

Soil microbial communities and soil quality drive Arabica coffee yield in pine-coffee agroforestry under varying management intensities

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Abstract. Wicaksono KP, Permanasari PN, Saitama A, Widaryanto E, Prayogo C, Adianingsih OR, Murtini ES, Tarno H. 2026. Soil microbial communities and soil quality drive Arabica coffee yield in pine-coffee agroforestry under varying management intensities. *Biodiversitas* 27 (2): d270240. <https://doi.org/10.13057/biodiv/d270240>. Pine-coffee agroforestry systems provide important ecological and economic benefits; however, the effects of management intensity on soil quality, microbial communities, and coffee productivity remain poorly understood. This study evaluated the effects of varying management intensities in a pine-coffee agroforestry system, focusing on soil quality, microbial populations, and coffee productivity and quality. Field observations and laboratory analyses were conducted to assess canopy cover, light intensity, litter accumulation, soil bulk density, particle density, porosity, infiltration rate, total nitrogen, organic carbon, and populations of cellulolytic bacteria, fungi, *Nitrobacter*, and *Nitrosomonas*. Coffee productivity and fruit quality attributes were also evaluated. The results showed that higher management intensities, specifically best management practices (BMP), positively enhanced soil physical and chemical properties, thereby directly improving coffee yield and quality. The result revealed that BMP management effectively reduced soil bulk density and increased porosity and infiltration rates, creating an optimal environment for coffee plant growth. BMP can offer soil media with good physical characteristics and high nutrient content. However, MC management can provide a more favorable ecosystem for the growth of soil microbial populations. The more stable abiotic factors of the ecosystem under non-intensive management can support the development of microorganisms through succession. It was also observed that BMP practices led to larger berry sizes, heavier bean weights, and higher sugar content in coffee beans, which are critical quality indicators. The study demonstrates that management intensity strongly influences the interactions among soil quality, microbial communities, and coffee performance in pine-coffee agroforestry systems. Moderate to intensive management can improve productivity, but balanced practices are required to maintain soil microbial diversity and long-term ecosystem sustainability.

Keywords: Agroforestry, coffee berry, coffee yield, microbial population, soil quality

INTRODUCTION

Agroforestry systems integrating trees and crops are increasingly recognized for their ecological and economic benefits, especially in sustainable agriculture. Pine-coffee agroforestry systems are particularly prevalent in tropical regions, combining shade, biodiversity conservation, and crop production (Fitch et al. 2022). However, the effectiveness of these systems depends heavily on management intensity, which influences key factors such as canopy cover, nutrient cycling, and soil health. Research has shown that variations in management practices can significantly affect both environmental conditions and productivity in agroforestry systems, underscoring the importance of understanding the role of management intensity in optimizing outcomes (Li et al. 2022). Although pine-coffee agroforestry provides important ecological and economic benefits, optimizing its management remains challenging due to complex interactions among biological, environmental, and agronomic factors. Management practices such as pruning, fertilization, and shade regulation strongly influence soil fertility, microbial

communities, coffee productivity, and bean quality (Ahmed et al. 2021; Beule et al. 2022; Nahon et al. 2024; Martinez et al. 2024).

Soil quality is a major determinant of crop health and yield in agroforestry systems. Physical properties such as bulk density, porosity, and infiltration rate affect water availability and root growth, two crucial factors in plant development (Haruna et al. 2020). For instance, high bulk density can hinder root expansion, reduce water infiltration, and subsequently limit plant growth and yield (Sainju et al. 2022). Intensive management practices, such as Best Management Practices (BMP), aim to mitigate these challenges by improving soil structure, thereby fostering a supportive environment for crops. By enhancing these physical properties, intensive management can contribute to long-term soil health and productivity.

In addition to physical soil properties, soil microbial communities play an essential role in agroforestry ecosystems. Microorganisms, such as bacteria and fungi, contribute to nutrient cycling, decomposition of organic matter, and overall soil fertility (Beule et al. 2022;

Singavarapu et al. 2023; Nahon et al. 2024). Beneficial microbes, including cellulolytic bacteria, *Nitrobacter*, and *Nitrosomonas*, assist in nutrient mineralization, making vital nutrients accessible to plants. Studies suggest that management practices with higher organic matter inputs, such as BMP, can enhance microbial activity, thereby improving soil health and supporting plant productivity (Lori et al. 2017). Exploring how microbial populations respond to different management intensities is crucial for developing sustainable agroforestry practices.

