

Multi-elemental and stable isotope characterization of soil from selected Carabao mango orchards in the Philippines

Nerrisa P. Bacerra^{*1}, Mica G. Binongo^{1,2}, Kurt Louis B. Solis¹, Maria Carmela A. Garcia^{1,3}, Lorraine S. Lao¹, Leslie R. Alapag^{1,4}, Anane R. Serenina^{1,2}, John Leonard R. Labides¹, Gerald P. Dicen¹, and Roland V. Rallos¹

¹Department of Science and Technology - Philippine Nuclear Research Institute, Commonwealth Avenue, Diliman, Quezon City, 1101 Philippines

²Department of Soil Science, Faculty of Agriculture and Food Science, Visayas State University, Visca, City of Baybay, Leyte, 6521 Philippines

³Department of Environment and Natural Resources - Mines and Geosciences Bureau, North Avenue, Diliman, Quezon City, 1104 Philippines

⁴Rizal Medical Center, Bagong Ilog, Pasig City, 1600 Philippines

ABSTRACT

Mango productivity in the Philippines is challenged by declining yields and site-specific soil constraints. These challenges highlight the need to assess site conditions and identify key indicators that are associated with mango productivity. In this study, we evaluated the soil characteristics of selected orchards in six major mango-producing provinces in the Philippines using multi-elemental and stable $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotope techniques to determine the governing geochemical processes related to location and depth interactions, the nutrient status, and historical land-use changes. Location proved to be a major driver of soil parameter variation, while depth exerted a less significant influence. Redox-driven nutrient cycling, particularly involving Mn–Fe–C–N interactions, was identified as an important geochemical process influencing soil elemental dynamics across sampling sites. Stable isotope analysis revealed a distinct shift in soil $\delta^{13}\text{C}$ values from C4 to C3-derived signatures, indicating progressive enrichment of $\delta^{13}\text{C}$ with depth and confirming the historical transition from C4 grasslands to long-term C3 mango monocultures. Meanwhile, $\delta^{15}\text{N}$ values varied significantly among provinces, with depleted $\delta^{15}\text{N}$ signatures indicating a greater reliance on synthetic N fertilizers, whereas enriched $\delta^{15}\text{N}$ values reflected long-term organic matter inputs and enhanced microbial N transformations. These findings demonstrate that the combined application of stable isotopes and multi-elemental analysis is an effective approach for assessing the

nutritional status and land use history of mango orchard soils. The results also provide valuable baseline information for developing site-specific nutrient management strategies and recommendations to improve mango productivity in the Philippines.

INTRODUCTION

Mango (*Mangifera indica* L.), particularly the Philippine Carabao cultivar, is a leading export fruit and a major livelihood crop in the Philippines. In 2025, the Philippine Statistics Authority (PSA 2026a) reported a total mango production of 710,925.33 metric tons from around 182,000 hectares, with Carabao mango accounting for 579,174.65 metric tons, or about 81 % of the national production (PSA 2026b). Total mango production amounted to approximately ₱26.87 billion (PSA 2026c), with Carabao mango accounting for an estimated ₱21.89 billion based on its production share. This emphasizes its significance as the country's dominant commercial mango variety. National trends show declining yield in the last three decades, culminating in an all-time low trend of -2.3 % growth between 2016 and 2020. This pattern was observed despite expansion of planted area between 2000 and 2009 (3.9 %), with a slight dip in yield for mangoes (<0.3 %) in the last decade. Peak harvest typically occurs from March to June, and off-season production from November to January is increasingly being explored to enhance overall yield (Edale 2024). However, such an approach may pose its own challenges in the form of unpredictable climate, insufficient planting materials and infrastructure, and the need for additional agrochemical inputs to

*Corresponding author

Email Address: nvpaduit@pnri.dost.gov.ph

Date received: 31 May 2026

Dates revised: 08 August 2026; 05 September 2026; 08 September 2026

Date accepted: 08 September 2026

DOI: <https://doi.org/10.54645/202619SupDOH-83>

KEYWORDS

Agriculture, Carabao cultivar, mango production, elemental profiling, isotope fingerprint

induce flowering (Singh et al. 2026). Thus, more strategies are necessary to maximize production and achieve the potential yield, both during the peak season and off season.

A crucial factor influencing the quality and production of mangoes is soil characteristics. Bukhari et al. (2025) described the intricate relationship between soil health and mango output, which is further complicated by the impacts of climate change. While mangoes can be cultivated in low fertility soils, optimal growth, nutrient uptake, and yield are achieved with balanced macro- and micronutrient supply. This underscores the need to analyze soil samples and assess its nutrient status, as well as evaluate the management techniques being used that influence soil conditions (Khan and Ahmed 2020).

Applying analytical techniques such as multi-elemental and stable isotope analyses provide critical insights into the nutritional status of soils, as well as the environmental conditions and management practices influencing crop growth (Wang et al. 2020). Multi-elemental analysis of soil provides a comprehensive list of macro- and micronutrients potentially available to plants. It also identifies deficiencies or toxicities and guides precise fertilizer and soil management decisions (Sinha et al. 2017). Previous studies have demonstrated the value of conducting soil multi-elemental analysis in identifying key limiting factors to mango production. Ahmed et al. (2020) found micronutrient deficiencies and antagonistic effects between certain elements in the soils of mango orchards in Punjab, India and identified specific strategies for nutrient management. Kumar et al. (2012) identified Zn and B as the limiting factors for mango productivity in Uttar Pradesh, India. Sinha et al. (2017) found variations in the mineral accumulation of mango fruit, and they attributed this to differences in the absorption capacity and available nutrients in soil, among other factors, since the samples tested underwent similar management practices.

Stable isotope techniques, on the other hand, may offer insights on climatic conditions, plant and microbial metabolism, and management practices (Li et al. 2019). At present, studies employing stable isotopes in relation to soil and mango analysis commonly revolve around traceability and authentication studies (Muñoz-Redondo et al. 2021) or fertilizer tracers to determine uptake efficiency (Asis et al. 2024). However, stable isotope techniques may have underutilized applications to support yield and productivity. The $\delta^{13}\text{C}$ signatures help determine plant metabolic pathways and differentiate between C3, C4, or CAM plants, which can then be used to investigate land-use changes (Bernoux et al. 1998; IAEA 2001). Such investigations are useful in the context of understanding soil legacy effects—defined as the influence that previous land-use activities have on current ecosystems and soil function—which could provide key information for management decisions (Turner et al. 2018). Mzezwa et al. (2025), for example, found that the conversion of a grassland to an avocado orchard contributed to significant changes in the soil hydraulic properties, which in turn determined the appropriate management strategies. Aside from $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ signatures can describe whether soil and plants received organic or inorganic N-based farming inputs (Kelly et al. 2018). These may

reveal site-specific soil nutrient dynamics and how farming inputs behave in the soil after application.

In both multi-elemental analysis and stable isotope techniques, the depth of soil sampling is an important consideration. Deep sampling is advantageous as soil water and nutrient availability in tree-based cropping systems vary with depth (Lehmann 2003). Generally, the nutrient concentrations are higher in the top layer and decrease with deeper layers. However, previous studies in mango orchards have shown that the rate at which the nutrient content decreases with depth varies (Adak et al. 2016; Naik et al. 2015), which may reflect differences in soil characteristics and nutrient uptake. Although subsoil sampling is difficult to conduct routinely due to the laborious work, adsorption of nutrients in the subsoil is possible, and this can delay leaching of nutrients below the root zone. Subsoils can therefore constitute an important nutrient pool for tree crops, especially in humid tropical climates like the Philippines where leaching is high (Lehmann 2003). Moreover, deep sampling is necessary for investigating land-use history using stable isotopes, which are done based on variations of $\delta^{13}\text{C}$ with depth (Bernoux et al. 1998).

This study aims to investigate the use of stable $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotope techniques combined with multi-elemental profiling to reveal key information on the status of mango orchard soils in the Philippines, which are not apparent from conventional soil tests alone. Specifically, this study aims to (1) describe the geochemical processes influenced by location–depth interactions, to (2) assess the nutritional status, and to (3) determine the land use history of selected mango orchard soils across different provinces in the Philippines. The findings will inform specific recommendations for orchard management, offering practical insights for mango farmers operating under similar growing conditions and contributing to efforts aimed at reversing the nationwide decline in mango productivity.

MATERIALS AND METHODS

Study Area and Site Selection

This study targeted the major mango-producing provinces across the Philippines, namely: Abra, Ilocos Norte, Pangasinan, and Zambales in Luzon; Guimaras in Visayas; and Davao in Mindanao (Figure 1). A convenience nested sampling design was used (six provinces; three farms per province; $n = 18$). Site selection was coordinated with the Department of Agriculture - Regional Field Offices (DA-RFO), and all samples were collected during the dry season (January to May), except for Davao (November to December). Soil samples from Mindanao could not be analyzed for total C and N and their stable isotope compositions due to transport restrictions in accordance with the Department of Agriculture - Bureau of Plant and Industry (DA-BPI) Special Quarantine Order No.1 S. 2019, which is imposed in response to phytosanitary concerns related to the presence and spreading of *Fusarium* wilt caused by *Fusarium oxysporum* f. sp. *cubense*.

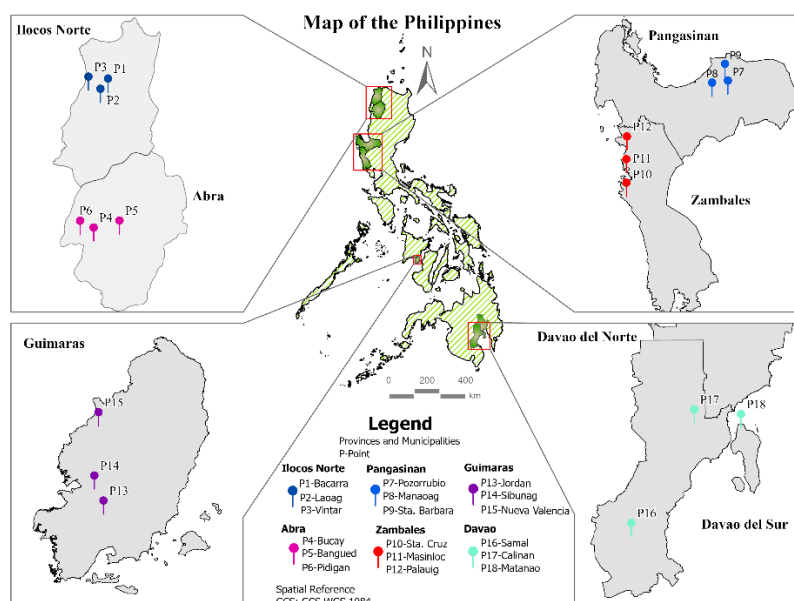


Figure 1: Location of selected mango orchards sampled across the Philippines.

