast, low Ca levels in Jordan and parts of Nueva Valencia suggest highly weathered, acidic soils with reduced base saturation, where Ca is depleted through prolonged leaching.

Within municipalities, variability was also evident. For example, in Sibunag, exchangeable Ca ranged from 196 ppm (Jem Homes Farm) to 1,027 ppm (Ramzen Farm), highlighting the influence of localized soil conditions and management practices.

Importantly, the relationship between total Ca and exchangeable Ca was not consistent across plantations. Some sites with high total Ca did not exhibit proportionally high exchangeable Ca, indicating that a portion of Ca is present in non-exchangeable mineral forms. This further reinforces that total nutrient content does not necessarily reflect plant-available fractions.

From an agronomic perspective, calcium plays a critical role in fruit quality, structural integrity, and resistance to physiological disorders in mango. Therefore, plantations with low exchangeable Ca may be at risk of reduced fruit quality despite adequate total Ca reserves.

Overall, the strong spatial variability in exchangeable Ca highlights the need for site-specific calcium management, particularly in acidic soils where liming can simultaneously improve soil pH and Ca availability.

3.2.4. Exchangeable Magnesium: Hidden Depletion Risk

Exchangeable magnesium (Mg) ranged from 11 ppm (Supang Mango Farm) to 659 ppm (Fatima Farms Organic Site) (Table 3), showing moderate to high variability across plantations. Higher Mg concentrations were observed in San Lorenzo and selected Sibunag plantations (e.g., Ramzen Farm, 551 ppm), whereas Buenavista and Jordan plantations generally exhibited lower Mg levels (<100 ppm).

This uneven distribution reflects the combined effects of soil texture, organic matter content, and leaching processes. In sandy, acidic soils, Mg is particularly susceptible to leaching due to its relatively weak retention on soil exchange sites (Senbayram et al., 2015). The generally low total Mg reserves observed in Section 3.1.5 further suggest that exchangeable Mg may not be sustained in the long term without replenishment.

The coexistence of moderate exchangeable Mg in some plantations despite low total Mg indicates a condition of transient nutrient availability, where short-term supply may not be supported by sufficient long-term reserves. This creates a risk of hidden depletion, particularly under continuous cropping systems.

At the municipal level, San Lorenzo consistently exhibited higher Mg levels, reinforcing the influence of parent material and soil buffering capacity, while Jordan and Buenavista showed greater susceptibility to Mg deficiency.

These findings highlight the importance of integrating Mg management into soil fertility strategies, particularly in tropical orchard systems where imbalances among base cations can affect nutrient uptake and crop performance.

3.2.5. Integrated Interpretation of Exchangeable Nutrients

Plantations in San Lorenzo and Buenavista generally exhibited higher base cation levels, whereas Jordan and Nueva Valencia were characterized by lower exchangeable K and Ca, suggesting reduced nutrient buffering capacity and greater susceptibility to leaching. Sibunag displayed intermediate variability, with some plantations exhibiting high Ca and Mg levels alongside others with moderate values.

These results indicate the presence of two contrasting fertility regimes: (1) base cation-enriched systems, primarily located in San Lorenzo and parts of Buenavista, and (2) base cation-depleted systems, predominantly found in Jordan and Nueva Valencia.

These patterns demonstrate that nutrient limitations in Guimaras mango plantations are not uniform, but rather governed by site-specific interactions among soil texture, organic matter, pH, and parent material. Sandy textures and low organic matter reduce CEC, limiting nutrient retention, while acidic conditions constrain phosphorus availability through fixation processes.

Overall, the results confirm that soil fertility constraints are driven primarily by nutrient availability rather than total nutrient reserves, supporting the concept of hidden hunger across multiple nutrients. Consequently, improving mango productivity in Guimaras requires integrated and site-specific soil management strategies, including pH correction, organic matter enhancement, and balanced nutrient application tailored to local soil conditions.

3.3. Interrelationships among Soil Chemical Properties

The Pearson correlation heatmap (Figure 3) illustrates the relationships among selected soil chemical properties in mango orchard soils across Guimaras Island. The integration of correlation coefficients and statistical significance allows identification of the dominant factors influencing soil fertility variability in the study area.