Coffee productivity and quality are also impacted by management intensity. Quality attributes, such as berry size, bean weight, and sugar content, are directly influenced by factors like nutrient availability and light exposure (Ahmed et al. 2021; Martinez et al. 2024). For example, increased light from reduced canopy cover can enhance photosynthesis, leading to larger berries with higher sugar content. Intensive management practices that strategically balance light and shade can thus improve both the quantity and quality of coffee yields (Ehrenbergerová et al. 2021). Effective management intensity is therefore essential for optimizing coffee quality, particularly in regions that rely on coffee for economic growth.

Although previous studies have examined the roles of individual factors, such as canopy cover, nutrient inputs, and microbial diversity, in agroforestry, there remains a significant gap in understanding the integrated impacts of these components across different management conditions, especially within the framework of pine-coffee agroforestry. Most existing studies tend to focus on a single variable, for example, focusing only on soil fertility or yield, without simultaneously assessing microbial community dynamics and soil physical properties related to coffee performance. Furthermore, comparative assessments across a gradient of management intensity of simultaneous evaluation of ecological and agronomic indicators have been scarce. This

condition requires empirical support on the relationship between coffee-pine agroforestry management intensity and environmental and agronomic indicators to obtain a suitable model to be developed by farmers. An integrated perspective plays a vital role to maximize the benefits of agroforestry, especially in regions where coffee plays a central economic role.

The objective of this study was to evaluate the effects of varying management intensities in a pine-coffee agroforestry system, focusing on soil quality, microbial populations, and coffee productivity and quality. Specifically, this study investigates whether best management practices (BMP) enhance soil structure, support greater microbial abundance, and improve coffee yield and quality compared to lower-intensity management practices. By addressing these factors, this research seeks to contribute to sustainable agroforestry practices that achieve an optimal balance of environmental health and economic productivity, providing insights for future management strategies.

MATERIALS AND METHODS

Study site

The research was conducted from February to July 2024 in UB Forest, Boro Summersari Hamlet, Tawangargo Village, Karangploso Sub-district, Malang District, Indonesia (Figure 1). The observation area consisted of four different intensification pine-coffee agroforestry system management options (Table 1): LC (Low Coffee Management), MC (Medium Coffee Management), HC (High Coffee Management), and BMP (Best Management Practice). Observed coffee plant samples were 13-year-old Arabica coffee of the variety Lini (S-795) growing under the shade of 27-32-year-old pine trees.

