

Soil acidification and nutrient imbalance under intensive black pepper plantations in the Central Highlands of Vietnam

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Abstract. Long NV, Do N, Anh NTV, Hanh DTN, Cuong VC, Ngoc NQ, Van NTC. 2025. Soil acidification and nutrient imbalance under intensive black pepper plantations in the Central Highlands of Vietnam. *Asian J Agric* 9: 906-916. Black pepper, Vietnam's most valuable spice crop, is concentrated in the Central Highlands, where it plays a significant role in global supply, yet its long-term productivity is increasingly constrained by soil degradation. However, production is increasingly threatened by soil degradation and rising disease pressure. To evaluate substantial constraints, the soil fertility in 150 intensive black pepper plantations across Dak Lak, Dak Nong, and Gia Lai was assessed based on key physicochemical properties. Results revealed three critical constraints: (i) strong to very strong soil acidification (pH 3.55-6.40), (ii) low Cation Exchange Capacity (CEC 2.50-14.50 Cmolc kg⁻¹), and (iii) pronounced nutrient imbalances. Excessive phosphorus occurred in 82% of samples, while potassium deficiency affected up to 57.6% of plantations, with calcium and magnesium ratios varying substantially among provinces. Organic matter levels were generally adequate but unevenly distributed. Correlation and principal component analyses highlighted soil pH and organic matter as the primary regulators of nutrient availability. Notably, Dak Lak exhibited the strongest acidity and lowest CEC, Dak Nong showed more balanced fertility with higher CEC, and Gia Lai displayed higher nutrient levels but greater variability among farms. These constraints collectively reduce nutrient efficiency, weaken crop resilience, and intensify vulnerability to soilborne diseases. Practical interventions should therefore prioritize correcting acidity, enhancing buffering capacity, and managing nutrients in a balanced manner to sustain productivity and safeguard soil health. The findings provide an essential evidence base for soil restoration and sustainable intensification of black pepper cultivation in Vietnam's Central Highlands.

Keywords: Black pepper, nutrient imbalance, soil acidification, sustainable cultivation, Vietnam

INTRODUCTION

Black pepper (*Piper nigrum* L.) is one of Vietnam's most valuable crops. The country is the world's leading exporter, cultivating around 120,000 hectares (ha) and supplying nearly 58% of global demand (IPC 2022; DCP 2024). The Central Highlands provinces of Dak Lak, Dak Nong, and Gia Lai account for 73,000 ha, representing over 60% of the national area (DCP 2024). Favorable agroecological conditions, including a tropical monsoon climate, moderate elevation, and fertile basaltic soils, combined with intensive management, support vigorous vine growth and high productivity (Byrareddy et al. 2019; Dinh et al. 2022). Over the past decade, national yields averaged 2.5 tons per hectare per year, while the Central Highlands consistently exceeded 3.0 tons per hectare per year, the highest globally (DCP 2024).

Soil health is fundamental to sustaining crop productivity, as it regulates nutrient cycling, supports beneficial microbial communities, and enhances plant defense against pests and diseases. Key chemical indicators of soil fertility include optimal pH, sufficient Cation Exchange Capacity (CEC), and balanced levels of organic matter (OM), macronutrients (N, P, K), and secondary nutrients (Ca, Mg) (Lehmann et al. 2020). Healthy soils not

only supply nutrients efficiently but also buffer against acidification, maintain structural stability, and suppress soilborne pathogens (Lehmann et al. 2020; Bhaduri et al. 2022). However, in perennial spice systems such as black pepper, decades of intensive cultivation, continuous monocropping, and heavy reliance on agrochemicals have progressively degraded soil health (Dung et al. 2019; Dommanige et al. 2020; Varghese and Ray 2024).

Soil acidification is the most severe challenge in black pepper-growing regions globally. Intensive nitrogen fertilization, limited liming, and continuous monocropping accelerate acidification, causing soil pH to decline by 1-2 units within several years of cultivation (Li et al. 2016; Dung et al. 2019; Babu et al. 2024). Studies from Vietnam, India, China, Indonesia, and Sri Lanka consistently reported black pepper soils well below the optimum pH range (5.5-6.5) (Zu et al. 2014; Dung et al. 2019), with average values typically between 3.6 and 5.0 (Xiong et al. 2015; Gontijo et al. 2016; Dung et al. 2019; Dommanige et al. 2020; Hartono et al. 2020). This acidification depletes base cations (Ca, Mg, K), increases toxic Al and Mn concentrations, suppresses beneficial microbial communities, and weakens root resistance conditions that predispose black pepper to soilborne pathogens (Obieze et al. 2023; Deng et al. 2024). Collectively, these changes

create a feedback loop of declining fertility, weakened plant resilience, and heightened disease vulnerability in long-term monoculture black pepper systems.

Nutrient imbalances, alongside acidification, play a critical role in black pepper decline (Hartono et al. 2020; Lekberg et al. 2021; Varghese and Ray 2024). Excess nitrogen promotes pathogen growth and weakens plant defenses (Lekberg et al. 2021; Martinez et al. 2021). Surplus phosphorus disrupts nutrient cycling, and excessive potassium destabilizes Ca-Mg balance, favoring pathogens such as *Phytophthora* and *Fusarium* and plant parasitic nematodes (Rashmi et al. 2014; Datnoff and Elmer 2016). By contrast, sufficient K strengthens cell walls and defense responses (Ortel et al. 2024). Long-term monocropping and fertilizer misuse further degrade soil health, reduce beneficial microbes, and intensify pathogen buildup (Hoang et al. 2021; Van et al. 2025a). Consequently, around 10,000 ha of black pepper in Vietnam were devastated (Trang et al. 2019), contributing to a 23.9% decline in national production (DCP 2021; VPA 2022).