Soil pH showed a strong positive correlation with exchangeable Ca ($r = 0.73$, $p < 0.01$) (Figure 3), indicating that calcium is strongly associated with soil acidity in the sampled orchards. This relationship may reflect the role of Ca^{2+} as a base-forming cation that contributes to soil buffering capacity and base saturation. In highly weathered tropical soils, such as those in the Philippines, the depletion of base cations through leaching commonly results in acidic conditions (Asio et al., 2006). The observed pattern suggests that variations in soil pH across Guimaras mango orchards are primarily associated with differences in calcium availability.

A moderate positive correlation between soil pH and exchangeable Mg ($r = 0.34$) was also observed, although it was not statistically significant. Magnesium, similar to calcium, contributes to base saturation; however, its weaker association with pH indicates a less dominant role in regulating soil acidity in these soils. This finding is consistent with previous studies in tropical systems where Ca exerts a stronger influence on soil reaction compared to Mg (Brady & Weil, 2017).

Exchangeable Ca and Mg exhibited a strong positive correlation ($r = 0.64$, $p < 0.01$), suggesting a coupled behavior of these cations within the soil exchange complex. This association likely reflects their common origin from soil parent materials and/or simultaneous application through fertilization practices. Similar relationships have been reported in orchard systems where Ca and Mg dynamics jointly influence nutrient balance and soil structure (Somasundaram et al., 2018).

Total nitrogen showed a moderate negative correlation with soil pH ($r = -0.59$, $p < 0.05$), indicating that relatively more acidic soils tended to contain higher nitrogen concentrations. This pattern may be attributed to localized accumulation of organic residues and nitrogen mineralization processes in perennial systems such as mango orchards. However, despite higher total N levels, nitrogen availability to plants may still be constrained under acidic conditions due to reduced microbial efficiency and potential nutrient imbalances.

A moderate positive correlation between available P and exchangeable K ($r = 0.55$, $p < 0.05$) was observed (Figure 3), suggesting that these nutrients tend to co-vary across the study sites. This relationship is likely associated with fertilization practices, as phosphorus and potassium are commonly applied together in orchard management to support reproductive development and fruit yield. The relatively weak correlations of available P with other soil properties further indicate that phosphorus dynamics are influenced by soil chemical constraints, particularly fixation by iron and aluminum oxides, which is characteristic of acidic tropical soils (Sanchez, 2019).

Organic matter exhibited weak and non-significant correlations with most soil properties, including Ca (r = 0.29), Mg (r = 0.30), P (r = −0.20), and K (r = −0.14). Although organic matter is known to enhance cation exchange capacity and nutrient retention, its limited association with other variables suggests that short-term nutrient variability in Guimaras mango soils is more strongly influenced by inherent soil properties and management practices than by organic matter content alone.

Overall, the correlation analysis indicates that base cations, particularly calcium and magnesium, play a central role in regulating soil chemical conditions in Guimaras mango orchards, while nutrient inputs, especially phosphorus and potassium, reflect management-driven variability. These findings are consistent with studies conducted in other tropical mango-producing regions, where soil pH and base saturation are critical determinants of nutrient availability and crop performance (Singh et al., 2014; Silva et al., 2017).

From a management perspective, the results highlight the importance of maintaining adequate base cation levels to mitigate soil acidity and improve nutrient availability. Integrated soil fertility management strategies, including balanced fertilization and the use of amendments that enhance base saturation, are therefore essential to sustain mango productivity in Guimaras.