Soil Sampling and Field Data

A total of 53 soil cores were collected across all sites to a depth of 60 cm using a soil auger and subsampled by depth intervals (0–20, 20–40, and 40–60 cm). For the determination of total C and N and their stable isotope compositions ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), soil samples were collected to a maximum depth of 100 cm. This depth was selected to characterize their vertical distribution and capture the isotopic signatures of relatively old, stabilized soil organic matter in the subsoil, which is generally less influenced by recent surface inputs and management practices. In some sites, sampling depth was limited by shallow soils and other obstructions, resulting in variations in the depth of soil samples collected across sites. All soil samples were placed in properly labeled plastic bags and were brought to the Soil Science and Plant Nutrition Laboratory, Agriculture Research Section of the Philippine Nuclear Research Institute (DOST-PNRI) for sample preparation. Then, the samples were air dried for 5 to 7 days, pulverized, sieved to the appropriate particle size (2 mm and 425 μm), and placed in properly labeled containers for analysis. Complementary farmer interviews were conducted to record tree age, farm size, cultural management practices, and the types of fertilizers and pesticides applied.

Laboratory Analyses

Chemical parameters of the collected soil samples were measured at DOST-PNRI, except for the samples from Davao, which were obtained from an accredited third-party laboratory. Soil pH was determined by mixing fine soil with distilled water at a 1:2.5 soil: water w/v ratio, and measured with a pH meter (pH 700, Eutech Instruments, Singapore) (FAO 2021a).

Available phosphorus (P) was extracted following the Olsen method (FAO 2021b) and measured colorimetrically using a UV-Vis spectrophotometer (Optizen Pop, Mecasys Co., Ltd., Korea) at 880 nm wavelength. Exchangeable bases (K, Ca, Mg) were extracted with 1 M ammonium acetate (pH 7.0) (FAO 2022a), whereas extractable micronutrients (Cu, Zn, Fe, and Mn) were extracted using the DTPA-TEA method (FAO 2022b). Element concentrations were subsequently measured using an atomic absorption spectrophotometer (Shimadzu AA-7000, Japan).

Total carbon (%C), total nitrogen (%N), and stable isotopic ratios were determined using an elemental analyzer - isotope ratio mass spectrometer (Sercon GSL - Sercon 20-22 IRMS, Sercon Limited,

UK), following the sample preparation described by the International Atomic Energy Agency (IAEA 2019). Approximately 15 mg of fine soil samples (<425 μm) were placed into 8×5 mm tin capsules and weighed using a semi-microbalance. The tin capsules were then carefully folded and crimped to ensure airtightness before being placed in a 96-well plate prior to analysis. To ensure analytical accuracy, certified reference materials (CRMs) were also analyzed alongside the samples. Raw isotopic data were calibrated using a three-point scale normalization against these CRMs. System stability and background interference were monitored and corrected using routine blank corrections. The analytical precision for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ measurements was maintained at ± 0.2 ‰. Isotope ratios (δ /‰) were calculated using the equation below:

$$\delta^{13}\text{C} \text{ or } \delta^{15}\text{N} \text{ (per mille, ‰)} = \frac{R_{\text{sample}} - R_{\text{reference}}}{R_{\text{reference}}} \times 1000$$

Eq. 1

where R is the ratio of heavier isotope over lighter isotope ($^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$), $R_{\text{reference}}$ was based on Vienna Pee Dee Belemnite (VPDB) standard for $\delta^{13}\text{C}$, and air standard for $\delta^{15}\text{N}$ values. All reagents used are analytical grade, and standard QA/QC procedures and instrument calibrations were followed.

Statistical Analysis

Statistical analysis and plot generation of soil data from Abra, Davao, Guimaras, Ilocos Norte, Pangasinan, and Zambales at three depth levels (0–20, 20–40, and 40–60 cm) were carried out using R (version 4.5.2), and JMP (JMP Pro 17, SAS Institute Inc., Cary, NC, USA). Missing data (%C, %N, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$) for Davao was imputed using multiple imputation by chained equations (MICE) package in R. Next, a two-way ANOVA (type III SS) was conducted to evaluate differences in the individual parameters across location and soil depths. MANOVA was also used to determine if location, depth, and location vs depth interactions are significant considering all measured parameters. Post-hoc comparisons were performed using Tukey's HSD test to identify specific sites and depth layers with significant variation.

Principal component analysis (PCA) was utilized on standardized data to determine significant soil parameter interactions as a function of location and depth. Then, soil parameter data was correlated to mean yield data (mt ha^{-1}) from a published PSA report

(PSA 2026b) using Akaike Information Criterion (AIC)-refined multiple regression modelling. Because the yield data represented only six independent values from provincial average, yield was not included in the initial component extraction. Instead, it was projected as a supplementary variable by examining its correlation with the province-centroid PC scores.

RESULTS AND DISCUSSION

Site Characteristics and Management Practices

The study sites were characterized by predominantly flat to gently rolling topography, except in Davao where the topography ranged from flat to hilly. Landform, soil type, and farm inputs are summarized in Table 1. Most sampling sites fall under the Type I climate of the Modified Coronas Climate Classification, having a dry season from November to April and wet season from May to October. In contrast, Davao falls under Type IV, which features evenly distributed rainfall year-round with no pronounced dry season. Average temperature is warm year-round ranging from 25 to 32 °C. This is ideal for mango growth and production due to minimal waterlogging and rain during the flowering period (Carating et al. 2014).

Most mango orchards are characterized by a combination of century-old seedling trees (approximately 70–100 years old) and younger grafted trees (10–33 years old). Notably, Guimaras mango orchards are predominantly characterized by century-old trees that were usually planted in backyards with banana, coconut, and rice, or located adjacent to residential areas. Farming practices also varied across locations. In terms of fertilizer application, most

farms used a combination of inorganic fertilizers, such as urea and complete (NPK) fertilizer, and organic inputs. In contrast, farms in Guimaras relied on organic nutrient sources, particularly plant litter, animal manure, and vermicast. Pest management was implemented in all mango orchards through the application of pesticides. Additionally, pruning and fruit bagging were practiced in most of the mango orchards to improve fruit quality and reduce pest damage, except in Abra, where smoke from burning was traditionally used as an alternative method for repelling insect pests.

Flower induction was widely practiced in most of the mango orchards to synchronize flowering and ensure off-season yield despite variable climatic conditions, whereas growers in Abra depended largely on the natural flowering cycles of mango trees. The reliance on flower inducers and plant growth regulators particularly in Davao is associated with its Type IV climate, where the absence of a pronounced dry season reduces the natural flowering of mango trees. Moreover, farmers also deliberately target off-season production to capitalize on periods of limited market supply, allowing them to obtain premium prices and improve profitability.

Distinct site-specific management practices were also observed. In Guimaras, a strict local ordinance requires mango fruits to be harvested at 120 days after flower induction and subjected to hot water treatment to ensure compliance with phytosanitary standards for export markets. In Zambales, growers reduce postharvest losses by processing them into dried mango products.

Table 1: Landforms, soil type, and farm inputs in the study sites.

Province	Landforms	Soil Type*	Declared farming inputs**
Guimaras	Flat plain to gentle sloping	Guimaras gravelly loam	No declared inorganic fertilizer inputs; Organic inputs only such as plant litter, animal manure, and vermicast; Insecticide (Magnum, Chess, Sevin); Fungicide (Antracol)
Zambales	Flat plain	Bani clay/Bolinao clay loam; Alaminos sandy loam	Fertilizer (complete, urea, vermicast, YaraLiva Tropicote); Insecticide (Alika, Double Seven, Cocktail, Actara, Malathion, Lambda, Vasthrin); Fungicide (Goldazim, Amistar, Antracol)
Ilocos Norte	Flat plain to gentle sloping	San Manuel loam; Cervantes clay loam; San Manuel silt; San Manuel silt loam; San Miguel silt loam	Fertilizer (muriate of potash (MOP), complete, urea, calcium nitrate, NutriVant); Fungicide (Luna); Insecticide (Alika, Solomon)
Pangasinan	Flat plain	San Fabian clay loam; San Manuel fine sandy loam; San Manuel silty clay loam	Fertilizer (urea, complete, MOP); Insecticide (Approve, Grandmaster, Ariba, Cypermectin, Carbaryl); Fungicide (Mancozeb)
Abra	Flat plain to gentle sloping	Bauang clay loam; Maligaya sandy clay loam	Fertilizer (cow and poultry manure, complete); Insecticide (Malathion, Magnum)
Davao	Flat plain to hilly	Miral clay loam; Tugbok clay; Bolinao clay	Fertilizers (urea, complete, chicken dung); Plant growth regulator/fungicide (Cultar)

* Soil series (Bureau of Soils and Water Management 2026)

** Based on interview data

Soil pH

Tables 2 and 3 summarize the elemental composition of soils collected from selected mango orchards in six major mango-producing provinces in the Philippines. Table 2 shows the mean values of each measured parameter per depth level, while Table 3 summarizes the two-way ANOVA results, indicating the effects of location, soil depth, and location vs depth interaction to measured variation. Location is a very strong contributor ($p < 0.001$) to

variation in pH measurements. On average, soils in Guimaras were moderately acidic ($\bar{x} = 5.89$; range = 5.28–6.90), while those in Abra ($\bar{x} = 6.43$; range = 5.80–6.79) and Davao ($\bar{x} = 6.36$; range = 4.90–8.00) were mildly acidic. In contrast, soils in Ilocos Norte ($\bar{x} = 6.70$; range = 6.33–7.10), Pangasinan ($\bar{x} = 7.15$; range = 6.35–8.03), and Zambales ($\bar{x} = 7.11$; range = 6.81–7.37) were generally neutral to mildly alkaline. Despite these regional differences, the pH values were generally within the suitable pH range for mango

cultivation (Sys et al. 1993). Soil pH is a major factor controlling nutrient availability and can therefore influence mango growth, yield, and fruit quality. Changes in soil pH affect the solubility and mobility of essential nutrients, including N, P, K, and micronutrients, thereby influencing their uptake and utilization by plants (Wang et al. 2026; Singh et al. 2025). Overall variations in pH values are not influenced by depth; however, differences in pH per depth is unique per location ($p < 0.01$).

In contrast to the other orchards, nutrient inputs in Guimaras were limited to organic inputs such as naturally deposited plant litter, animal manure, and vermicast, with no reported fertilizer application (Table 1). Leaf litter accumulation and decomposition primarily affect the topsoil by releasing organic acids and recycling nutrients, but their effects decrease with depth (Keen et al. 2011;

Pritchett 1979). As a result, the lower pH observed in the subsoil of Guimaras is most likely attributed to natural soil-forming processes such as long-term weathering and leaching of exchangeable base cations (Hettithanthri et al. 2026). Conversely, the increasing pH with depth observed in Davao, Pangasinan, and Zambales is consistent with the findings of Naik et al. (2015), who reported a gradual increase in soil pH to a depth of 120 cm in mango orchards in India and attributed this trend to the deposition of exchangeable base cations in the lower soil horizons during periods of heavy rainfall. This pattern is consistent with Weil and Brady's (2017) general observation that pH in upper soil horizons is lower than in deeper horizons, but variations in values may still exist depending on soil-forming factors and site conditions.