Despite increasing documentation of acidification, nutrient imbalance, and disease intensification in black pepper systems, existing studies in Vietnam remain fragmented, often limited to small geographic areas, single nutrients, or narrow sets of soil indicators. Critically, there is a lack of systematic spatial evaluation of soil fertility in Vietnam's black pepper sector, hindering a clear understanding of how soil degradation patterns vary across key producing provinces. This gap limits the development of site-specific nutrient management and soil restoration

strategies. To address these gaps, the objectives of the study are to (i) quantify soil pH, CEC, and key nutrients (N, P, K, Ca, Mg, and organic matter) across 150 plantations; (ii) analyze interactions among soil parameters to identify drivers of fertility; and (iii) compare provincial differences using multivariate analysis. By identifying soil health constraints and their spatial distribution, this study provides a basis for site-specific management strategies to restore fertility, improve nutrient-use efficiency, and enhance the resilience of Vietnam's black pepper industry. This study tests the hypothesis that long-term intensive black pepper cultivation has produced measurable declines in soil pH and cation exchange capacity, alongside pronounced nutrient imbalances, and that these shifts collectively represent the primary drivers of spatial variation in soil fertility and disease susceptibility in Vietnam's Central Highlands.

MATERIALS AND METHODS

Description of survey sites

Multiple field surveys and laboratory analyses were conducted to evaluate soil properties on black pepper farms in Vietnam's Central Highlands. Sampling was conducted in the main black pepper-growing areas of the three largest producing provinces: Dak Doa (Gia Lai), CuKuin, Krong Nang, and Buon Ho (Dak Lak), and Dak Song (Dak Nong) (Figure 1).

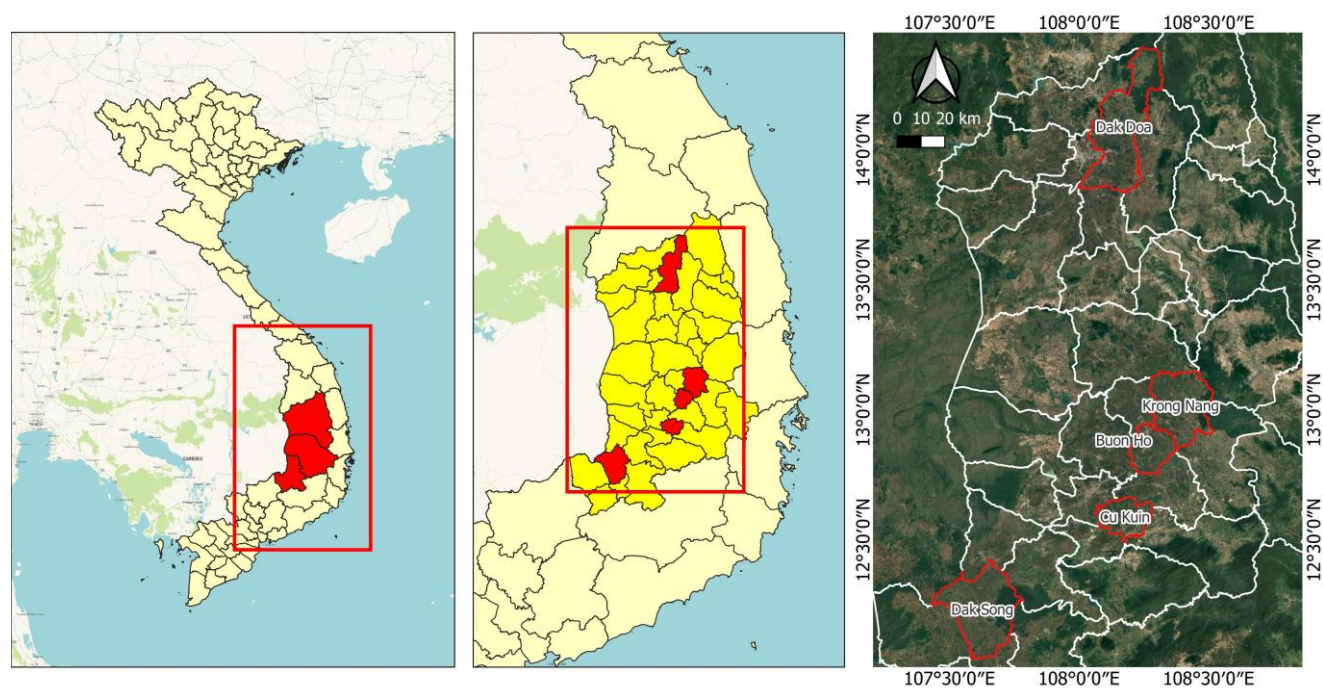


Figure 1. Multiple province surveys of black pepper plantations in Vietnam's Central Highlands (Gia Lai, Dak Lak, Dak Nong). Red dots represent farm GPS locations where soil samples were collected. All spatial data were processed under the WGS 1984 geographic coordinate system. The maps were generated in QGIS version 3.28 (Quantum GIS) using the geographic coordinates of each farm site

A total of 150 productive farms (25 in Gia Lai, 59 in Dak Lak, and 66 in Dak Nong) were planted on two main soil types (Rhodic Ferralsols and Acrisols). Productive farms (10-20% visible disease incidence) were selected to represent functional, high-yielding plantations typical of regional management conditions. Infestation levels were visually assessed, with affected vines showing interveinal chlorosis, smaller leaves, premature leaf drop, and canopy thinning, often accompanied by stunted growth and a gradual decline. Root examination revealed infections caused by gall-inducing nematodes (Thao et al. 2024; Phung et al. 2025). Black pepper plantations were grown using conventional farming practices.

The topography of the farms surveyed is flat to slightly sloped, at 600 and 700 m above sea level. Plant ages span from 5 to 20 years, and farm sizes range from 0.5 to 1.0 hectares. Farms were distributed over distances of 3-10 km within the region and around 200 km between provinces, minimizing spatial dependence among samples. The dominant cultivar was Vinh Linh, grown in monoculture systems at a density of roughly 1,300 to 1,600 vines per hectare. The region has a tropical monsoon climate, characterized by two distinct seasons: a rainy season from May to October and a dry season from November to April. The five-year average temperature is about 23°C (22.6-23°C), with humidity at 81.5% (81.1-82.2%), and annual precipitation totaling 2,200 mm (2,062-2,425 mm) (GSO 2023).