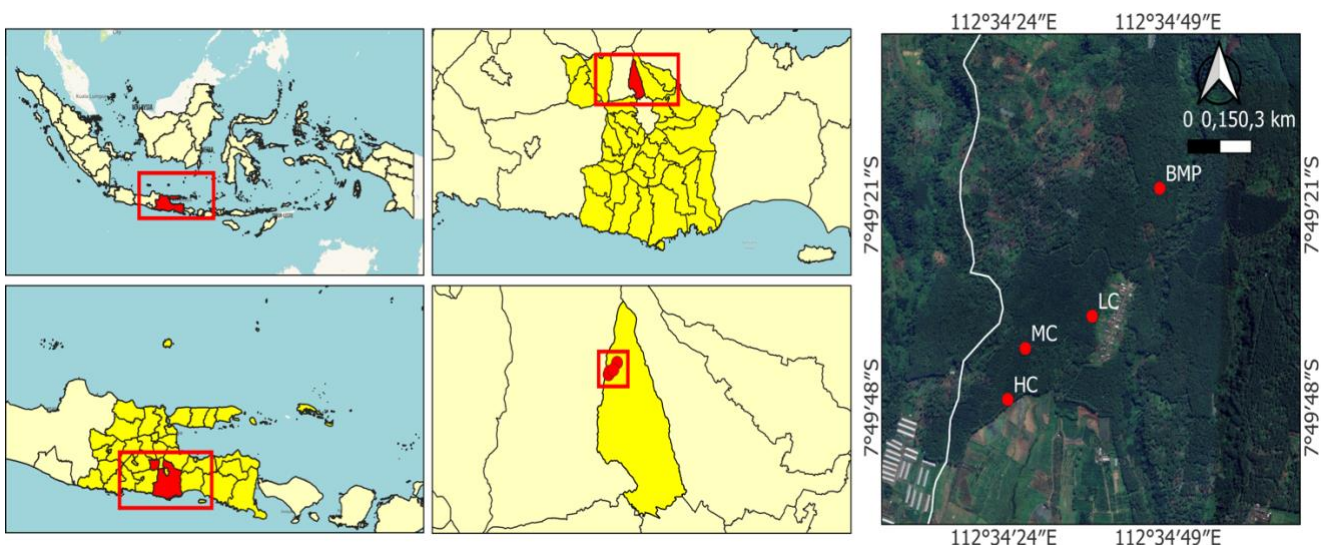
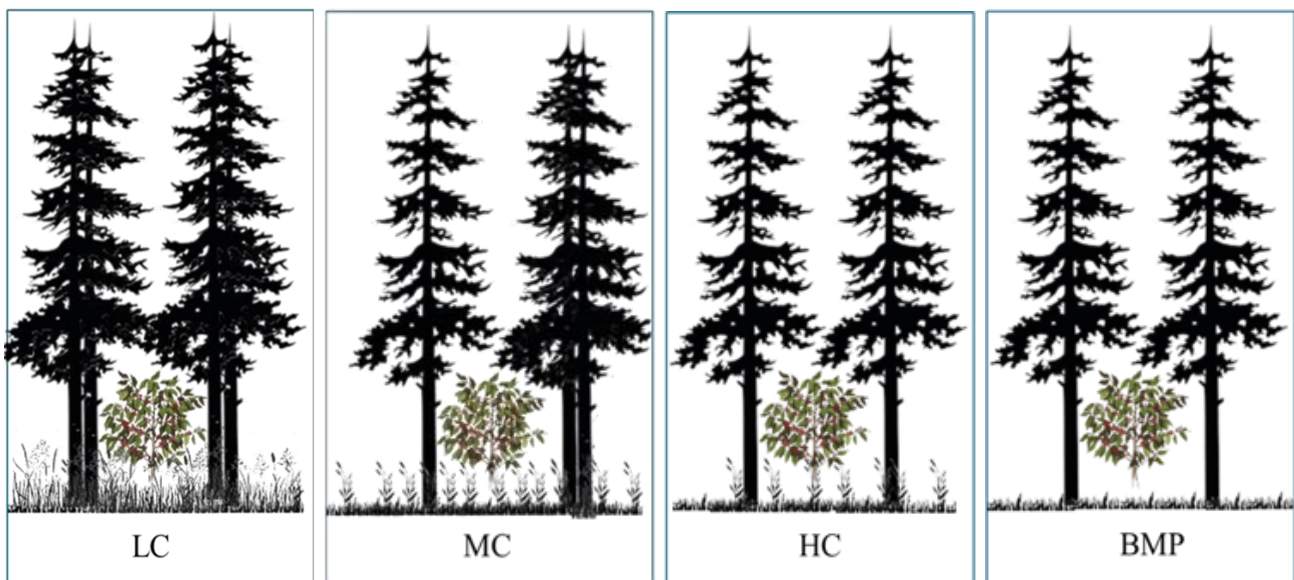


Figure 1. Research plots of the pine-coffee agroforestry system based on its management

Table 1. Description of four managements of pine-coffee agroforestry system based on cultivation input intensity