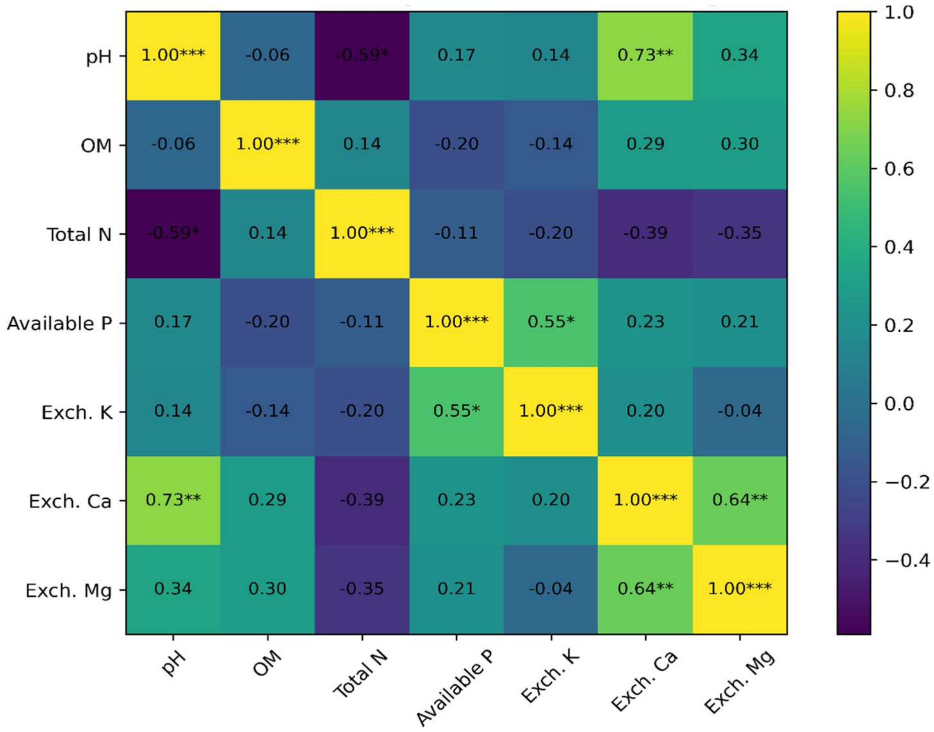

Figure 3. Correlation matrix of soil properties visualized as a heatmap, showing Pearson correlation coefficients and their significance levels.

3.4. Integrated Assessment of Soil Fertility Status of Mango Plantations in Guimaras

The integrated assessment of soil fertility indicators across mango plantations in Guimaras (Table 4) reveals a consistent pattern of acidic soil conditions, low organic matter (OM), and variable base cation availability, reflecting the combined influence of inherent soil properties and management practices. While individual parameters provide insight into specific nutrient dynamics, their collective evaluation highlights broader spatial trends and functional constraints affecting mango productivity.

Across all municipalities, soil acidity emerged as the dominant and widely consistent constraint, with the majority of plantations classified under strongly acidic conditions. This pattern was particularly evident in Jordan, Sibunag, and Nueva Valencia, where low pH values were uniformly observed. In contrast, plantations in San Lorenzo and parts of Buenavista exhibited relatively higher pH levels, notably in Fatima Farms and Getulio Mango Farm, suggesting localized buffering effects associated with limestone-derived parent materials or historical liming practices. These findings indicate that soil acidity in Guimaras is both a province-wide structural limitation and a site-specific management outcome.

Table 4. Integrated Physical and Chemical Soil Fertility Indicators of Mango Farms Across Municipalities in Guimaras Province

Municipality	Plantation	pH	OM	Total N	Avail P	Exch. K	Exch. Ca	Exch. Mg
BUENAVISTA	Getulio Mango Farm	H	L	L	M	M	H	H
	Oro Verde Production Site 1	L	L	L	M	M	M	M
	Supang Mango Farm	M	L	L	M	L	L	L
JORDAN	BPI– GNCRDPSC Mango Orchard	L	L	L	L	L	M	L
	Guimaras Wonders Farm (Organic Site)	L	M	M	M	L	L	M
	Guimaras Wonders Farm (Conventional Site)	L	L	H	M	L	L	L
	GSU-Mosqueda Campus Mango Scion Groove	L	L	L	M	M	L	L
SIBUNAG	Jem Homes Farm	L	L	L	M	M	L	M
	Kokomojo Farm	L	M	M	M	L	L	M
	Ramzen Farm	L	L	L	M	L	H	H
SAN LORENZO	GSU-Baterna Campus Mango Orchard	L	L	L	M	L	M	H
	Fatima Integrated Farms BPI Adapted Site	H	L	L	M	M	H	H
	Fatima Integrated Farms Organic Site	M	M	L	M	M	H	H
	Oro Verde Production Site 2	M	L	L	M	L	L	L
NUEVA VALENCIA	A. Chan Farm	L	L	L	L	L	M	M
	Saladan Warden Farm	L	L	M	M	M	L	L