Table 2: Elemental analysis of soils from selected mango orchards in the Philippines.

Depth cm	Site	Soil pH	Ca	Mg	K	P	Zn	Cu	Fe	Mn
			-----	cmol ⁺ kg ⁻¹	-----	-----	-----	mg kg ⁻¹	-----	-----
0–20	Guimaras	6.29	9.38	5.49	0.47	3.25	1.61	3.37	56.97	122.36
	Zambales	6.94	8.73	16.05	0.55	15.45	2.26	7.91	91.98	58.41
	Ilocos Norte	6.70	30.20	8.61	1.42	20.02	1.33	4.45	39.41	64.36
	Pangasinan	7.19	25.19	5.04	0.75	31.12	21.57	15.14	50.45	39.28
	Abra	6.40	42.77	8.49	0.95	11.13	1.14	3.59	30.30	37.78
	Davao	6.10	21.01	7.73	0.69	5.38	1.56	5.99	60.50	82.38
20–40	Guimaras	5.72	6.65	11.26	0.28	3.15	1.57	2.03	19.61	78.69
	Zambales	7.14	8.66	20.71	0.55	3.27	0.90	6.49	44.91	38.96
	Ilocos Norte	6.70	36.33	8.56	0.73	11.56	0.56	4.08	28.78	55.43
	Pangasinan	7.12	29.16	8.57	0.58	12.50	3.81	8.75	56.66	78.70
	Abra	6.48	45.85	8.73	0.72	6.77	1.32	3.64	29.06	33.65
	Davao	6.33	22.30	8.62	0.52	3.40	0.53	4.87	37.28	62.66
40–60	Guimaras	5.67	6.67	13.83	0.29	0.89	0.79	1.76	13.96	66.57
	Zambales	7.23	6.91	21.89	0.52	2.48	0.54	5.92	44.29	42.06
	Ilocos Norte	6.71	41.36	8.65	0.59	7.10	0.48	3.97	24.33	63.84
	Pangasinan	7.15	29.74	10.22	0.39	4.77	1.12	6.39	45.41	58.68
	Abra	6.39	39.25	7.96	0.45	4.71	1.06	3.52	30.30	62.59
	Davao	6.65	25.26	12.81	0.50	1.25	0.34	1.85	16.73	27.59

Table 3: Summary of two-way ANOVA for elemental analysis of soils from selected mango orchards in the Philippines.

Soil property	Location	Depth	Location × Depth
Soil pH	***	ns	***
Available P, mg kg ⁻¹	ns	**	ns
Exchangeable Ca, cmol ⁺ kg ⁻¹	*	ns	ns
Exchangeable Mg, cmol ⁺ kg ⁻¹	*	ns	ns
Exchangeable K, cmol ⁺ kg ⁻¹	ns	ns	ns
Extractable Zn, mg kg ⁻¹	***	ns	**
Extractable Cu, mg kg ⁻¹	***	ns	ns
Extractable Fe, mg kg ⁻¹	ns	ns	ns
Extractable Mn, mg kg ⁻¹	ns	ns	ns

Legend: $p < 0.001 = ***$, $p < 0.01 = **$, $p < 0.05 = *$, $p < 0.1 = .$, $ns = \text{not significant}$

Macronutrients

Available P did not differ significantly among regions. However, vertical distribution showed a distinct surface enrichment pattern, with concentrations depleting in deeper soil layers ($p < 0.05$). In Ilocos Norte, Pangasinan, and Zambales, higher P concentrations were observed in the topsoil (0–20 cm) with P levels ranging from 15 mg kg⁻¹ up to 31 mg kg⁻¹, whereas subsoil layers (below 40 cm) generally showed lower P concentrations (Table 2). A similar trend has been reported in a study on acidic mango orchards in Jharkhand, India, which showed higher P levels (1.8–7.3 kg ha⁻¹) at 0–30 cm that declined with increasing depth (Naik 2014). Yan et al. (2024) likewise reported a decrease in available P with soil depth from 88.4 mg kg⁻¹ at 0–15 cm to only 7.1 mg kg⁻¹ at 15–30 cm. Higher available P in surface soils can be attributed to fertilizer and manure application, organic matter, soil pH, and climate by increasing the concentration of soluble phosphorus near the soil surface (Weil and Brady 2017).

On the other hand, K concentrations did not differ significantly across provinces nor soil depths. The mean value was 0.54±0.43 cmol⁺ kg⁻¹, with a range of 0.07–2.34 cmol⁺ kg⁻¹. K usually becomes depleted due to continuous fruit harvesting, as mango fruits remove substantial amounts of K from the soil. Additionally, imbalances with other cations, such as Ca and Mg, can affect K uptake due to competitive interactions in the soil. K promotes flowering, reduced fruit drop, improved fruit retention, and mango quality (Khattab et al. 2007). Most of the sites measured K levels between 0.20 and 1.4 cmol⁺ kg⁻¹. Landon (1991) suggested that values exceeding 0.6 cmol⁺ kg⁻¹ are typically adequate for most field crops (Table 4). The relative stability of K at soil depth below 40 cm suggests a consistent mineralogical source or balanced leaching and capillary rise dynamics.

Marked differences in Ca and Mg concentrations were observed among sites ($p < 0.1$). Ca content was recorded at the lowest levels in Guimaras ($\bar{x} = 7.56$ cmol⁺ kg⁻¹) and Zambales ($\bar{x} = 8.10$ cmol⁺ kg⁻¹), whereas Davao ($\bar{x} = 22.86$ cmol⁺ kg⁻¹), Pangasinan ($\bar{x} = 28.02$ cmol⁺ kg⁻¹), Ilocos Norte ($\bar{x} = 35.96$ cmol⁺ kg⁻¹), and Abra ($\bar{x} = 42.62$ cmol⁺ kg⁻¹) exhibited three to five times higher Ca values. Mg concentrations were also significantly elevated in Zambales ($\bar{x} = 19.55$ cmol⁺ kg⁻¹), nearly double those observed in other sites (7.94–10.19 cmol⁺ kg⁻¹; $p < 0.05$). Neither Ca nor Mg content varied significantly with soil depth.

Ca influences fruit development, mineral composition, fruit firmness, yield, and quality of mangoes (Rodrigues et al. 2025; Ullah et al. 2024), while Mg is an important component of chlorophyll, protein synthesis, and enzyme catalysis (Hawkesford et al. 2012). Sites with higher pH, such as Abra, Ilocos Norte, and Pangasinan, showed Ca concentrations ranging from 25 to 46 cmol⁺ kg⁻¹, while those in Guimaras, with more acidic profiles, remained below 10 cmol⁺ kg⁻¹. Weil and Brady (2017) emphasized that high Ca and Mg levels are characteristic of soils with minimal leaching intensity or those derived from basic parent materials. Ca availability is closely linked to soil pH, as it is more abundant in neutral to slightly alkaline soils. Exchangeable cations not only

indicate existing nutrient status but can also be used to assess balances amongst cations.

Micronutrient Content

Significant differences were observed among sites for Cu and Zn but not for Fe and Mn. Cu was notably high in Pangasinan at 0–60 cm ($\bar{x} = 10.09 \pm 1.19$ mg kg⁻¹, range = 1.25–27.05 mg kg⁻¹; $p < 0.001$) as compared with the other sites (0.59–10.74 mg kg⁻¹). Cu levels in provinces were considered sufficient for optimal plant growth in most tropical systems. Cu also has an antagonistic effect with Fe, Mg, N, P, and Zn. Cu tends to bind strongly to organic matter and clay particles, reducing its mobility and availability to plants.

Fe solubility in soils is highly influenced by soil pH and redox potential, which decreases as the pH increases (Lindsay 1972). Generally, low Fe concentrations are often observed in calcareous soils due to Fe precipitation (Krauskopf 1972); however, all values across different sites and between depths showed moderate to high levels of Fe (Table 2) (Jones 2001). This is due to the high concentration of Fe oxides, which occurs as a coating of soil aggregates in a more advanced stage of soil development that is very common in tropical soils like the Philippines. High Fe solubility in soil often limits the availability of other essential nutrients, especially P due to fixation. Fe concentration showed no significant difference among all sites and between depths (Table 3). Despite this, the levels of Fe concentration were highly suitable for mango production (Table 4).

In tropical mango-growing regions, Mn behaves similarly to Fe, as availability of both elements is strongly influenced by soil pH, with higher solubility under acidic conditions and reduced availability in neutral to alkaline soils. Mn concentrations were beyond the critical levels in soils but showed no significant difference across sites and between depths. However, in slightly acidic areas like Guimaras and Davao, the Mn solubility drastically increased, such that the values are over the optimal level for mango production, in contrast to the sites with alkaline soils like Pangasinan (Table 2 and 3).

Zn concentration showed high significant difference across sampling areas ($p < 0.01$), with notably high Zn solubility in the soils of Pangasinan (1.12–21.57 mg kg⁻¹). However, the values showed no significant difference across depths (Table 2 and 3). Most surface soils across all sites were near the critical level, while some areas were lower than the critical levels, which could limit soil productivity for mango production. High pH calcareous soils impede Zn availability because of its adsorption on clay (Zhao et al. 2014). Additionally, Landon (1991) identified Zn deficiency as a widespread constraint in Philippine soils, particularly in areas with higher pH or continuous anaerobic conditions. Zinc concentrations were notably insufficient across the majority of the sites, with most values below 4 mg kg⁻¹.

Table 4: Suggested optimal/threshold soil mineral concentration ranges for mango production according to different sources.

Mineral	¹ Queensland Department of Agriculture and Fisheries 2015	² Landon 1991	² Jones 2001
Nitrogen (%)	0.001	0.200	0.004
Carbon (%)	1–2	4.00	nd
Phosphorus (mg kg ⁻¹)	60–80	5.00	2.00
Potassium (cmol ⁺ kg ⁻¹)	0.25–0.40	0.60	0.15
Calcium (cmol ⁺ kg ⁻¹)	3–5	4.00	0.40
Magnesium (cmol ⁺ kg ⁻¹)	0.75–1.25	0.50	0.24
Copper (mg kg ⁻¹)	0.30–10	2.00	0.80
Manganese (mg kg ⁻¹)	4–50	20.00	8.00
Iron (mg kg ⁻¹)	4–100	2.50–4.50	10.00
Zinc (mg kg ⁻¹)	2–15	1.40–3.00	1.00

¹Optimal soil mineral concentration

²Threshold/critical level

nd = no data

Total Carbon and Nitrogen Content

Figure 2 shows the variation in soil C and N content from five provinces, except for Davao. Data for %C, %N, and stable isotopic ratios were unavailable for Davao due to the phytosanitary restrictions described in the Materials and Methods. Soil %C was generally higher in the surface layer (0–20 cm) across the five provinces, with Guimaras exhibiting the highest surface soil C ($\bar{x}$ = 2.92 %), followed by Zambales ($\bar{x}$ = 1.95 %) and Pangasinan ($\bar{x}$ = 1.79 %). In contrast, Abra and Ilocos Norte had lower surface C concentrations, both below 1.0 %. Carbon concentrations generally decreased with increasing soil depth across all provinces (Figure 2). High %C in the surface soil indicates organic matter accumulation and litter inputs in the topsoil from mango trees. This can be attributed to the greater quantity and quality of organic matter inputs, such as fresh litterfall, living organisms, and root activity (Naik et al. 2016). In contrast, deeper layers exhibited lower %C due to limited downward movement of organic matter. As soil depth increases, the contribution of organic inputs declines, leading to lower organic C contents in the subsoil. Additionally, root density and microbial activity generally decrease with depth, further reducing C accumulation in deeper soil layers. Although microbial communities can persist at greater soil depths, their activity levels are generally lower than those in surface soils (Rajapaksha et al. 2025). Notably, the surface soil in Guimaras showed relatively higher %C than other areas, which can be attributed to greater organic inputs such as compost or manure application. The results confirmed the declared farming practices of Guimaras farmers from the interviews.