Soil sampling

Soil samples were collected during the rainy season (July-September 2023) when field access and soil sampling were feasible. On each farm, five representative vines were selected along a zigzag transect (Figure 2.A). At each vine

(Figure 2.B), composite soil samples were taken from four directions at a depth of 0-30cm, approximately 80 cm from the trunk, after removing the surface layer. This depth corresponds to the primary nutrient-absorption and fine-root zone in black pepper, accounting for more than 70% of active roots. The subsamples were thoroughly mixed to create a composite sample (1 kg), which was stored in ziplock bags, kept in cool conditions, and transported to the laboratory as quickly as possible. Composite sampling across five vines provides a farm-level mean, minimizing microsite heterogeneity and measurement error (WASI 2024).

For soil pH profiling, an additional set of samples was collected from 100 farms (50 in Dak Lak and 50 in Dak Nong) among the 150 farms surveyed. The two-distance pH sampling (30 and 80 cm from the trunk) was conducted to detect nutrient-driven basin gradients created by fertilizer placement and water flow patterns. On each farm, soil samples were collected near the trunk (30 cm) and in the outer rooting zone (80 cm) using the same procedure (Figure 2.B). These paired samples were analyzed solely for soil pH.

Soil property analysis

Soil properties were analyzed using national standard procedures. Soil pH was measured in a 1:2.5 soil-to-water suspension, and Organic Matter (OM) was determined by the Walkley and Black method (1934). Total nitrogen (N) and available phosphorus (P) were analyzed using the Kjeldahl method (Cung 1998). Exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were determined following Chapman (1965), and Cation Exchange Capacity (CEC) was measured by the ammonium acetate method (Cung 1998).

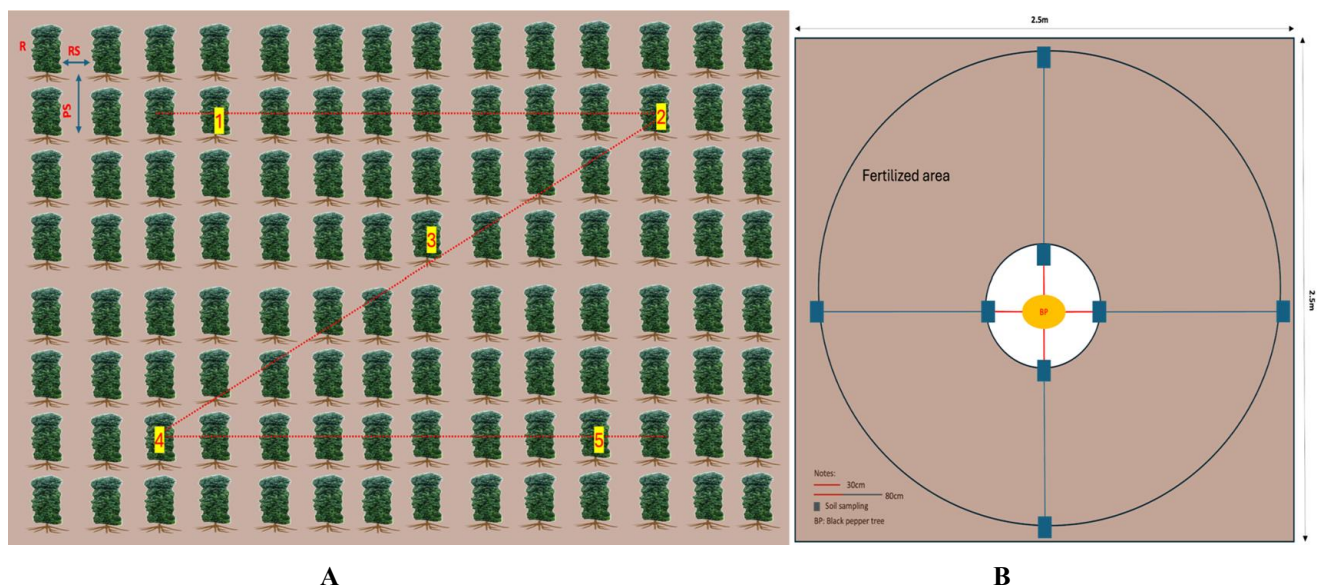


Figure 2. Sampling scheme in an intensive black pepper plantation. A. Field layout with five sampled plants. B. Soil subsamples were collected around each plant at 30 cm and 80 cm from the trunk. Note: S: Planting row, RS: Row Spacing (2.5 m), PS: Plant Spacing (2.5 m)

Data analysis

All statistical analyses were conducted using Microsoft Excel and RStudio (RStudio Team 2024). Differences in soil properties among provinces were evaluated with one-way Analysis of Variance (ANOVA) using the stats package. When significant effects were found, Tukey's Honest Significant Difference (HSD) test was used to identify pairwise differences at a 95% confidence level. Advanced multiple comparisons and compact letter displays were employed using the multcompView, emmeans, and agricolae packages. Soil pH values between sampling locations relative to the trunk of black pepper were compared using a paired t-test and Tukey's HSD test to detect within-farm acidity gradients. Raw values were transformed using the natural logarithm [ln(x)] before analysis to achieve normality and uniform variance across variables.

Pearson correlation analysis was performed to assess linear relationships among soil physicochemical parameters, with statistical significance consistently set at the 5% level. Correlation structures were visualized with a heatmap generated by the ggcorrplot package in RStudio, where color gradients showed the strength and direction of positive and negative associations.

Additionally, to explore broader fertility patterns, Principal Component Analysis (PCA) was performed with the FactoMineR package and visualized using factoextra. The first three principal components were extracted, capturing the majority of variance in soil properties. Provincial grouping served as a spatial stratifier representing aggregated management and soil conditions rather than a causal factor. Provincial groupings were plotted with 95% confidence ellipses to highlight similarities and differences among fertility profiles. Supporting packages (cluster, ggpubr, patchwork, and ggplotify) were used to refine clustering, add statistical annotations, and generate composite multi-panel figures suitable for publication.