Legend: H – High; M – Medium; L - Low

Organic matter and total nitrogen exhibited closely aligned spatial distributions, with generally low to moderate levels across plantations. Sites in Buenavista and Jordan consistently recorded lower OM (<1.5%), indicating reduced organic inputs and limited nutrient buffering capacity. In contrast, plantations in Sibunag and selected areas of San Lorenzo (e.g., Kokomojo Farm and Fatima Organic Site) showed relatively higher OM levels, reflecting improved nutrient retention and biological activity. These patterns underscore the critical role of organic matter in sustaining soil fertility in sandy tropical soils, where nutrient retention is inherently constrained.

A clear divergence between total and plant-available nutrients was observed across all plantations, reinforcing the presence of hidden hunger. Although total phosphorus levels were consistently moderate to high, Truog-extractable phosphorus remained uniformly low across municipalities, confirming that phosphorus limitation is primarily driven by fixation under acidic soil conditions rather than depletion of total reserves. These findings are consistent with established mechanisms of phosphorus immobilization in tropical soils, where interactions with iron and aluminum oxides reduce solubility and plant availability (Saentho et al., 2022; Hartemink and Barrow, 2023).

In contrast to phosphorus, exchangeable base cations (K, Ca, and Mg) exhibited strong spatial variability, revealing distinct fertility regimes across municipalities. Plantations in San Lorenzo and Buenavista consistently showed higher exchangeable Ca and Mg levels, with sites such as Fatima Farms and Getulio Mango Farm exhibiting elevated base saturation. Conversely, plantations in Jordan and Nueva Valencia were characterized by consistently low exchangeable K and Ca, indicating reduced nutrient buffering capacity and greater susceptibility to leaching losses. Sibunag displayed intermediate variability, with some plantations (e.g., Ramzen Farm) exhibiting high Ca and Mg alongside others with moderate levels.

This spatial differentiation reflects the presence of two contrasting fertility regimes within the province: base cation-enriched systems, primarily located in San Lorenzo and parts of Buenavista, and base cation-depleted systems, predominantly found in Jordan and Nueva Valencia. These regimes are shaped by differences in parent material, soil weathering intensity, and management practices, demonstrating that soil fertility in Guimaras is not homogeneous but strongly governed by localized soil-forming factors.

The interaction among soil acidity, organic matter, and base cation dynamics further explains the observed variability in nutrient availability. Acidic conditions promote phosphorus fixation and base cation leaching, while low organic matter reduces cation exchange capacity (CEC), limiting nutrient retention (White, 2005; Senbayram et al., 2015). In contrast, plantations with higher OM and base cation levels exhibit improved buffering capacity and greater nutrient availability, supporting more favorable soil fertility conditions.

From a functional perspective, these findings demonstrate that nutrient availability—not total nutrient reserves—is the primary limiting factor in Guimaras mango plantations. The widespread occurrence of hidden hunger, combined with strong spatial variability in base cations, indicates that uniform fertilizer recommendations are unlikely to be effective across the province.

Therefore, improving soil fertility and sustaining mango productivity in Guimaras requires integrated and site-specific soil management strategies. These include pH correction through liming to reduce acidity and enhance nutrient availability, organic matter enhancement to improve soil structure and nutrient retention, and balanced fertilization tailored to the nutrient status of individual plantations. Such targeted approaches are essential to address both systemic constraints (e.g., soil acidity and phosphorus fixation) and localized variability in nutrient availability, thereby enhancing nutrient use efficiency, improving soil resilience, and sustaining long-term mango productivity in the province.