A similar pattern was observed for total %N, with higher concentrations in the topsoil (0–20 cm) that decreased with increasing soil depth (Figure 2). Guimaras exhibited the highest surface soil N concentration ($\bar{x}$ = 0.21 %), followed by Pangasinan and Zambales ($\bar{x}$ = 0.19 %), whereas Abra ($\bar{x}$ = 0.13 %) and Ilocos Norte ($\bar{x}$ = 0.14 %) had comparatively lower concentrations. Higher %N in the surface soil reflects the influence of fertilizer application (both synthetic and organic), as well as organic inputs from mango leaves and pruning residues. This also indicates active nutrient cycling near the soil surface. However, despite this trend, the measured N levels (0.2–0.5 %) are still considered low for optimal

plant use, suggesting the need for continued or improved nutrient management (Landon 1991).

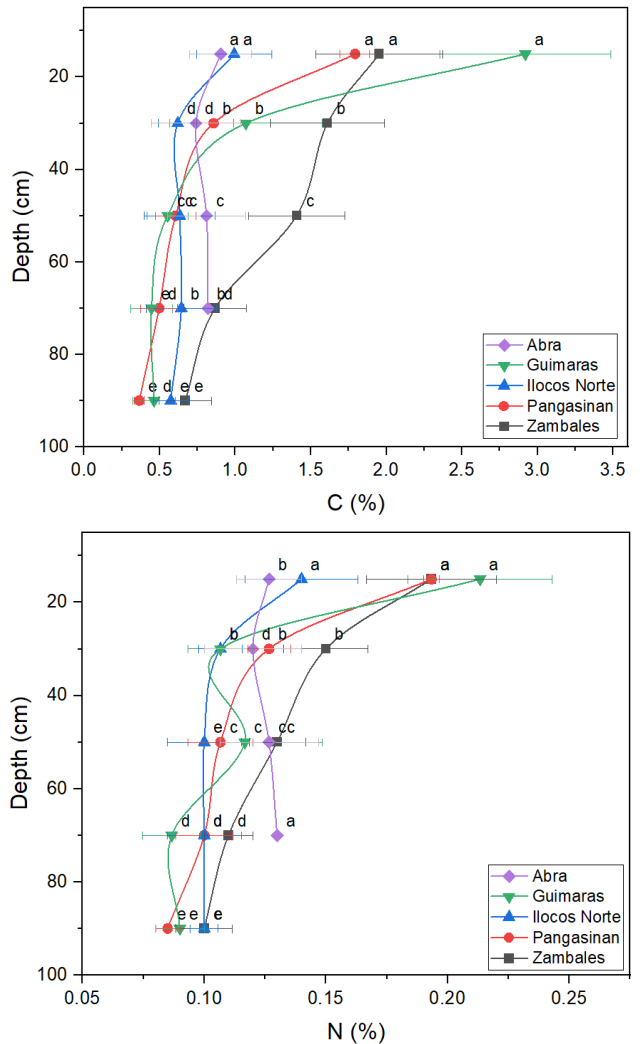


Figure 2: Total carbon and nitrogen content with soil depth.

Stable Isotope Data

The $\delta^{13}\text{C}$ values suggest a more pronounced C4 plant origin in the underlying soil layers (-10.30 to -29.62 ‰ at 20–100 cm depth), and a shift to C3 plant origin in the uppermost soil (0–20 cm) as shown in Figure 3. Deeper soil layers retained a strong C4 signal, indicating the legacy of previous grassland conditions, whereas the uppermost layer had a distinct C3-like signature due to recent mango biomass inputs and organic nutrient sources. The observed shift in soil $\delta^{13}\text{C}$ from C4- toward C3-derived signatures indicates the progressive incorporation of mango-derived organic residues into the soil, demonstrating long-term C sequestration and establishing mango as the dominant source of soil organic matter (Saiz et al. 2015).

The shift towards more positive $\delta^{13}\text{C}$ in the deeper layers also suggests organic matter (OM) degradation, which favors the mineralization of lighter C isotopes. This happens because soil microbes preferentially break down compounds containing the lighter C isotope, leaving behind material enriched in ^{13}C . As organic matter decomposes with depth, microbial activity consumes easily degradable substrates like carbohydrates and proteins. This selective breakdown alters the isotopic composition of the residual OM. In addition, during mineralization, microbes respire ^{12}C -rich compounds, releasing CO_2 that is isotopically lighter. The residual OM becomes progressively enriched in ^{13}C , producing the observed isotopic shift (Krüger et al. 2024).

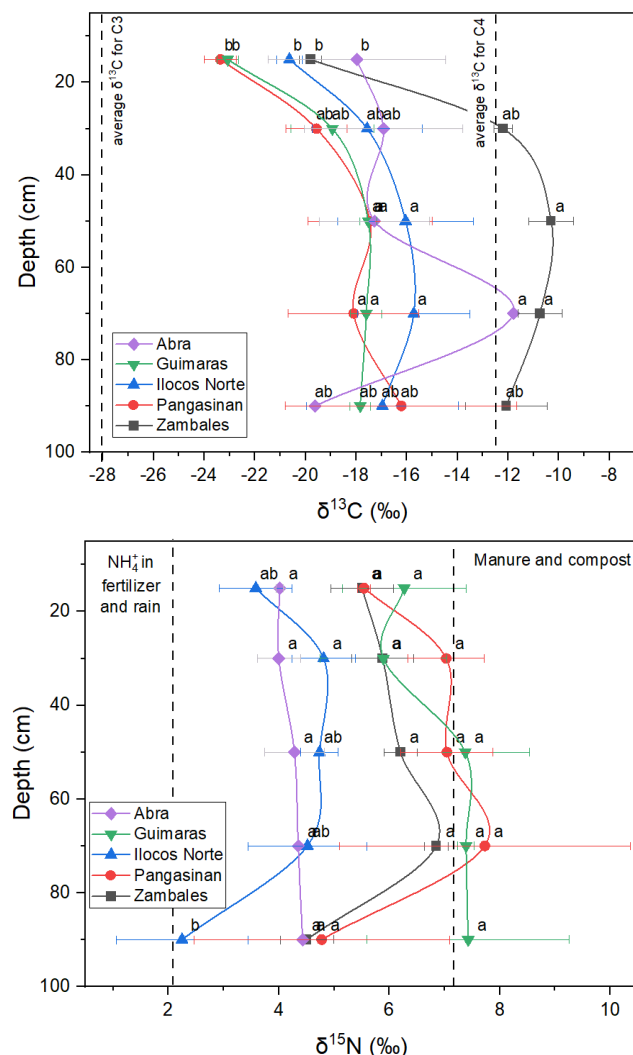


Figure 3: $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ composition with soil depth.

The $\delta^{15}\text{N}$ values ranged from 2 ‰ to 10 ‰, indicating variability in N sources and cycling among the study sites. Higher $\delta^{15}\text{N}$ values are generally associated with organic fertilizers, whereas lower values are more characteristic of synthetic or inorganic fertilizers. Bateman and Kelly (2007) reported that synthetic fertilizers typically exhibit $\delta^{15}\text{N}$ values between -2 ‰ and +2 ‰ (generally <4 ‰), while organic fertilizers have a mean $\delta^{15}\text{N}$ value of 8.6 ‰ and may reach as high as +36.7 ‰. Therefore, the relatively enriched $\delta^{15}\text{N}$ values observed in selected mango orchards are consistent with a substantial contribution of organic fertilizer inputs and/or prolonged microbial processing of soil N, rather than inputs derived solely from synthetic or inorganic fertilizers. Furthermore, these findings support the claims of Guimaras mango growers that they primarily use organic nutrient sources, such as plant litter, to enrich the soil. Likewise, the N isotopic signatures of soils from Pangasinan and Zambales suggest that organic materials may have played a more significant role in nutrient cycling. Although farmers in Abra claimed to use organic fertilizers, a considerable amount of inorganic fertilizers from their own application as well as from the adjacent rice paddies may have influenced the N isotopic signatures of nearby orchard soils. Mango trees can develop taproots extending 6–8 m deep, together with a dense network of shallow feeder roots around the base of the trunk, enabling nutrient uptake across a broad soil area (Yadav et al. 2018). The relatively lower $\delta^{15}\text{N}$ values observed in Abra may be attributed, in part, to the transport of fertilizer-derived N through hydrological pathways. An isotope tracer study in a paddy field demonstrated that fertilizer-derived N is exported through lateral seepage, runoff, and artificial drainage, with lateral seepage accounting for a substantial proportion of fertilizer N loss (Yu et al. 2020). This indicates that fertilizer-derived N can move beyond the site of application, suggesting that synthetic N from adjacent rice paddies could potentially influence the isotopic composition of nearby orchard soils. Since synthetic fertilizers generally exhibit lower $\delta^{15}\text{N}$ values than organic fertilizers, this may partially mask the $\delta^{15}\text{N}$ signature expected under long-term organic management.

The progressive enrichment of soil $\delta^{15}\text{N}$ from the surface to subsurface depth is consistent with established patterns of long-term N cycling in soils. Progressive decomposition and microbial N transformations preferentially utilize the lighter isotope of N (^{14}N), resulting in residual soil organic N enriched in ^{15}N isotope (Baisden et al. 2002). Hobbie and Ouimet (2009) further proposed that downward transport of ^{15}N -depleted nitrate followed by immobilization or re-assimilation can produce a $\delta^{15}\text{N}$ enrichment peak in subsurface horizons, after which $\delta^{15}\text{N}$ decreases in deeper soil layers. Supporting this concept, Spohn and Stendahl (2023) demonstrated that non-linear vertical $\delta^{15}\text{N}$ profiles are common in soils, where enhanced microbial N processing and vertical N redistribution generate enrichment in the subsurface before a decline in deeper horizons. Furthermore, Gurmesa et al. (2022) observed that bulk soil $\delta^{15}\text{N}$ progressively increased from the surface up to the 50 cm soil horizon, with an enrichment of approximately 8 ‰, resulting from isotopic fractionation during decomposition and the preferential loss of ^{15}N -depleted inorganic N. The decrease of $\delta^{15}\text{N}$ composition at deeper horizons further suggests that nitrate leaching redistributes N within the soil profile. Collectively, these studies suggest that the observed vertical distribution of $\delta^{15}\text{N}$ in our study reflects cumulative N transformations and redistribution within the soil profile, indicating that soil $\delta^{15}\text{N}$ integrates long-term fertilizer management and microbial N cycling rather than recent fertilizer applications alone.