RESULTS AND DISCUSSION

Soil pH and black pepper cultivation

The soil physicochemical properties of productive black pepper varied significantly among provinces, ranging from

3.55 to 6.40 (Table 1). Dak Lak had the lowest average (4.59), while Dak Nong (5.31) and Gia Lai (5.09) recorded higher, statistically different values. The significant variation in soil pH observed in this study could be due to differences in crop age, soil type, slope, agronomic practices, and climatic conditions (Gontijo et al. 2016). In addition, soil pH distribution varied widely across provinces (

Figure 3). Strongly acidic soils (pH 4.5-5.5) were dominant across all regions, accounting for 49.2% in Dak Lak, 57.6% in Dak Nong, and 56.0% in Gia Lai. Soils near the optimal pH (5.5-6.5) were more common in Dak Nong (34.8%) and Gia Lai (32.0%) than in Dak Lak (5.1%). Conversely, very strongly acidic soils (pH 4.0-4.5) were most prevalent in Dak Lak (37.3%), compared to Dak Nong (7.6%) and Gia Lai (12.0%). Extremely acidic soils (pH 3.5-4.0) were found only in Dak Lak (8.5%). Overall, the Central Highlands are dominated by strongly acidic soils, with Dak Lak being the most limited by soil acidity.

This pattern matches previous reports from black pepper farms in Vietnam (Dung et al. 2019) and other black pepper-growing regions (Xiong et al. 2015; Abd-Hamid et al. 2023; Varghese and Ray 2024). For instance, strongly acidic soils were found on black pepper farms in Sri Lanka, Brazil, Indonesia, and China (Xiong et al. 2015; Gontijo et al. 2016; Dommanige et al. 2020; Hartono et al. 2020). Furthermore, evidence from India, Vietnam, and China shows that long-term monoculture reduces soil pH by 0.46-0.6 units when comparing older to newer plantations (Xiong et al. 2015; Dung et al. 2019; Babu et al. 2024). Although basalt-derived soils are naturally acidic (Hong 2017; Tien et al. 2020), decades of intensive ammonium- and urea-based fertilization, limited liming, and scarce organic inputs have accelerated acidification and decreased buffering capacity (Xiong et al. 2015; Varghese and Ray 2024). The current study found that 65-95% of soils fell below the ideal range of 5.5-6.5 for black pepper (Zu et al. 2014; Dung et al. 2019), which is consistent with reports in India where 65% soil is strongly acidic (Varghese and Ray 2024), emphasizing the need for pH correction to sustain productivity.

Table 1. Soil physicochemical properties of black pepper plantations in Gia Lai, Dak Lak, and Dak Nong, Vietnam

Provinces (n)	pH _{H2O}	CEC (Cmol _c kg ⁻¹)	OM (%)	N (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)
Gia Lai (n=25)	5.09a (4.15-6.14)	7.14a (4.20-11.60)	6.12a (4.72-7.32)	0.23a (0.17-0.30)	261a (13.2-1,149)	164a (32.3-448)	978a (261-2,506)	108b (17.6-471)
Dak Lak (n=59)	4.59b (3.55-5.85)	5.52b (2.50-8.80)	4.22b (2.06-6.78)	0.18b (0.10-0.27)	193ab (29.0-1,478)	119b (52-255)	427b (140-1,879)	118b (13.8-306)
Dak Nong (n=66)	5.31a (4.22-6.40)	8.15a (5.20-14.50)	5.66a (3.41-7.35)	0.23a (0.15-0.29)	109b (51.0-184)	170a (124-261)	365b (160-700)	161a (72-336)

Note: For each variable, mean values followed by the different letters in the same column are significantly different at $\alpha=0.05$ according to Tukey's HSD test. The lowest to highest values were in brackets

Soil pH is a key indicator of soil health, influencing nutrient availability, microbial diversity, and crop performance (Deng et al. 2024). Indeed, acidification constrains crop growth by increasing the solubility of toxic Al^{3+} and Mn^{2+} while reducing nutrient availability (Tian and Niu 2015; Zhang et al. 2022). Moreover, low pH accelerates base cation leaching, weakens buffering capacity, and drives nutrient imbalances (Neina 2019). For instance, P availability declines to 30% below pH 6, while N and K decrease by 30-50% at pH 5.5-5.0 compared with neutral soils (Zimdahl 2015). In addition to altering soil chemistry, soil acidification severely disrupts soil biology, reducing microbial diversity, enzymatic activity, and nutrient cycling, while suppressing beneficial microbes and weakening plant defenses (Xiong et al. 2015; Obieze et al. 2023; Deng et al. 2024). Acid stress further damages roots and favors pathogen proliferation. Beneficial bacteria are susceptible to pH shifts, making acidic soils hotspots for disease (Deng et al. 2024).

Additionally, soil pH is strongly shaped by management practices, as reflected in its spatial variation around black pepper plants (

Figure 4). Samples collected closer to the tree trunk (30 cm) had a significantly higher average pH (6.05), whereas those farther away (80 cm) were more acidic (5.33). Fertilizer histories varied substantially across farms and were not fully quantifiable, potentially confounding the interpretation of spatial patterns in soil pH and nutrient availability. Nevertheless, this gradient likely arises from fertilizer placement, since most fertilizers are applied within the 50-100 cm root zone around the plant inside the basin. In these outer zones, repeated mineral fertilizer applications, especially nitrogen, stimulate nitrification and leaching processes that release protons (H^+), thereby

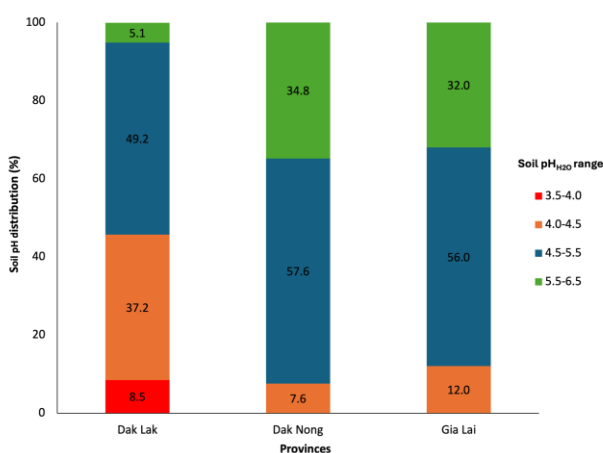


Figure 3. Soil pH classes distribution in black pepper plantations of Dak Lak, Dak Nong, and Gia Lai Provinces, Vietnam. The stacked bars represent the percentage of soils within each pH range

lowering soil pH (Zhang et al. 2022; Van et al. 2025a). Conversely, soil near the trunk receives fewer inputs and remains relatively less acidic. This uneven acidification has substantial agronomic impacts. The outer root zone, where nutrient uptake is most active, is also the most vulnerable to acidity and pathogen pressure, which helps explain why disease symptoms commonly emerge first on the peripheral roots. To address this, corrective soil-amelioration practices such as uniformly incorporating lime, dolomite, biochar, or organic matter across the fertilized zone are therefore essential (Thanh et al. 2020). These practices help neutralize acidity, improve nutrient use efficiency, and foster an environment less favorable to soilborne pathogens.