The findings of this study allow a clearer distinction between hidden hunger and hidden depletion within mango production systems. Hidden hunger refers to conditions where total nutrient reserves are sufficient, but nutrient availability is limited due to soil physicochemical constraints such as acidity, low organic matter, and nutrient fixation. In contrast, hidden depletion represents a condition where both total and plant-available nutrient pools are insufficient, posing a longer-term risk to soil fertility sustainability. In the present study, phosphorus limitation is primarily associated with hidden hunger, whereas the low total magnesium observed in several plantations suggests a potential risk of hidden depletion. This distinction is critical for nutrient diagnostics, as it informs whether management interventions should focus on improving nutrient availability (e.g., liming, organic amendments) or replenishing nutrient stocks through fertilization. Consequently, integrating both concepts provides a more comprehensive framework for site-specific soil fertility management in mango orchards.

4. Conclusions

This study provides the first integrated, province-scale assessment of soil fertility in mango plantations across Guimaras, Philippines, combining total nutrient reserves and plant-available fractions to evaluate functional soil fertility under tropical conditions. This integrated assessment, based on province-wide sampling and the combined analysis of total and plant-available nutrient fractions, provides a functionally relevant evaluation of soil fertility conditions in mango orchard systems. The results demonstrate that soil fertility constraints in these orchards appear to be primarily associated with nutrient availability limitations rather than depletion of total nutrient stocks, highlighting the relevance of the hidden hunger concept in perennial cropping systems.

Across the province, soils were predominantly strongly acidic (pH 4.14–5.82) with generally low organic matter (0.47–2.57%) and total nitrogen (0.06–0.22%), conditions that collectively reduce cation exchange capacity and nutrient retention. Although total phosphorus and potassium reserves were moderate to high in several plantations, plant-available phosphorus remained consistently low (6–14 ppm), indicating widespread phosphorus limitation associated with fixation under acidic conditions. In contrast, exchangeable potassium, calcium, and magnesium exhibited marked plantation-level variability, reflecting differences in parent material, soil buffering capacity, and management practices.

The results further reveal the presence of contrasting fertility regimes, characterized by base cation-enriched systems (e.g., San Lorenzo and parts of Buenavista) and base cation-depleted systems (e.g., Jordan and Nueva Valencia), demonstrating that soil fertility in Guimaras is spatially heterogeneous and strongly influenced by site-specific soil-forming factors. These findings directly address the study objectives by identifying soil acidity, low organic matter, phosphorus fixation, and base cation variability as the primary constraints limiting nutrient availability and mango productivity.

From a practical perspective, improving mango productivity in Guimaras requires integrated soil fertility management strategies that address both systemic and site-specific constraints. Key interventions include: (1) soil acidity correction through liming to enhance nutrient availability and reduce phosphorus fixation. Farms with low exchangeable magnesium levels may be prioritized for the application of dolomitic lime to simultaneously correct soil acidity and replenish magnesium deficiency. In contrast, farms with adequate magnesium status may apply calcitic lime for soil pH correction and calcium supplementation. Indicative lime application rates may range from 1–2 t/ha for slightly acidic soils, 3–4 t/ha for moderately acidic soils, and 5–6 t/ha for strongly acidic and nutrient-depleted areas, subject to confirmation through site-specific lime requirement analysis and soil testing; (2) organic matter enhancement through the incorporation of compost, mulches, or other organic amendments to improve soil structure, microbial activity, and cation exchange capacity may be recommended as a complementary strategy. Accordingly, 10–15 t/ha of organic amendments may be considered for low OM and low N sites. Sites with low OM but medium to high N may receive 5–10 t/ha as maintenance to improve soil condition and nutrient retention, whereas farms with medium OM and medium N may require only 3–5 t/ha for maintenance inputs; and (3) site-specific and balanced fertilization based on soil testing to optimize nutrient supply and minimize losses in sandy soils. These approaches are particularly important in base cation-depleted areas, where nutrient retention is limited and fertilizer efficiency is low.

Overall, the findings demonstrate that effective soil fertility management in tropical mango systems must move beyond conventional assessments based solely on total nutrient concentrations and instead focus on improving nutrient availability and soil chemical balance. The results provide a robust baseline for developing evidence-based, site-specific nutrient management strategies tailored to the conditions of Guimaras, with broader implications for sustainable mango production in similar tropical environments.

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