The combined use of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ provides complementary indicators of long-term soil processes, with $\delta^{13}\text{C}$ tracing historical vegetation inputs and SOC turnover, and $\delta^{15}\text{N}$ integrating fertilizer history with N transport and transformation processes. Generally, isotope data provide a valuable approach for evaluating the long-

term influence of mango orchard management on soil characteristics, complementing conventional soil fertility analyses that primarily reflect current soil conditions. Therefore, this can serve as an effective tool for assessing the sustainability of orchard management practices and guiding nutrient management strategies for long-term soil health improvement.

Soil Properties Across Depths and Their Associations with Mango Yield

Parallel analysis supported the retention of three principal components, which together accounted for >50 % of the variation

in the standardized soil dataset. Principal component 1 (PC1) accounted for 25.9 % of the variance and showed strong positive loadings for total C (0.87), total N (0.86), Fe (0.80), Cu (0.55), Mn (0.50), and Zn (0.39), along with a negative loading for $\delta^{13}\text{C}$ (−0.51) (Figure 4). This pattern identifies PC1 as a broad organic matter–N–micronutrient gradient. The strong, positive correlation of the Mn–Fe–C–N cluster, as shown in the heatmap (Figure S-2) suggests that soil organic matter is a major source of coordinated redox-driven nutrient variation across the orchards in the different provinces similarly observed by Mesele et al. (2026).

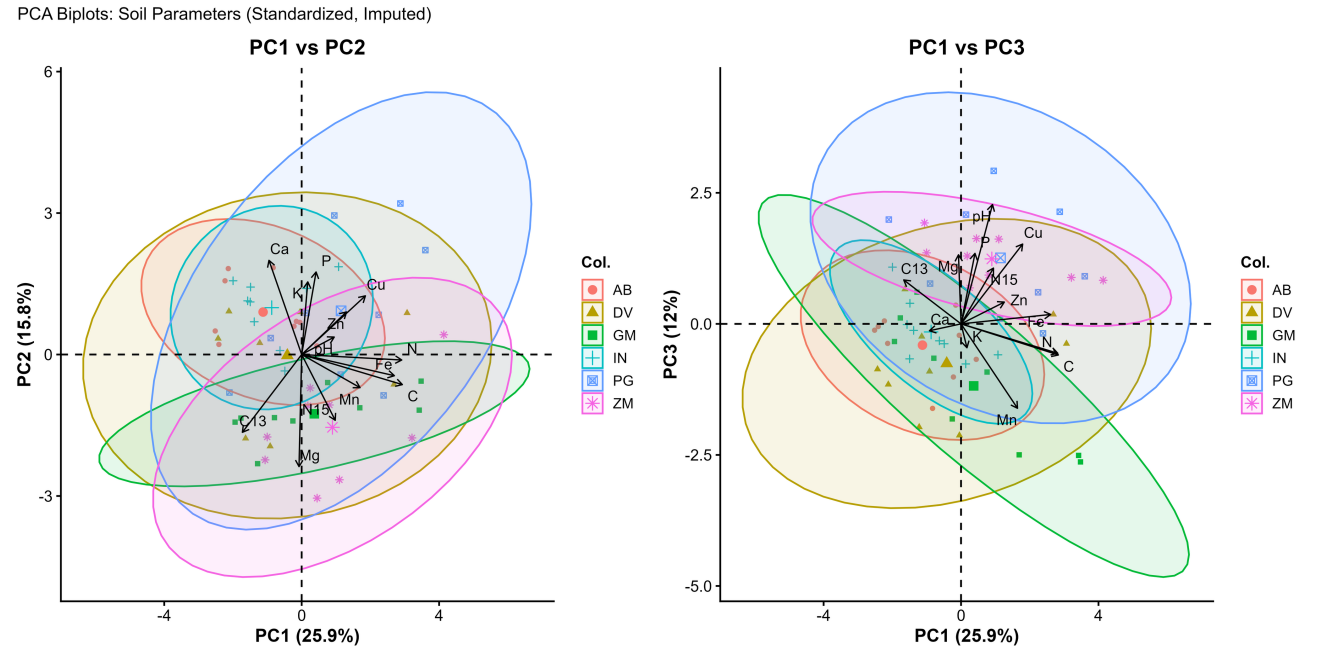


Figure 4: Principal component analysis (PCA) biplot of standardized soil properties at depths of 20, 40, and 60 cm across the study sites. Site abbreviations: AB, Abra; DV, Davao; GM, Guimaras; IN, Ilocos Norte; PG, Pangasinan; and ZM, Zambales.

PC2 explained 15.8 % of the variance and was defined mainly by positive loadings for Ca (0.59), P (0.52), K (0.46), Cu (0.37), and pH (0.11), together with a negative loading for $\delta^{15}\text{N}$ (−0.41). This component reflects a base-fertility and P-availability gradient. Among the retained components, mango yield was most closely associated with this cluster ($r = 0.37$) as supported by AIC-refined multiple regression modelling (Figure S-3). The relatively high-yielding Abra and Pangasinan orchards had positive PC2 scores, which is consistent with a beneficial role of coordinated Ca, P, and K fertility. However, this relationship was only moderate, and orchards such as in the province of Ilocos Norte and Guimaras did not follow a simple PC2–yield ranking. This indicates that the fertility gradient represented by PC2 alone was not sufficient to explain differences in provincial productivity. PC3 accounted for a further 12 % of the variance and was characterized by pH (0.70), $\delta^{15}\text{N}$ (0.33), $\delta^{13}\text{C}$ (0.26), P (0.41), and Mg (0.40), representing a distinct Mg–P–isotopic–pH gradient (Figure S-1).

Soil depth also showed a clear multivariate pattern. Mean PC1 scores declined from 1.49 at 20 cm to −0.38 at 40 cm and −1.12 at 60 cm, indicating that the surface soil was relatively high in the C–N–Fe–Zn–Cu–Mn contents. In contrast, mean PC3 scores increased from −0.51 at 20 cm to 0.46 at 60 cm, suggesting that the Mg– $\delta^{13}\text{C}$ –pH pattern became more pronounced with soil depth. Exploratory province-level correlations further suggested positive relationships between yield and Zn ($r = 0.74$) and Ca ($r = 0.48$), and negative relationships with $\delta^{13}\text{C}$ ($r = -0.56$) and total C ($r = -0.46$), as indicated in Table S-3. Because these correlations were based on

only six provinces with limited sampling farms, they should be interpreted cautiously and not treated as confirmatory evidence.

Overall, the findings suggest that mango yield reflects coordinated soil-fertility conditions alongside other influences, including orchard cultural and nutrient management, tree age, water availability, pest pressure, climate, and additional factors not measured in this study.

Mango Orchard Management Recommendations

Based on the soil fertility gradients among sites, nutrient management in these mango orchards should be adapted to site-specific conditions rather than following a generalized recommendation. Nutrient application rates should be based on soil testing, standardized leaf analysis, tree age, crop load, soil pH, and fertilizer history. Balanced management of Ca, P, and K should be prioritized because these nutrients defined the fertility gradient most closely associated with yield. Phosphorus should be placed within the active feeder-root zone and applied only at rates based on soil and plant analyses, as excessive application may provide little additional yield while increasing the risk of P accumulation and loss (Wang et al. 2022). Where Cu or Zn deficiency is confirmed, corrective soil or foliar applications may be considered. Higher-pH orchards, such as those in Pangasinan and Zambales, require closer monitoring, particularly for Zn, because its availability may be restricted under such conditions (Naik and Bhatt 2017). Correcting verified Zn deficiency has been shown to improve mango fruit retention, yield, and quality, although responses depend on orchard conditions and application method (Ahmad et al. 2018).

In all sites tested, the decline in the C–N–micronutrient gradient with soil depth emphasizes the need to improve organic matter and nutrient cycling throughout the rooting zone. The slight increase in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ attributed to microbial-nutrient (Mg, Ca) interactions suggests stable C pooling but N loss via leaching and/or gaseous emissions. Recommended practices include cover cropping, organic mulching, shallow application of well-decomposed compost beneath the canopy, reduced soil disturbance, and recycling of healthy litter and pruning residues. Mango litter and pruning biomass contain considerable amounts of macro- and micronutrients and may contribute to orchard nutrient budgets when appropriately recycled (Niscioli et al. 2025). Maintaining nutrient reserves in the permanent tree structure is also important for sustaining new growth and fruit production (Kotur and Keshava Murthy 2010). Tracking isotope shifts over an extended period helps identify nutrient depletion zones and may be used to perform site-specific fertilization application or intercropping to replenish nutrients in deeper layers.

CONCLUSION

Multi-elemental and stable isotopic characterization of mango orchard soils across the Philippines provided unique insights to geochemical processes, nutrient cycling, and land-use history. Location proved to be the dominant driver of soil parameter variation, whereas depth exerted a comparatively weaker influence. Evidence of significant depth vs location interaction showed that these variations are different per site. Redox-driven nutrient cycling, particularly mediated through Mn–Fe–C–N interactions, was consistently observed, underscoring the central role of coupled mineral–microbial processes in regulating soil biogeochemistry. Mineralization demonstrated in the Mg–Ca cluster contributed to the measured $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ variation with depth.

Nutrient interaction and availability are pH-driven as demonstrated by the Ca–K–Zn–Cu–P–pH cluster. Surface enrichment of P and K, low micronutrient (Cu, Zn) level, and yield correlation with Ca, K, Zn, $\delta^{15}\text{N}$, and $\delta^{13}\text{C}$ suggested that current orchard management systems (e.g. application of fertilizers) may not be enough to reverse the decline in observed yield due to widespread micronutrient deficiency.

Isotopic evidence of land-use conversion from C4 grassland to C3 orchard is useful to describe soil microbial adaptation, reconstruct soil organic C and N sources and turnover rates, and predict fertility changes from natural and anthropogenic processes. Integrating these analytical approaches provides a more comprehensive understanding of site conditions and a robust basis for targeted nutrient management that supports both agronomic improvement and supply-chain traceability.