Cation Exchange Capacity (CEC) and black pepper cultivation

Cation exchange capacity values were significantly varied (2.50-14.50 $Cmol_c kg^{-1}$), with Dak Nong having the highest average (8.15) and Dak Lak the lowest (5.52) (Table 1). Approximately 70% of soils had CEC below 8 $Cmol_c kg^{-1}$, including 95% of samples in Dak Lak, 53% in Dak Nong, and 60% in Gia Lai (

Table 2). These findings confirm that nutrient buffering limitations remain a persistent constraint. The trend observed in this study is consistent with previous reports, where CEC values in black pepper farms ranged from 5.5-8.2 $Cmol_c kg^{-1}$ in Sri Lanka (Dommanige et al. 2020), 8.06 $Cmol_c kg^{-1}$ in Indonesia (Hartono et al. 2020), and 4.52-6.33 $Cmol_c kg^{-1}$ in Brazil (Ferde et al. 2021). For sustainable perennial cropping in this region, the optimal CEC range is generally considered to be 8-16 $Cmol_c kg^{-1}$ (WASI 2024).

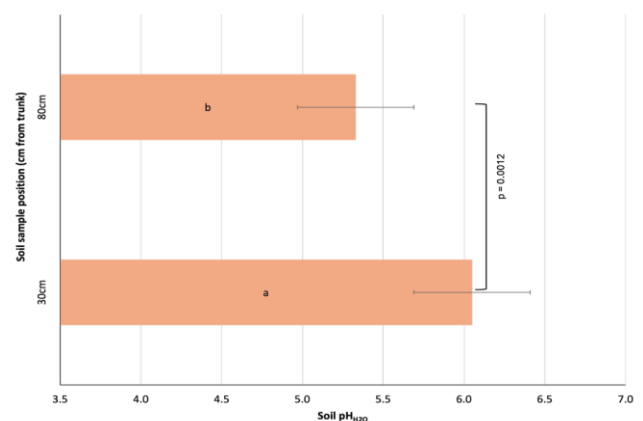


Figure 4. Soil pH at 30 cm and 80 cm from black pepper tree trunks across 100 farms. Bars represent mean values, and error bars indicate the standard error of the mean. Different letters (a, b) denote significant differences (Tukey's HSD test, $p < 0.05$)

Table 2. Soil pH, Cation Exchange Capacity (CEC), Organic Matter (OM), available potassium (K), and available phosphorus (P) classes and the percentage of samples in each category across Dak Lak, Dak Nong, and Gia Lai, Vietnam. Value classes are defined according to the Varghese and Ray (2024) and WASI (2024) soil quality assessment scale

Factors	Value class	Dak Lak (%)	Dak Nong (%)	Gia Lai (%)
Soil pH _{H2O}	3.5-4.0 (Extremely acidic)	8.5	0.0	0.0
	4.0-4.5 (Very strongly acidic)	37.3	7.6	12.0
	4.5-5.5 (Strongly acidic)	49.2	57.6	56.0
	5.5-6.5 (Moderated acidic)	5.1	34.8	32.0
CEC (Cmolc kg ⁻¹)	<8 (Poor)	94.9	53.0	60.0
	8-16 (Medium)	5.1	47.0	40.0
	>16 (Good)	0.0	0.0	0.0
OM (%)	<2.5 (Poor)	16.9	0.0	0.0
	2.50-3.50 (Medium)	25.4	1.5	0.0
	>3.50 (Good)	57.6	98.5	100.0
N (%)	<0.12 (Poor)	11.9	27.3	8.3
	0.12-0.20 (Medium)	49.2	72.7	91.7
	>0.20 (Good)	39.0	0.0	0.0
K (mg kg ⁻¹)	<12.00 (Poor)	57.6	0.0	48.0
	12.00-25 (Medium)	40.7	97.0	40.0
	>25 (Good)	1.7	3.0	12.0
P (mg kg ⁻¹)	<12 (Poor)	1.7	0.0	8.0
	12-96 (Medium)	30.5	6.1	8.0
	> 96 (Good)	67.8	93.9	84.0

The low CEC could be a consequence of high rainfall and over-irrigation practices in the Central Highlands (GSO 2023; Nguyen et al. 2023). Seriously, long-term monocropping and intensive fertilizer use further deplete CEC, often in tandem with declines in soil pH (as discussed above) and organic matter (Van et al. 2025b). These coupled processes quickly accelerate nutrient leaching, reduce soil buffering capacity, and increase crop susceptibility to soilborne pathogens, thereby threatening the long-term viability of black pepper farming systems. In response, farmers often compensate by applying higher fertilizer rates, which aggravates acidification, induces nutrient imbalances, and heightens environmental risks. Therefore, strategies to enhance CEC, such as incorporating organic amendments, recycling crop residues, and applying lime or dolomite, are critical for restoring soil fertility, improving nutrient-use efficiency, and sustaining black pepper production in the Central Highlands.

Organic Matter (OM) and black pepper cultivation

The data in Table 1 indicate that OM content varied significantly, ranging from 2.06% to 7.35%. Generally, these data fall within the recommended range for black pepper cultivation, although depletion was evident in some plantations, with 17% of samples in Dak Lak below 2.5% (WASI 2024). This observation is consistent with soil surveys in India, Sri Lanka, Indonesia, and Malaysia, which also reported relatively rich OM in pepper-growing regions (Dommanige et al. 2020; Hartono et al. 2020; Abd-Hamid et al. 2023; Varghese and Ray 2024). Furthermore, provincial differences were pronounced: mean OM levels were significantly higher in Gia Lai (6.12%) and Dak Nong (5.66%) than in Dak Lak (4.22%) (Table 1). Despite the favorable OM status, many soils exhibited low Cation

Exchange Capacity (CEC). This suggests that mineralogical constraints, particularly the dominance of low-activity clays, limit nutrient retention and buffering capacity. Thus, high OM inputs alone cannot fully compensate for weak soil chemical resilience.