Managements	Description of each coffee plant treatment on each management condition
Low Coffee Management (LC)	Low management under high pine shade. Coffee plants were grown under dense pine canopy without fertilization, pruning, or weeding, and were left to establish naturally after transplanting.
Medium Coffee Management (MC)	Moderate management. Coffee received a single application of goat manure compost (2 tons ha ⁻¹) after transplanting, formative pruning at two years of age before entering a productive phase, and occasional manual weeding.
High Coffee Management (HC)	High management. Plants were fertilized annually with 3 tons ha ⁻¹ goat manure compost combined with 100 kg ha ⁻¹ NPK fertilizer, coffee pruned at two years of age before entering a productive phase, and routinely weeded manually.
Best Management Practice (BMP)	Management of coffee plant according to Perhutani standards which include twice fertilization in one year using 5 tons ha ⁻¹ goat manure compost and 300 kg ha ⁻¹ NPK, pruning the shape of the plant by maintaining a plant height of ±150 cm, non-productive branch preservations, branch subjugation, primary branches maintenance, pruning production, pruning of sucker shoots, and routine application of herbicides together with fertilization.

Note: Perhutani is a state-owned enterprise in the form of a public company of Indonesia with the authority to manage state forest resources on the islands of Java and Madura

**Figure 2.** The percentage of pine-canopy cover between each management: BMP (56.26%), HC (63.06%), MC (64.11%), and LC (68.15%)

Data collection

Light intensity analysis was divided into observations of pine canopy cover percentage and sunlight radiation intensity. The percentage of pine canopy cover was measured using the canopy app, and the intensity of light radiation was measured with a digital lux meter. Measurements were carried out based on observation points according to the predetermined treatment repetitions.

Soil profile documentation was collected by digging with a soil shovel in each treatment, measuring 0.5 m × 0.5 m × 0.5 m. The purpose of a mini pit was to obtain the morphological properties of the characteristic horizon and to determine the distribution of variations in soil properties that were specifically related to differences in the level of litter thickness in different pine-coffee agroforestry management.

Sampling of intact and decomposed agroforestry litter was conducted by placing a 0.5 m x 0.5 m square at a

predetermined point. The litter in the square plot was then weighed using a digital scale for analysis. Intact litter was characterized by the shape of brown litter that was still in the form of a plant's organ. In contrast, decomposed litter was characterized by brittle, soil-like litter (sometimes with decomposer fungal hyphae) (Figure 3).

Particle density can be measured using liquid-displacement methods, such as the pycnometer method, which determines the volume of soil solids by measuring the displacement of a liquid (Amoozegar et al. 2023). Bulk density was measured in the laboratory using undisturbed soil samples collected in the field. Soil sampling using a sample ring at a depth of 0-30 cm by inserting the sample ring into the soil and pressing the sample ring until ¾ full, then the master ring was placed on the sample ring and pressed until the sample ring was filled. The sample ring filled with soil was placed in a plastic bag and labeled. Weighing the wet weight of the soil sample, then the soil

sample was dried for 24 hours, at a temperature of 105°C using a laboratory oven, then weighing the soil sample along with the ring. Data from the observation were applied to the subsequent equations, i.e., Equations 1 (bulk density), 2 (particle density), and 3 (soil porosity). Based on equations, three terms were used: S_m , S_v , and M_v . S_m , S_v , and M_v were soil mass, soil volume, and mass volume, respectively.

$$\text{Bulk density} = \frac{S_m}{S_v} \quad [1]$$

$$\text{Particle density} = \frac{S_m}{M_v} \quad [2]$$

$$\text{Soil Porosity} = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100\% \quad [3]$$

The analysis was conducted to determine the soil's capacity to absorb water. The observation was conducted using a single-ring infiltrometer placed on the soil surface at a depth of 5-10 cm. Water was then introduced into the single-ring infiltrometer, and changes in the infiltration rate were recorded. Related to the soil infiltration rate, two equations were described in Equation 4 (infiltration rate) and 5 (constant).

$$f = f_c + (f_0 - f_c)e^{-kt} \quad [4]$$

$$K = \frac{-1}{m \cdot \log e} \quad [5]$$

Where, Infiltration rate ($\text{cm} \cdot \text{hour}^{-1}$), initial infiltration rate ($\text{cm} \cdot \text{hour}^{-1}$), final infiltration rate ($\text{cm} \cdot \text{hour}^{-1}$), time (hour), and gradient were symbolized by f , f_0 , f_c , t , and m simultaneously. In addition, the value of e was 2.718.