ACKNOWLEDGMENTS

Research funding was provided through the Food Authenticity and Traceability Program funded by DOST Grants-in-Aid Program (DOST-GIA). Appreciation goes to our DA-RFO partners, participating farmers, and laboratory interns.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Author	Role / Assignments
Nerrisa P. Bacerra	Presenting author, laboratory and data analysis, sampling, methodology, results and discussion,
Mica G. Binongo	Laboratory and data analysis, sampling, methodology, results and discussion
Kurt Louis B. Solis	Principal Investigator, introduction, graphical abstract, sampling, results and discussion
Maria Carmela A. Garcia	Laboratory and data analysis, sampling, results and discussion
Lorraine S. Lao	Data analysis, introduction, language editing
Leslie R. Alapag	Laboratory and data analysis, sampling
Anane R. Serenina	Laboratory and data analysis, sampling, results and discussion
John Leonard R. Labides	Laboratory and data analysis, sampling, results and discussion
Gerald P. Dicen	Co-principal investigator, sampling, proofreading
Roland V. Rallos, PhD	Project consultant, laboratory and data analysis, results and discussion

REFERENCES

Adak T, Kumar K, Singh VK. Variations in soil physical properties, distribution and storage of micronutrients in soil as influenced by high density mango (*Mangifera indica* L.) plantations. *J Soil Water Conserv* 2016; 15(1):75-86.

Ahmad I, Bibi F, Ullah H, Munir TM. Mango fruit yield and critical quality parameters respond to foliar and soil applications of zinc and boron. *Plants* 2018; 7(4), 97. <https://doi.org/10.3390/plants7040097>

Ahmed N, Umer A, Ali MA, Iqbal J, Mubashir M, Grewal AG, Butt B, Rasheed MK, Chaudhry UK. Micronutrients status of mango (*Mangifera indica*) orchards in Multan region, Punjab, Pakistan, and relationship with soil properties. *Open Agriculture* 2020; 5(1):271-279. <https://doi.org/10.1515/opag-2020-0033>

Asis CA, Tilbrook J, Anson D, Niscioli A, Bristow M, Friedl J, Rowlings D. Estimating nitrogen uptake efficiency of mango varieties from foliar KNO₃ application using ¹⁵N tracer technique. *Nitrogen* 2024; 5(4):1124-1134. <https://doi.org/10.3390/nitrogen5040072>

Baisden WT, Amundson R, Brenner DL, Cook AC, Kendall C, Harden JW. A multiisotope C and N modeling analysis of soil organic matter turnover and transport as a function of soil depth in a California annual grassland soil chronosequence. *Global Biogeochemical Cycles* 2002; 16(4):82-1.

Bateman AS, Kelly SD. Fertilizer nitrogen isotope signatures. *Isotopes in environmental and health studies* 2007; 43(3):237-247.

Bernoux M, Cerri CC, Neill C, de Moraes JFL. The use of stable carbon isotopes for estimating soil organic matter turnover rates. *Geoderma* 1998; 8:43-58. [https://doi.org/10.1016/S0016-7061\(97\)00096-7](https://doi.org/10.1016/S0016-7061(97)00096-7)

Bukhari SFH, Farhan M, Kiran R, Hayat R, Bukhari SZH . Impact of soil health on mango cultivation and production under changing climatic scenarios. In: Naqvi SAH, Ahmad S, Ahmed M., eds. *Climate Change and Mango Production*.

- Cham:Springer, 2025: 247-267. https://doi.org/10.1007/978-3-031-87035-4_12
- Bureau of Soils and Water Management. Soil Series Map of the Philippines. 2026.
- Carating RB, Galanta RG, Bacatio CD. Soils and the Philippine Economy. In: The Soils of the Philippines, World Soils Book Series. Dordrecht:Springer, 2014:187-271. https://doi.org/10.1007/978-94-017-8682-9_5
- Edale Jr. M. Isabela mango growers encouraged to venture into off-season production. Philippine Information Agency 2024. <https://pia.gov.ph/news/isabela-mango-growers-encouraged-to-venture-into-off-season-production/>
- FAO. Standard operating procedure for soil pH determination. Rome, 2021a.
- FAO. Standard operating procedure for soil available phosphorus Olsen method. Rome, 2021b,
- FAO. Standard operating procedure for cation exchange capacity and exchangeable bases IN ammonium acetate, pH 7.0 method. Rome, 2022a.
- FAO. Standard operating procedure for soil available micronutrients (Cu, Fe, Mn, Zn) and heavy metals (Ni, Pb, Cd), DTPA extraction method. Rome, 2022b.
- Gurmesa GA, Hobbie EA, Zhang S, Wang A, Zhu F, Zhu W, Koba K, Yoh M, Wang C, Zhang Q, Fang Y. Natural ^{15}N abundance of ammonium and nitrate in soil profiles: New insights into forest ecosystem nitrogen saturation. *Ecosphere* 2022; 13(3):e3998.
- Hawkesford M, Horst W, Kichey T, Lambers H, Schjoerring J, Möller IS, White P. Functions of Macronutrients. In: Marschner P, ed. Marschner's Mineral Nutrition of Higher Plants. Third edition. San Diego: Elsevier, 2012:135-189. <https://doi.org/10.1016/B978-0-12-384905-2.00006-6>
- Hettithanthri O, O'Connor J, Solaiman ZM, Siddique KHM, Bolan N. Unravelling subsoil acidification: mechanisms, consequences and remediation. *Soil Use and Manage* 2026; 42(1): e70191. <https://doi.org/10.1111/sum.70191>
- Hobbie EA, Ouimette AP. Controls of nitrogen isotope patterns in soil profiles. *Biogeochemistry* 2009; 95(2):355-371.
- International Atomic Energy Agency. Use of isotope and radiation methods in soil and water management and crop nutrition (IAEA-TCS-14). Vienna, 2001.
- International Atomic Energy Agency. Sample Preparation of Soil and Plant Material for Isotope Ratio Mass Spectrometry (IAEA-TECDOC-1870). Vienna, 2019.
- Jones JB. Laboratory guide for conducting soil tests and plant analysis. Boca Raton: CRC Press, 2001.
- Keen YC, Jalloh MB, Ahmed OH, Sudin M, Besar NA. Soil organic matter and related soil properties in forest, grassland and cultivated land use types. *Int J Phys Sci* 2011; 6(32):7410-7415. <https://doi.org/10.5897/IJPS11.427>
- Kelly S, Brodie C, Hilkert A. Isotopic-Spectroscopic Technique: Stable Isotope-Ratio Mass Spectrometry (IRMS). In: D. Sun, ed. Modern Techniques for Food Authentication. Second Edition. Massachusetts: Academic Press, 2018:349-413. <https://doi.org/10.1016/B978-0-12-814264-6.00011-6>
- Khan M, Ahmed N. Sustainable management of mango nutrition for better yield and quality. *Cercet Agron Mold* 2020;53(4):473-501. <https://doi.org/10.46909/cerce-2020-040>
- Khattab M, Haseeb G, Shaban A, Arafat M. Effect of paclobutrazol and potassium nitrate on leaves nutritional status of Ewais and Sidik mango trees 1- carbohydrates and nitrogen. *J Plant Prod* 2007; 32:4669-4681. <https://doi.org/10.21608/jpp.2007.208787>
- Kotur SC, Keshava Murthy SV. Nutrient dynamics of annual growth-flush in mango (*Mangifera indica* L.). *Journal of Horticultural Sciences* 2010; 5(1): 75-77. <https://doi.org/10.24154/jhs.v5i1.507>
- Krauskopf KB. Geochemistry of micronutrients. In: Mortvedt JJ, ed. Micronutrients in Agriculture. Wisconsin: Soil Science Society of America, 1972:7-40.
- Krüger N, Finn DR, Don A. Soil depth gradients of organic carbon-13 – A review on drivers and processes. *Plant Soil* 2024; 495:113-136. <https://doi.org/10.1007/s11104-023-06328-5>
- Kumar K, Adak T, Singha A, Shukla SK, Singh V. Appraisal of soil fertility, leaf nutrient concentration and yield of mango (*Mangifera indica* L.) at Malihabad region, Uttar Pradesh. *Current Advances in Agricultural Sciences (An International Journal)* 2012; 4(1):13-19.
- Landon JR. Booker Tropical Soil Manual, London: Routledge, 1991. <https://doi.org/10.4324/9781315846842>
- Lehmann J. Subsoil root activity in tree-based cropping systems. *Plant Soil* 2003;255(1):319-331. <https://doi.org/10.1023/A:1026195527076>
- Li Z, Yao Q, Guo X, Crits-Christoph A, Mayes MA, Hervey IV WJ, Lebeis SL, Banfield JF, Hurst GB, Hettich RL, Pan C. Genome-resolved proteomic stable isotope probing of soil microbial communities using $^{13}\text{CO}_2$ and ^{13}C -Methanol. *Front Microbiol* 2019; 10:2706. <https://doi.org/10.3389/fmicb.2019.02706>
- Lindsay WL. Inorganic phase equilibria of micronutrients in soils In: Mortvedt JJ, ed. Micronutrients in Agriculture. Wisconsin: Soil Science Society of America, 1972:41-58.
- Mesele SA, Katar A, Ouassar M, Steverink-Mosugu M Soil geochemical associations of micronutrients in arid agroecosystems: insights from machine learning and structural equation modeling. *Front Soil Sci* 2026; 6:1851937. doi: 10.3389/fsoil.2026.1851937
- Muñoz-Redondo JM, Bertoldi D, Tonon A, Ziller L, Camin F, Moreno-Rojas JM. Tracing the geographical origin of Spanish mango (*Mangifera indica* L.) using stable isotopes ratios and multi-element profiles. *Food Control* 2021; 125:107961. <https://doi.org/10.1016/j.foodcont.2021.107961>
- Mzezewa J. Impacts of converting native grassland into arable land and an avocado orchard on soil hydraulic properties at an experimental farm in South Africa. *Agronomy* 2025; 15(5):1039. <https://doi.org/10.3390/agronomy15051039>