Functionally, OM plays a pivotal role in nutrient cycling, soil structure, and natural disease suppression. It improves nutrient availability and supports beneficial microbial antagonists that inhibit soilborne pathogens (Bonanomi et al. 2018). Nevertheless, in soils with low buffering capacity, nutrients remain vulnerable to leaching, and acidification can continue despite OM additions. Therefore, integrated soil amendments such as lime, dolomite, or biochar are essential to complement OM inputs. These practices enhance CEC, stabilize soil pH, improve fertilizer-use efficiency, and strengthen root defenses, ultimately promoting black pepper productivity and resilience against soilborne pests and diseases (Priyadarshini et al. 2025).

Total nitrogen (%N) and black pepper cultivation

Total N content was widely variable across provinces (0.10-0.30%). Average soil N concentrations differed significantly among provinces (Table 1), with values in Dak Nong and Gia Lai (0.23%), compared to Dak Lak (0.18%). Overall, 84% of soils exceeded the sufficiency threshold of 0.12%, while 16% were deficient, with the highest deficiency rate in Dak Nong (27.3%) (WASI 2024). Reports on N dynamics in pepper cultivation are inconsistent, with both accumulation (Xiong et al. 2015) and depletion (Nguyen et al. 2022; Varghese and Ray 2024) documented under different production systems. While nitrogen deficiency was reported in conventional black pepper farms in Indonesia and Sri Lanka (Dommanige et al. 2020; Hartono et al. 2020), our study

found that most plantations maintained adequate nitrogen levels. This likely reflects intensive and frequent application of N-based fertilizers (Rigal et al. 2023; Van et al. 2025b), though localized deficiencies persist. Nitrogen is a critical nutrient in black pepper, serving as the principal component of chlorophyll and a key determinant of berry set and yield (Abd-Hamid et al. 2023). Both N deficiency and excess pose risks. Insufficient N reduces root vigor, photosynthetic capacity, and berry yield, whereas excessive N promotes succulent tissue growth, increases susceptibility to soilborne fungi and nematodes, and destabilizes nutrient balance (Obieze et al. 2023). Consequently, balanced N management is essential. Soil- and leaf-based diagnostics, coupled with moderate fertilization rates and organic amendments, can minimize both deficiency and excess, thereby sustaining productivity, preserving root health, and enhancing resilience against soilborne pathogens.

Phosphorus availability (P) and black pepper cultivation

This study revealed that available P levels varied widely across plantations, ranging from 13.2 to 1,478 mg kg⁻¹, with significant differences among provinces ($p < 0.05$). Such high variability likely reflects differences in fertilizer applications and localized soil accumulation, which may influence P uptake and growth in black pepper. Extreme values suggest uneven availability, potentially limiting root development and fruit set in phosphorus-deficient zones. Mean value was the highest in Gia Lai (261 mg kg⁻¹), followed by Dak Lak (193 mg kg⁻¹), and Dak Nong (109 mg kg⁻¹). Overall, 82% of soils exceeded the sufficiency threshold (12-96 mg kg⁻¹), in line with previous reports (Varghese and Ray 2024; WASI 2024). High P values were confirmed by quality control and are typical of long-term P accumulation under intensive fertilization. In contrast, P deficiency in black pepper farms has been reported by many studies in Sri Lanka and Indonesia (Dommanige et al. 2020; Hartono et al. 2020). The high soil P in our study likely reflects prolonged use of P-rich fertilizers in some fields (Rigal et al. 2023; Varghese and Ray 2024), whereas lower P concentrations may result from reduced application rates and the inherently slow release of P from rock phosphates (Dommanige et al. 2020). While adequate P supports root growth and metabolic processes, excessive accumulation can disrupt soil microbial communities, suppress arbuscular mycorrhizal colonization, and exacerbate nutrient imbalances. Conversely, P deficiency impairs root development and reduces plant resilience to stress (Shen et al. 2011). These findings underscore the importance of soil test-based P management to avoid overapplication, which is critical for preserving beneficial microbial associations, maintaining balanced nutrient cycling, and minimizing conditions that predispose black pepper to soilborne diseases.

Exchangeable potassium (K) and black pepper cultivation

Exchangeable K concentration in the study ranged from 32.3 to 448 mg kg⁻¹ (Table 1). K is critical for water

regulation, enzyme activation, carbohydrate partitioning, and cell wall reinforcement; suboptimal levels can reduce stress tolerance and compromise disease resistance in black pepper. Average levels were significantly higher in Dak Nong (170 mg kg⁻¹) and Gia Lai (164 mg kg⁻¹) compared with Dak Lak (119 mg kg⁻¹). Nevertheless, 57.6% of soils in Dak Lak and 48.0% in Gia Lai were below the sufficiency threshold of 120 mg kg⁻¹ (Table 2). This finding is consistent with observations in Indian black pepper systems (Varghese and Ray 2024), but inconsistent with reports in Sri Lanka (Dommanige et al. 2020). The inconsistency could result from differences in soil mineralogy, fertilizer practices, and agroecological conditions. Potassium plays central roles in carbohydrate partitioning, enzyme activation, osmotic regulation, and reinforcement of cell walls. Consequently, K deficiency can impair fruit set, reduce yield potential, and compromise resistance to soilborne pathogens (Ortel et al. 2024). Conversely, excessive K application may antagonize Ca and Mg uptake, destabilize membrane function, and predispose roots to waterborne pathogens (Datnoff and Elmer 2016). These findings underscore the need for site-specific K management, including addressing deficiencies in Dak Lak and Gia Lai, but over-application should be avoided to maintain cation balance. Soil test-based K fertilization is essential for maintaining productivity, enhancing host defenses against soilborne diseases, and ensuring balanced nutrient uptake.

Exchangeable Calcium (Ca) and magnesium (Mg), and black pepper cultivation

The survey revealed that both Ca and Mg were generally present at adequate levels but varied significantly across provinces (Table 1). Gia Lai soils contained the highest Ca concentrations (978 mg kg⁻¹), whereas Dak Nong soils exhibited the greatest Mg levels (161 mg kg⁻¹). The results align with the previous report in Sri Lanka as 218-231 mg Ca kg⁻¹ and 232-236 mg Mg kg⁻¹ (Dommanige et al. 2020). Despite overall sufficiency, there are provincial differences indicating nutrient imbalance, as Gia Lai soils are characterized by Ca enrichment, while Dak Nong soils are disproportionately Mg-rich.