Soil C-organic content

Agricultural land classifications and environmental assessments often incorporate total organic carbon measurements, as its presence or absence greatly influences the chemical interactions within soil or sediment. Various methods are available to quantify soil organic carbon (SOC) levels in soils and sediments; thus, the Walkley-Black SOC measurement method was based on Abu El Haija et al. (2024). Soil samples were collected at observation points and analyzed for material content in the Soil Chemistry laboratory. Soil C-organic analysis was carried out using the Walkley and Black method. In the first stage of soil sampling, up to 0.5 g of sample was passed through a 0.5 mm sieve. Soil samples were homogenized with $\text{K}_2\text{Cr}_2\text{O}_7$ and H_2SO_4 solutions and then allowed to rest for 30 minutes. Furthermore, the homogenized mixture was diluted with 200 mL H_2O , and 10 mL of 85% H_3PO_4 was added. Then, Difenyamine indicator was added in 30 drops, and the mixture was titrated with $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1N until a color change from dark to bright green. The C-Organic content was calculated with the following formula.

$$\text{C-Organic} = \frac{\text{mL.extractant} - \text{mL.sample}}{\text{mL.extractant} \times \text{sample mass}} \times 3 \times \text{FKa} \quad [6]$$

$$\text{FKa} = \frac{\% \text{Water content} + 100}{100} \quad [7]$$

The soil sample was weighed at 0.5 g and put into a Kjeldahl flask. 1 g mixture of selenium and 5 mL of H_2SO_4

were added. After the soil/plant solution was completely destructed at 300°C, it was cooled and then diluted with 50 mL of H_2O . The dilution result was diluted with 20 ml of 40% NaOH, then distilled, and the distillate was collected in 20 mL of boric acid. Distillation stopped when the container volume reached 50 mL, and the distillate turned green. The distillation product was titrated with H_2SO_4 until the endpoint was indicated by a color change from green to red wine (the original borax color). Then the volume of H_2SO_4 used was recorded to be processed into N-total. The N-total value indicates the soil nitrogen content. The formula of the FKa (Water Content Factor) was shown in Equation 7. The N-total formula is described in Equation 8.

$$N_{\text{total}} = \frac{\text{ml extractant} - \text{ml sample}}{\text{sample mass}} \times 0.014 \times N \cdot \text{H}_2\text{SO}_4 \times 100 \times \text{FKa} \quad [8]$$

Soil samples were collected from the research plots in a composite of 1000 g, placed in plastic bags, and transported to the laboratory in a cooler box. 10 g of the soil sample was dissolved into 90 mL of physiological solution (NaCl 0.85% $\text{m} \cdot \text{v}^{-1}$ in distilled water) (standard as 10^{-1} solution). Then, 1 mL of the dilution was serially diluted into 10 mL of sterile distilled water (10^{-2}) to 10^{-7} . 1 mL of the last three special series was spread in duplicate on petri dishes, using selective media at dilutions 10^{-5} to 10^{-7} , on Carboxy-4 Methyl Cellulose (CMC). Colonies surrounded by transparent circles were counted as cellulolytic bacteria, as they can consume cellulose. The number of colonies was counted after 7 days of isolation, which was considered the bacteria's life cycle. Therefore, if no microbes are found until day 7, it means they were not present in the sample.

Observation of the vegetative aspect and coffee yield was carried out on July 9th, 2024. Coffee cherries were harvested after being considered physiologically ripe, as indicated by the cherry's redness. Harvesting was carried out per coffee plant from each treatment plot. The coffee beans were weighed to obtain the fresh weight of the coffee fruit for each sample. The color of ripe coffee fruit was observed using the RHS Color Chart. To measure the physical properties of the cherries, the diameter and length of the cherries were measured using a caliper. Measurement of the refractive index of the coffee fruit was carried out using a hand refractometer. Freshly picked coffee cherries were then processed in a standardized manner to produce green beans, and the bean weight and percentage yield were measured for each cultivation management. Yield analysis per hectare was done by converting the harvest per plant multiplied by the coffee population in 1 ha. The calculation of the yield (extraction rate) percentage was done by converting the weight of the coffee beans obtained compared to the weight of the cherries harvested.