- Naik S. Distribution of nitrogen, phosphorus, potassium and zinc content in mango grown acidic soils of Jharkhand. *The Ecoscan* 2014; 8:135-139.
- Naik SK, Das B, Kumar S, Bhatt BP. Evaluation of major and micronutrient status of acid soils of different mango orchards. *Int J Fruit Sci* 2015; 15(1):10-25. <https://doi.org/10.1080/15538362.2014.910048>
- Naik SK, Maurya S, Bhatt BP. Soil organic carbon stocks and fractions in different orchards of eastern plateau and hill region of India. *Agroforest Syst* 2016; 91(3):541-552. <https://doi.org/10.1007/s10457-016-9957-4>.
- Naik SK, Bhatt BP. Diagnostic leaf nutrient norms and identification of yield-limiting nutrients of mango in eastern plateau and hill region of India. *Commun Soil Sci Plant Anal* 2017; 48(13):1574-1583. <https://doi.org/10.1080/00103624.2017.1374396>
- Niscioli A, Asis CA, Tilbrook J, Anson D, Guinto D, Bristow M, Rowlings D. Litter and pruning biomass in mango orchards: Quantification and nutrient analysis. *Sustainability* 2025; 17(10):4452. <https://doi.org/10.3390/su17104452>
- Philippine Statistics Authority. 2021-2025 Crops Statistics of the Philippines. Quezon City, Philippines: Philippine Statistics Authority, 2026a.
- Philippine Statistics Authority. Fruit Crops: Volume of Production, by Region, Province, Quarter, and Semester, 2010-2026 [Data set]. OpenSTAT. 2026b.
- Philippine Statistics Authority. Fourth Quarter 2025 Value of Production in Philippine Agriculture and Fisheries. 2026c.
- Pritchett WL. Properties and management of forest soils. New York: Wiley, 1979.
- Queensland Department of Agriculture and Fisheries (QDAF). Food for Fruit – Nutrition management in mangos. AMIA. Part 1 – General Mango Nutrition and Part 2 – Designing a mango fertilizer program, 2015. www.industry.mangos.net.au/resource-collection/food-for-fruit-nutrition.
- Rajapaksha RPSK, Premarathna WDU, Madawala HMSP, Ratnayake RR. Soil organic carbon fractions across soil depths vary among key tropical vegetation types. *Discov Environ* 2025; 3(156). <https://doi.org/10.1007/s44274-025-00370-z>
- Rodrigues LS, Souto AGL, Cavalcante ÍHL, Carvalho LHM, Henrique JCGS, Silva GJN, Paiva Neto VB, Mendonça RMN, Gheyi HR, Lima GS, Batista RO, Sá CH, Silva WAO, Cunha VDL, Sousa Neto AT. Combined effects of calcium sources and water restriction on fruit yield and quality of ‘Ataulfo’ and ‘Kent’ mangoes. *Front Plant Sci* 2025; 16:1622533. <https://doi.org/10.3389/fpls.2025.1622533>
- Saiz G, Bird M, Wurster C, Quesada CA, Ascough P, Domingues T, Schrodte F, Schwarz M, Feldpausch TR, Veenendaal E, Djagbletey G, Jacobsen G, Hien F, Compaore H, Diallo A, Lloyd J. The influence of C₃ and C₄ vegetation on soil organic matter dynamics in contrasting semi-natural tropical ecosystems. *Biogeosciences* 2015; 12(16):5041-5059. <https://doi.org/10.5194/bg-12-5041-2015>
- Singh D, Singh D, Bikramaditya D. Influence of soil pH on nutrient availability and plant growth. *Journal of Science Innovations and Nature of Earth* 2025; 5:105-108. <https://doi.org/10.59436/jsiane.v5i1.29.2583-2093>
- Singh U, Dhar S, Raghuvanshi R, Roy P, Maiti CS, Pradhan R, Bhargava JU, Sarkar A. Sustainable approaches for off-season production of tropical and subtropical fruit crops. *Applied Fruit Science* 2026; 68(23). <https://doi.org/10.1007/s10341-025-01723-x>
- Sinha R, Jaiswal US, Ahmad M F, Mishra PK, Sinha S. Elemental accumulation in mango (*Mangifera indica* L.) as a function of maturity stage and variety. *J Plant Nutr* 2017; 40(13):1805-1815. <https://doi.org/10.1080/01904167.2016.1269348>
- Spohn M, Stendahl J. Spatial patterns of nitrogen isotope ratios in forest soils are related to latitude and soil phosphorus concentration. *Biogeochemistry* 2026; 165(1):43-56.
- Sys C, Van Eric R, Debaveye J, Beernaert F. Land Evaluation Part III. Crop Requirements. In: *Agricultural Publications No. 7*. Department of Geology, Universiteit Gent, N° 7, Brussels: General Administration for Development Cooperation, 1993.
- Turner BL, Wuellner M, Malo DD, Herrick JE, Dunn BH, Gates R. Ecosystem functions in mixed cropland–grassland systems influenced by soil legacies of past crop cultivation decisions. *Ecosphere* 2018; 9(12):e02521. <https://doi.org/10.1002/ecs2.2521>
- Ullah MA, Khanal A, Joyce P, White N, Macnish A, Joyce D. Internal disorders of mango fruit and their management—physiology, biochemistry, and role of mineral nutrients. *Plants* 2024; 13:2596. <https://doi.org/10.3390/plants13182596>
- Wang Z, Erasmus SW, Dekker P, Guo B, Stoorvogel JJ, van Ruth SM. Linking growing conditions to stable isotope ratios and elemental compositions of Costa Rican bananas (*Musa* spp.). *Food Res Int* 2020; 129:108882. <https://doi.org/10.1016/j.foodres.2019.108882>.
- Wang J, Elbagory M, He Y, Zhang X, Hui Y, Eissa MA, Ding Z, El-Nahrawy S, Omara AED, Zoghdan MG, Kheir AMS. Modeling of P-loss risk and nutrition for mango (*Mangifera indica* L.) in sandy calcareous soils: A four-year field trial for sustainable P management. *Horticulturae* 2022; 8(11):1064. <https://doi.org/10.3390/horticulturae8111064>
- Wang Y, Zha Y, Cai Q, Lu D, Chen X, Wang Y, Yokamo S, Wang B, Lu X, Wang H. Soil fertility assessment for mango production in karst agroecosystems of Southwest China. *J Agric Food Res* 2026; 26:102655. <https://doi.org/10.1016/j.jafr.2026.102655>
- Weil RR, Brady NC. The nature and properties of soils. Fifteenth edition. Harlow: Pearson, 2017.
- Yadav D, Yadav KS, Singh S. Mango: Taxonomy and botany. *Journal of Pharmacognosy and Phytochemistry* 2018; 7(2):3253-3258.
- Yu X, Xu Y, Zhu H, Shutes B, Yan B, Chen X, Rui C. Tracking the fate of fertilizer nitrogen in a paddy rice field using isotope technology. *Pol J Environ Stud* 2020; 29(1):419-428. <https://doi.org/10.15244/pjoes/103026>
- Zhao A, Tian X, Cao Y, Lu X, Liu T. Comparison of soil and foliar zinc application for enhancing grain zinc content of wheat when

grown on potentially zinc-deficient calcareous soils. J Sci Food
Agric 2014; 94:2016-2022. <https://doi.org/10.1002/jsfa.6518>

SUPPLEMENTAL INFORMATION

Table S-1: Coordinates of the sampling sites.

Point	Province	Location	Latitude	Longitude	Elevation (m)
1	Ilocos Norte	Brgy. 22 Bani, Bacarra, Ilocos Norte	N 18°16.056'	E 120°36.646'	39
2	Ilocos Norte	Brgy. 45 Tangid, Laoag, Ilocos Norte	N 18°11.533'	E 120°34.200'	41
3	Ilocos Norte	Brgy. 9 Lubnac, Vintar, Ilocos Norte	N 18°12.847'	E 120°40.317'	55
4	Abra	Palaquio, Bucay, Abra	N 17°32.561'	E 120°46.170'	134
5	Abra	Sapaac, Bangued, Abra	N 17°30.392'	E 120°38.241'	214
6	Abra	Alinaya, Pidigan, Abra	N 17°32.449'	E 120°34.102'	65
7	Pangasinan	Brgy. Nantangalan, Pozorrubio, Pangasinan	N 16°05.197'	E 120°30.104'	51
8	Pangasinan	Brgy. Baguihay, Manaoag, Pangasinan	N 15°59.446'	E 120°31.117'	28
9	Pangasinan	Brgy. Payas, Sta. Barbara, Pangasinan	N 15°58.698'	E 120°25.066'	13
10	Zambales	Brgy. Tubo Tubo South, Sta. Cruz, Zambales	N 15°43.446'	E 119°56.332'	17
11	Zambales	Pulangi Bani, Masinloc, Zambales	N 15°35.599'	E 119°56.107'	20
12	Zambales	San Vicente, Palauig, Zambales	N 15°27.005'	E 119°56.014'	11
13	Guimaras	Sitio Parin-an, Bulwangan, Jordan	N 10°33.097'	E 122°33.005'	36
14	Guimaras	Sitio Tiko, Concordia, Sibunag	N 10°32.078'	E 122°33.750'	130
15	Guimaras	Sitio Bangkiling, Brgy. Dracon, Nueva Valencia	N 10°29.933'	E 122°34.528'	109
16	Davao	Brgy. San Isidro, Samal, Davao del Norte	N 7°10.491'	E 125°42.514'	67
17	Davao	Brgy. Joaquin, Calinan, Davao City	N 7°11.724'	E 125°30.168'	235
18	Davao	Brgy Ceboza, Matanao, Davao del Sur	N 6°41.765'	E 125°13.580'	69

Table S-2: Multivariate ANOVA Results (Standardized Data, Imputed).

	Df	Pillai approx.	F num	Df density	Df	Pr (>F)	
Location	5	2.79263	2.9821	70	165	5.34E-09	***
Depth	1	0.62778	3.4936	14	29	0.002148	**
Location:Depth	5	2.01534	1.5916	70	165	0.008415	**
Residuals	42						

Legend: $p < 0.001 = ****$, $p < 0.01 = ***$, $p < 0.05 = **$, $p < 0.1 = *$, $ns = not\ significant$

Table S-3: Yield correlations with site-mean soil properties.

Variable	Correlation_with_Yield
Zn	0.74
$\delta^{13}C$	-0.56
Ca	0.48
C	-0.46
Mn	-0.30
N	-0.26
P	0.25
Mg	-0.24
$\delta^{15}N$	0.12
Cu	0.11
pH	0.10
K	0.07
Fe	0.07