Deficient or imbalanced Ca and Mg can impair cell wall integrity and chlorophyll production, affecting overall plant vigor. Calcium is essential for cell wall stabilization, root elongation, and defense signaling. Insufficient Ca can weaken cell walls, increase susceptibility to pathogenic fungi and nematode infection, and impair root function (Wang and Luan 2024). In contrast, excess Ca may restrict Mg and K uptake, leading to nutrient imbalances and reduced photosynthetic efficiency. Magnesium, as the central atom of chlorophyll, is critical for photosynthesis and energy metabolism. The deficiency commonly causes interveinal chlorosis, reduced carbohydrate transport, and stunted growth. However, excess Mg can antagonize Ca uptake, compromising structural integrity and reducing resistance to root rot (de Bang et al. 2021). These interactions highlight that nutrient ratios, particularly Ca:Mg:K, are more necessary than absolute nutrient concentrations. Regular monitoring of these ratios, coupled

with targeted corrective adjustments, is essential for maintaining soil fertility, supporting healthy root function, and enhancing disease resilience in black pepper cultivation systems.

Soil nutrient imbalances, including deficiencies or disproportionate levels of P, K, Ca, and Mg, can impair root development, weaken plant defenses, and increase susceptibility to black pepper diseases such as root rot, Phytophthora blight, and nematode infestations (de Bang et al. 2021; Wang and Luan 2024). Beneficial soil microbes are sensitive to pH and nutrient shifts, making acidic or imbalanced soils hotspots for disease (Deng et al. 2024). In the Central Highlands, strongly acidic soils under black pepper support 3-5 times higher populations of pathogenic fungi, oomycetes, and nematodes compared to background levels (Dung et al. 2019), consistent with our observation that disease symptoms were present in all surveyed plantations. These findings underscore the importance of site-specific soil fertility management, including balanced nutrient applications and pH correction, to maintain plant health, optimize nutrient uptake, and reduce vulnerability to soilborne pathogens.

Correlation among soil properties

Pearson correlation analysis revealed clear interactions among soil physicochemical properties in productive black pepper plantations in the Central Highlands (Figure 5). Soil pH is significantly and positively associated with total N, OM, CEC, and exchangeable cations (K, Ca, and Mg) ($r = 0.21-0.52$), but is negatively related to available P ($r = -0.18$, $p < 0.05$). Organic matter (OM) strongly correlates positively with K, P, and CEC ($r = 0.31-0.50$, $p < 0.001$), and with Ca ($r = 0.20$, $p < 0.05$). CEC shows a positive correlation with K ($r = 0.45$, $p < 0.001$). Total N is significantly linked with K ($r = 0.47$), Ca ($r = 0.18$), P ($r = 0.28$), CEC ($r = 0.53$), and notably OM ($r = 0.91$, all $p < 0.001$). Available P has positive relationships with K ($r = 0.21$, $p < 0.05$) and Ca ($r = 0.39$, $p < 0.001$), while K is strongly associated with Ca ($r = 0.44$) and Mg ($r = 0.39$, $p < 0.001$). Collectively, these interactions emphasize the central role of OM in enhancing CEC and nutrient availability, while also highlighting the regulatory function of soil pH in modulating cation accumulation and nutrient retention. From a management perspective, strategies should prioritize building OM to improve nutrient-holding capacity and correcting soil acidity to optimize cation balance. Integrated approaches that simultaneously enhance OM and stabilize soil pH are critical for sustaining fertility and resilience in black pepper systems (Van et al. 2025b).

Principal component analysis of soil fertility

Principal Component Analysis (PCA) revealed apparent spatial differences in soil fertility among black pepper plantations in Dak Lak, Dak Nong, and Gia Lai Provinces (Figure 6). The first three principal components accounted for most of the variation in soil properties, with F1 (39.3%), F2 (22.9%), and F3 (16.8%) together explaining 62.2% (F1-F2) and 56.1% (F1-F3) of the overall variability. Distinct clustering patterns appeared across provinces. Dak Lak soils are primarily distributed on the

negative side of F1 and exhibit greater spread, indicating more constrained and variable fertility conditions. Dak Nong soils clustered near the PCA origin, forming a smaller ellipse, which reflects more uniform fertility across plantations. Conversely, Gia Lai soils were positioned on the positive side of F1 and showed an elongated ellipse, suggesting relatively higher fertility levels but greater heterogeneity among farms. These results highlight evident spatial heterogeneity in soil fertility throughout the Central Highlands. Accordingly, soil fertility management should be tailored to provincial conditions. Dak Lak requires interventions to address severe acidity and low CEC. Dak Nong requires strategies to maintain uniform fertility with targeted adjustments, while Gia Lai advocates for site-specific nutrient balancing to manage variability and leverage higher fertility potential.

Overall, the widespread soil acidity, low CEC, and nutrient imbalances identified across black pepper plantations in Vietnam's Central Highlands highlight urgent challenges for sustaining productivity under intensification. These soil constraints not only reduce nutrient-use efficiency but also heighten vulnerability to soilborne pathogens, threatening the long-term viability of one of Vietnam's major export commodities. From a sustainable intensification standpoint, future management must prioritize strengthening soil buffering capacity, rebuilding organic matter, and rebalancing nutrient inputs. Farm-level interventions, such as integrated soil amendments combined with soil- and leaf-based diagnostics to guide fertilization, are crucial for correcting soil acidity and enhancing nutrient cycling. Diversifying inputs through intercropping, cover crops, and organic manures can further enhance CEC, sustain microbial diversity, and reduce disease pressure (Du et al. 2019; Van et al. 2025a). Collectively, these practices not only improve yields but also build resilience against future climate variability and pest outbreaks.