Data analysis

RStudio 2024.04.2 was used to conduct multiple statistical analyses in this research. Several packages, such as readxl, ggplot2, dplyr, tidyr, and agricolae, were chosen to run statistical analysis and visualize all data. Multiple statistical methods were employed to examine and compare soil microbes across conditions, followed by an

investigation of the refractive index of coffee berries under different treatments. These methods included regression analysis, Analysis of Variance (ANOVA), TukeyHSD for post hoc comparisons, and visualizations using boxplots. Each method provided unique insights and facilitated a comprehensive understanding of the relationships and differences between the variables across the studies.

Boxplots served as a visual aid for both microbial counts and refractive indices, highlighting differences in central tendency and spread. A regression chart was applied to describe the linear relationship between the weight of 100 coffee berries and beans. Together, these methods created a robust framework for analyzing soil microbes and coffee berry refractive indices across different treatments, providing both statistical significance and clear, interpretable visualizations.

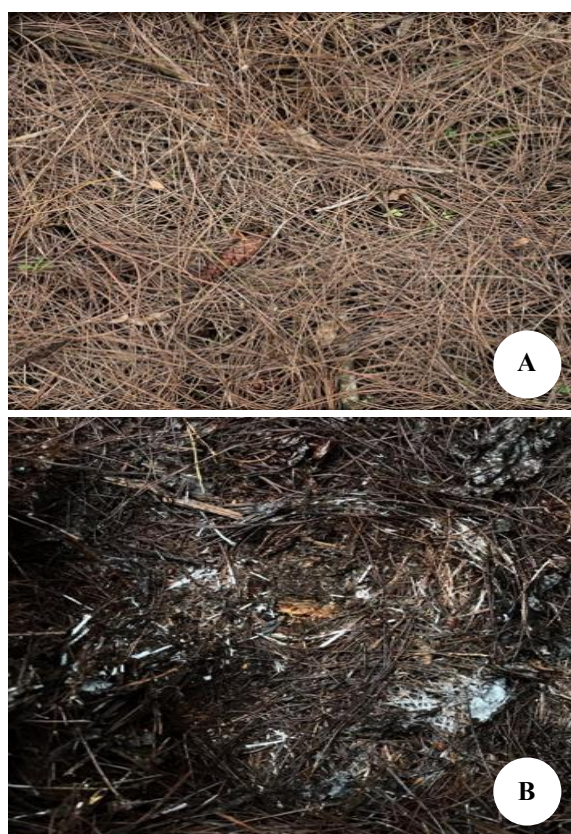


Figure 3. Differences in soil surface conditions between: A. Undecomposed, B. Decomposed litters

RESULTS AND DISCUSSION

Environmental conditions in pine-coffee agroforestry systems

Table 2 presents the environmental conditions within the pine-coffee agroforestry system under different management intensities (BMP, HC, MC, and LC). As management intensity increased (moving from LC to BMP), pine canopy

cover decreased, and light intensity reaching the coffee plants increased. BMP conditions had the lowest canopy cover at 56.26%, while LC conditions had the highest at 68.15%. Light intensity mirrors this trend, with BMP allowing for 3727.22 lux, significantly higher than the 1867.67 lux observed under LC. Additionally, LC management results in the highest undecomposed (1283.07 g) and decomposed litter weights (1336.767 g), indicating a potentially richer organic layer compared to the most intensive management, which has lighter litter layers.

The environmental characteristics in pine-coffee agroforestry systems vary significantly with management intensity. Lower canopy cover in BMP and HC systems increases light intensity, promoting photosynthetic activity and enhancing coffee growth and productivity. These findings align with research by Cerda et al. (2020) and Torrez et al. (2023) on shade management in agroforestry, which found that reduced canopy cover improves light conditions for understory crops such as coffee. Additionally, the high litter accumulation in LC, which did not differ significantly from the less intensive management (MC) and the high-intensity management (HC), indicates that greater canopy shading contributes to increased litter accumulation. Enhanced litter decomposition supports soil fertility by gradually releasing nutrients and act as a natural mulch, thus benefiting coffee plants in the agroecosystem (Maharjan et al. 2024).