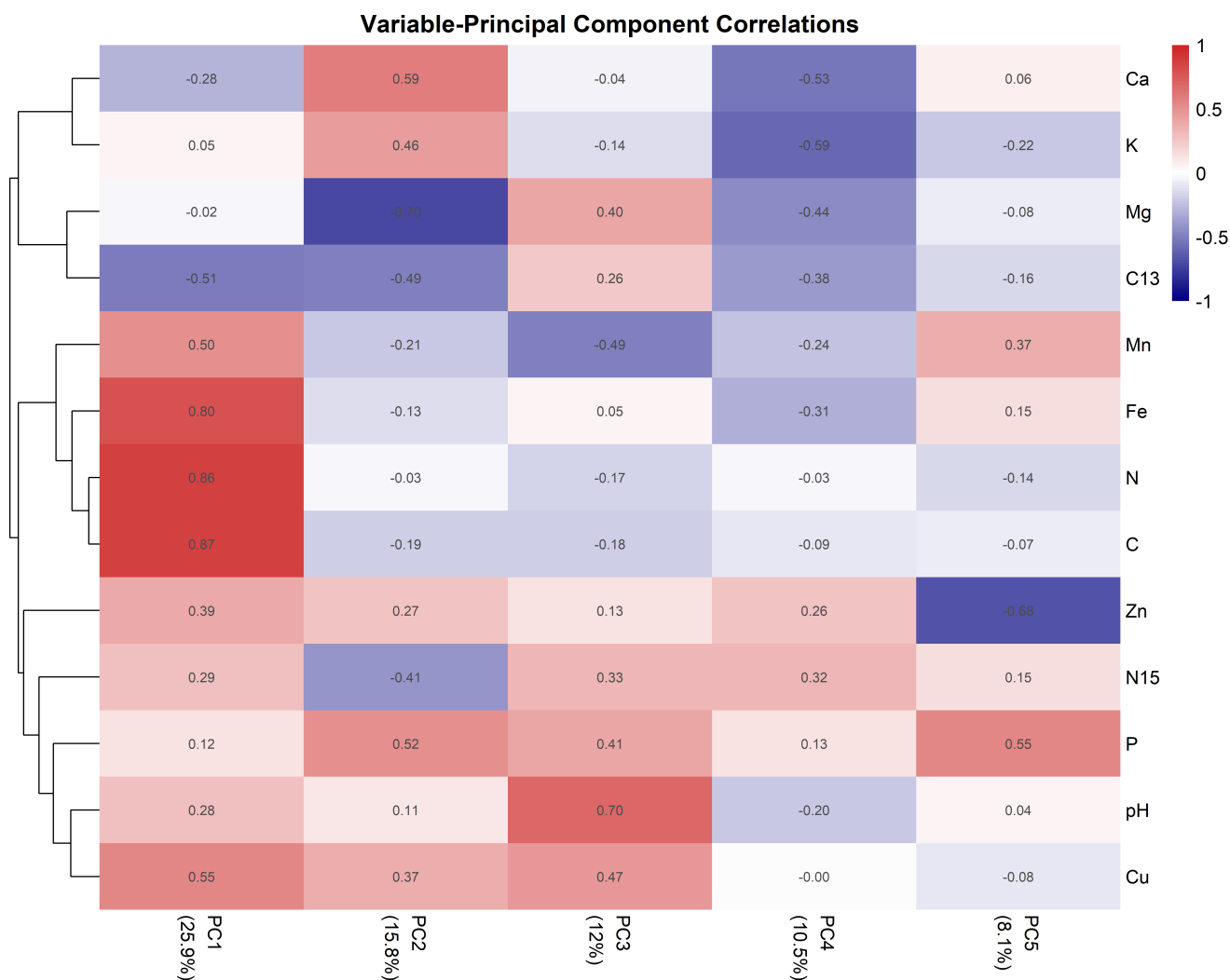


Figure S-1: Dimensions loadings and supplementary yield correlations.

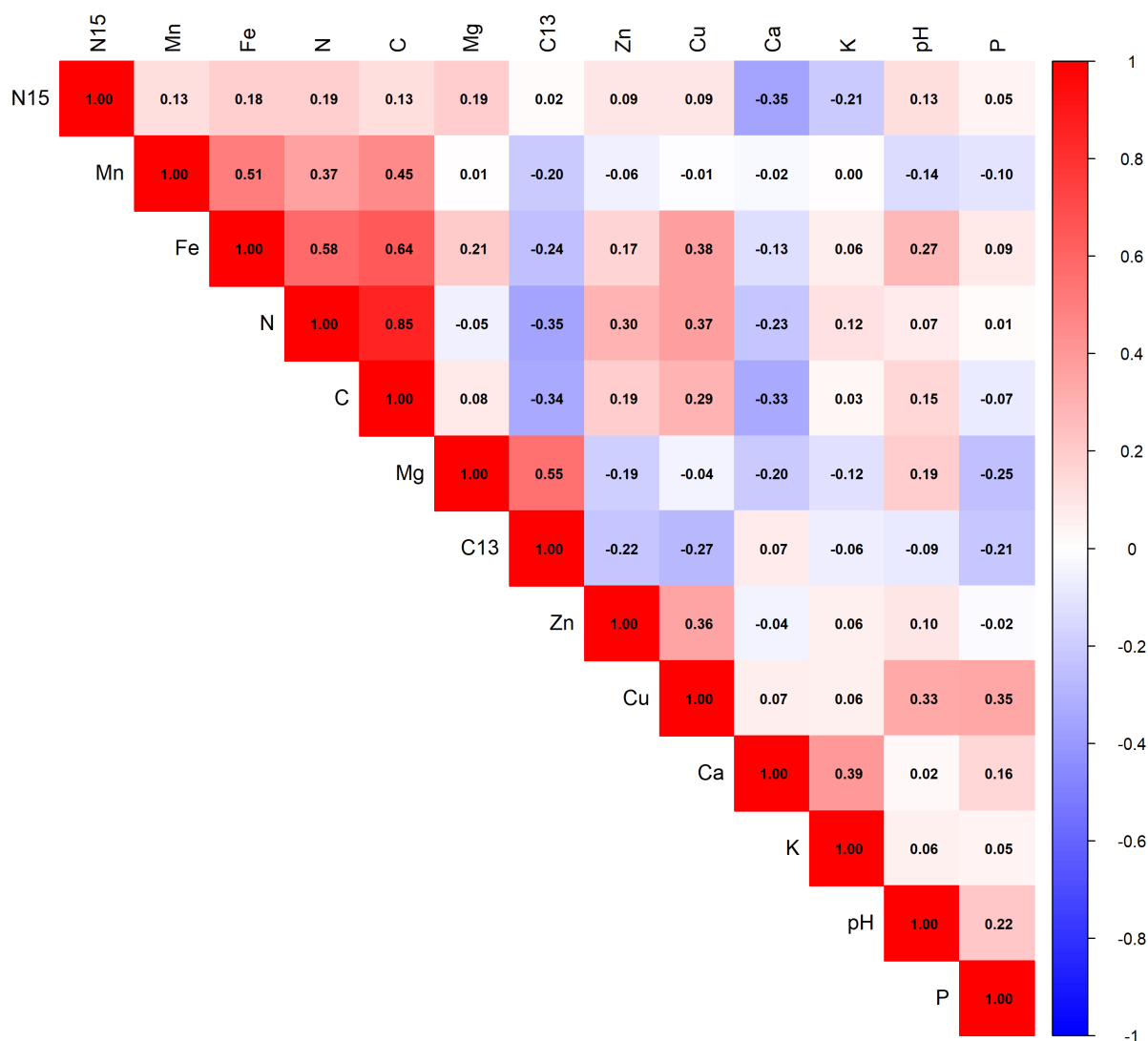


Figure S-2: Elemental heatmap based on PCA of soil parameters (all locations, depths: 0–20, 20–40, 40–60 cm). Strong positive correlation observed for Mn–Fe–N–C cluster (top left). pH-driven nutrient interactions are denoted by Ca–K–Zn–Cu–pH–P clusters.

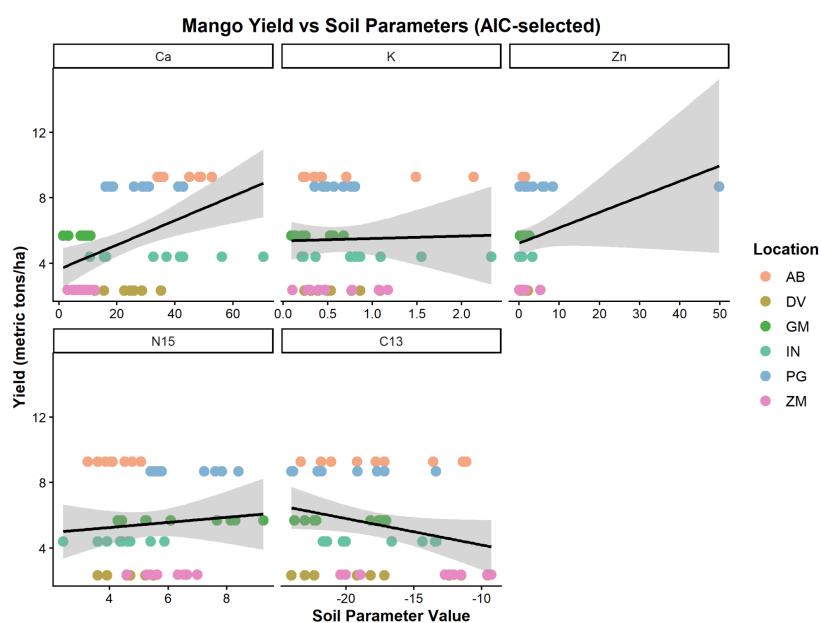


Figure S-3: Multiple regression models (refined using Akaike Information Criterion) identified Ca, K, Zn, and stable-isotope values having strong correlation with mango yield.

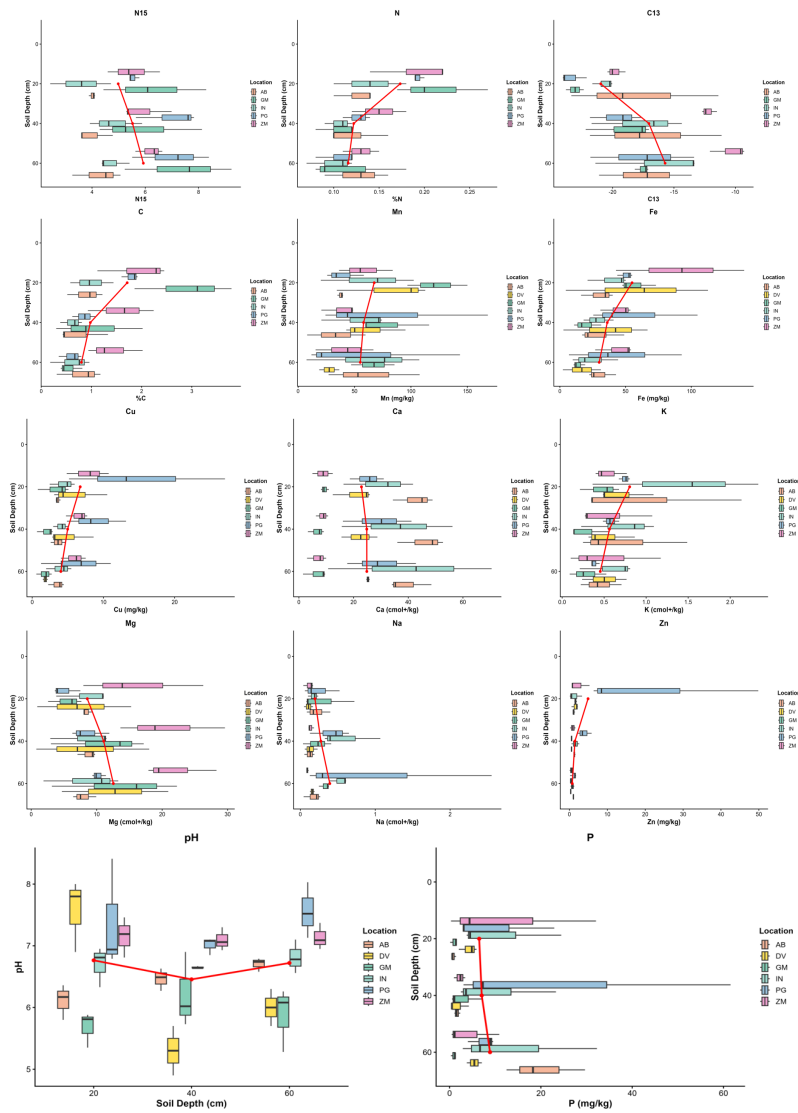


Figure S-4: Boxplot of individual soil parameters measured as a function of location and depth.