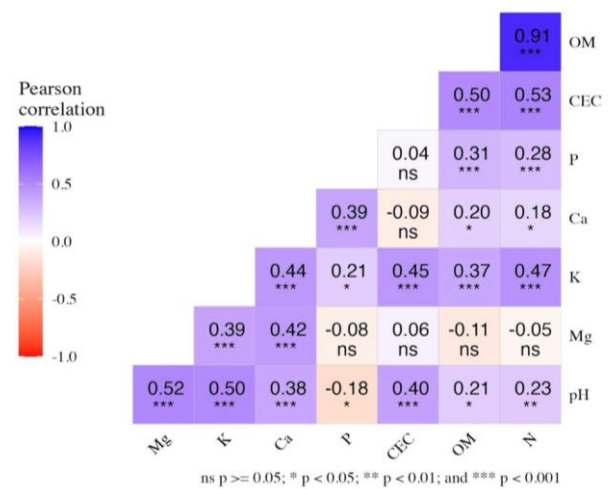


Figure 5. Pearson correlation heatmap showing relationships among soil physicochemical properties in black pepper plantations. Color indicates the direction and strength of correlations. Numbers within cells indicate coefficients; asterisks indicate significance levels. ns indicates not significant

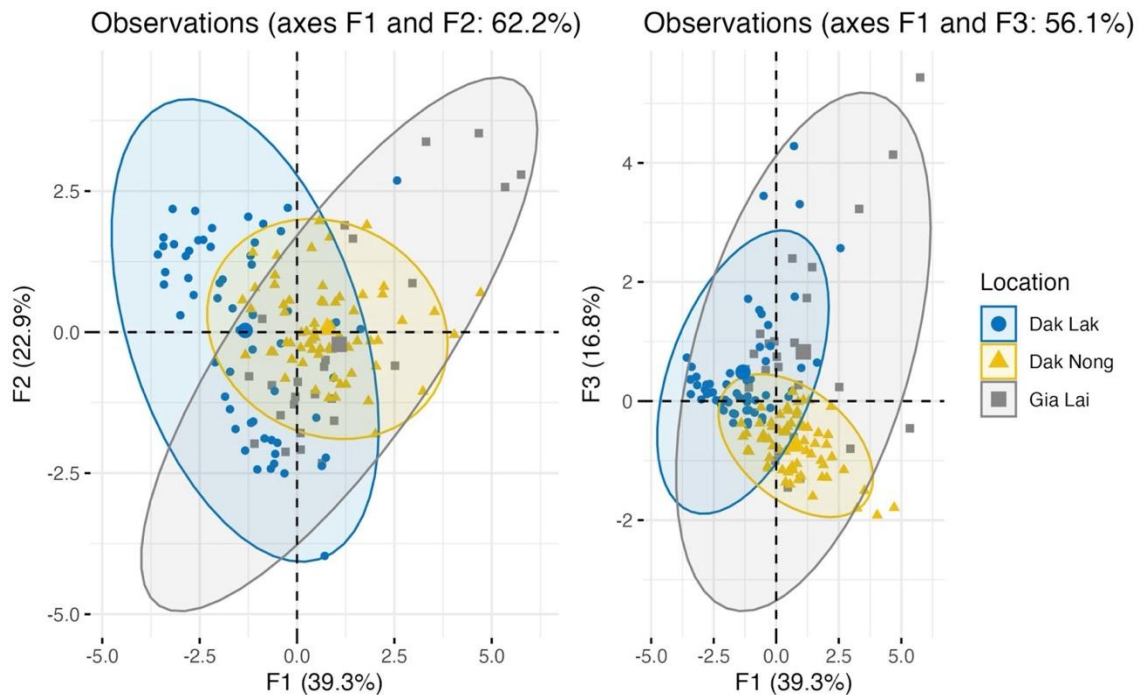


Figure 6. Principal component analysis (PCA) of soil fertility in intensive black pepper plantations: Dak Lak (blue), Dak Nong (yellow), and Gia Lai (gray), Vietnam. Left: Axes F1-F2 (62.2% variance). Right: Axes F1-F3 (56.1% variance). Ellipses indicate 95% confidence intervals by province

Additionally, at the policy level, coordinated interventions are also needed to support farmers in adopting these practices. Subsidies or credit schemes for liming and organic inputs could help overcome short-term economic barriers, while extension services should prioritize training on balanced fertilization and soil health monitoring (Kuppusamy et al. 2016; Han et al. 2023; Van et al. 2025b). National soil testing programs and digital advisory platforms could deliver site-specific nutrient recommendations, prevent over-application of N and P fertilizers, and reduce environmental risks. Incorporating soil health indicators such as pH and CEC into Vietnam's agricultural sustainability frameworks would align farm-level practices with regional land-use planning.

Ultimately, sustainable intensification of black pepper in Vietnam and other producing countries will require a transition from input-heavy approaches toward soil-centered management. Policies that incentivize soil restoration, promote knowledge transfer, and encourage collective action can create enabling conditions for the widespread adoption of sustainable practices. Addressing both the biophysical and socio-economic dimensions of soil fertility is essential for safeguarding black pepper productivity while meeting global sustainability and export standards.

In conclusion, this study identified that soil acidification, low cation exchange capacity, and nutrient imbalances are key constraints to intensive black pepper cultivation in Vietnam's Central Highlands. Strongly acidic soils, together with phosphorus excess, potassium deficiency, and uneven distribution of organic matter,

reduce nutrient-use efficiency and heighten vulnerability to soilborne pathogens. Our results highlighted soil pH and organic matter as pivotal regulators of fertility, disease susceptibility, and long-term productivity. Province-specific interventions are needed, including liming and organic amendments in Dak Lak, balanced nutrient application in Dak Nong, and integrated nutrient management in Gia Lai. More broadly, restoring buffering capacity, correcting acidity, and rebalancing nutrient ratios are critical to sustaining crop performance and reducing pathogen risks. However, the findings are constrained by the cross-sectional sampling design, reliance on visual disease assessment, variability in farm fertilizer histories, and analysis limited to the 0-30 cm soil layer. Future research should combine long-term soil monitoring, pathogen surveillance, field-based evaluations of management practices, deeper soil profiling, and field trials by farmer-participatory integrating liming, organic amendments, and biochar. Building soil resilience through organic amendments, diversified cropping systems, and developing site-specific nutrient decision tools will further support sustainable soil restoration and long-term resilience of black pepper production in the region.

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