The differences in light intensity and litter weights between management practices in Table 2 further emphasize the effect of canopy cover on understory conditions. Reduced shade in BMP and HC not only allows for more sunlight but also creates conditions conducive to litter decomposition, which enhances soil nutrient availability. Xu et al. (2023) found similar results in mixed agroforestry systems, where lower canopy cover increased light penetration and organic matter turnover, benefiting understory plant growth.

Soil physical and chemical characteristics

Variations in soil physical characteristics arise from differences in management practices (Figure 4). BMP management exhibits the lowest bulk density and particle density, along with the highest porosity percentage. Soil bulk density values can indicate changes in soil horizons, tillage practices, organic matter content, porosity index, water-holding capacity, drainage properties, and ease of root penetration. As bulk density increases, the soil becomes more compacted. The ratio of soil particle density to soil bulk density reflects the volume of pore space within the soil (Robinson et al. 2022). The lower values of soil bulk density and particle density are likely due to the regular, balanced application of manure and NPK fertilizer. Consistent and balanced fertilization promotes the accumulation of organic matter in the soil. Higher organic carbon content reduces soil bulk density because organic materials are lighter and increase soil volume without significantly adding more mass (Gu et al. 2022). Excessive soil bulk density, however, leads to compaction, which adversely affects plant root growth by limiting the soil's ability to store and supply water and nutrients. This

compaction reduces macroporosity and increases soil density and strength, resulting in diminished infiltration and water retention capacity. These detrimental effects can severely impact plant health and productivity by restricting root expansion and nutrient absorption (Wang et al. 2019).

On the soil porosity classifications, the porosity values across all management practices belong within the medium porosity classification, ranging from 35-50% (Schwyter and Vaughan 2020). Infiltration is influenced by land and crop management practices, which affect soil compaction and organic matter accumulation. The infiltration rate is influenced by several factors, including soil physical properties, particularly porosity. Infiltration directly correlates with soil porosity: higher porosity correlates with higher infiltration rates, and vice versa. According to the classification by Uhland and O'Neal (1951), the infiltration rate in BMP was categorized as fast, HC as moderately fast, and LC and MC as medium. Larger soil pores facilitate faster water infiltration. When soil pores are abundant,

water can flow rapidly into the soil, whereas smaller pores tend to impede infiltration. These pores allow air and water to circulate into the soil. The compaction and distribution of pores also affect the speed at which water can seep into the soil (Hamza and Anderson 2005).

The physical quality of soil varies across management intensities, as shown in Table 3 and Figure 4. BMP management had the lowest bulk density (0.62 g/cm^3) and particle density (1.22 g/cm^3), as well as the highest porosity (48.74%), suggesting that the soil was less compact and had better air and water permeability. Conversely, LC conditions display the highest bulk density (0.86 g/cm^3) and lowest porosity (41.40%), potentially restricting root growth and water infiltration. Soil nutrient levels (N-Total and C-Organic) also improve with BMP management, reaching 0.60% and 5.83%, respectively, while LC shows the lowest values for both. This indicates that intensive management promotes better soil structure and nutrient retention.



Figure 4. Differences in soil profiles between: A. BMP (Best management coffee), B. HC (High management coffee), C. MC (Medium management coffee), D. LC (Low management coffee)

Table 2. The environmental condition of pine-coffee agroforestry based on the percentage of canopy, light intensity, undecomposed and decomposed litter weights

Managements	Pine canopy (%)	Light intensity radiation (lux)	Weight of undecomposed litter (g)	Weight of decomposed litter (g)
BMP	56.26±7.02	3727.22±865.34 b	946.03±260.46 a	977.567±201.20 a
HC	63.06±4.85	3627.22±931.28 b	1104.43±30.76 ab	1063.433±96.81 ab
MC	64.11±6.66	2533.33±1033.21 a	1152.20±38.35 ab	1243.800±24.12 b
LC	68.15±10.70	1867.67±390.73 a	1283.07±36.45 b	1336.767±40.41 b
TukeyHSD (5%)	ns	834.12	246.38	254.10

Note: Numbers followed by the same letter in the same column showed no significant difference based on the TukeyHSD at $\alpha=0.05$, and ns means not significant. Conditions of the agroforestry system were LC (Low management coffee), MC (Medium management coffee), HC (High management coffee), and BMP (Best management coffee)

Table 3. The physical and chemical quality of soil due to the different Arabica coffee cultivation management under the pine-coffee agroforestry system

Managements	Bulk density (g/cm ³)	Particle density (g/cm ³)	Porosity (%)	Infiltration (cm ³ /s)	N-total (%)	C-organic (%)
BMP	0.63±0.03	1.22±0.07	48.74±10.03	4.8±2.14	0.60±0.02 c	5.66±0.04 c
HC	0.80±0.02	1.45±0.03	44.94±8.43	6.0±2.67	0.41±0.05 b	4.41±0.03 b
MC	0.78±0.06	1.41±0.09	44.56±4.81	7.2±2.80	0.37±0.02 ab	4.20±0.02 b
LC	0.86±0.07	1.61±0.20	46.12±6.99	13.2±3.87	0.34±0.03 a	3.29±0.05 a
TukeyHSD (5%)	ns	ns	ns	ns	0.06	0.34

Note: Numbers followed by the same letter in the same column showed no significant difference based on the Tukey HSD at $\alpha=0.05$, and ns means non-significant. Conditions of the agroforestry system were LC (Low management coffee), HC (High management coffee), and BMP (Best management coffee)

Soil physical qualities, such as bulk density, particle density, and porosity, are positively influenced by intensive management. BMP and HC practices yield lower bulk density and higher porosity, which improve water infiltration and root penetration. Similar outcomes were observed by Su et al. (2023) in managed agroforestry systems, where improved soil structure was linked to enhanced organic matter and microbial activity. The higher N-Total and C-Organic content in BMP systems indicates enriched soil nutrient levels, consistent with Matistic et al. (2024), who reported that frequent organic amendments elevate soil organic carbon and nitrogen levels, which are crucial for plant nutrition and productivity.

Enhanced soil porosity and lower bulk density in BMP-managed plots suggest better soil aeration and moisture retention, critical for coffee root development. According to Sudharta et al. (2022), these soil improvements can positively impact crop resilience to water stress. Their research highlighted that agroforestry management practices that promote organic matter integration, such as BMP, significantly improve soil physical properties and support long-term soil health.

Studies have shown that agroecosystem management practices significantly influence soil chemical properties and microbial communities, highlighting the critical role of management choices in determining soil health and composition. For instance, Lee et al. (2020) found that different land management practices in conventional vegetable fields resulted in distinct assemblages of bacteria and fungi, driven by variations in soil physical and chemical properties. Similarly, Jurburg et al. (2020) demonstrated that interactions between agricultural management practices and plant selection can affect soil microbial communities and chemical characteristics, underscoring the combined effects of these factors on soil ecosystems. In coffee agroecosystems, Sudharta et al. (2022) observed that variations in management practices resulted in differences in soil chemical properties and microbial composition.

The soil total nitrogen (N-total) content at the observation sites remains within the critical levels for optimal coffee cultivation, as recommended by the Coffee Research Foundation (CRF), which range from 0.3% to 0.6% (Sudharta et al. 2022). BMP exhibits the highest N-total and organic carbon (C-organic) values, which differ significantly from those of other management practices. This is attributed to the routine application of NPK fertilizers

and organic manure in coffee cultivation management. The integrated use of organic and inorganic fertilizers can enhance nutrient availability and improve soil health. The application of chemical fertilizers (NPK) can stimulate carbon mineralization and increase inorganic nitrogen reserves (Fahad et al. 2022). LC management shows the lowest values for N-total and C-organic among the other managements. This is attributed to the lack of additional inputs applied to the agroecosystem, resulting in low nutrient availability. Unmanaged agroforestry systems that do not consider nutrient cycling and the addition of essential nutrients to the land will cause nitrogen to be depleted through plant uptake without any replacement being returned to the soil Schmidt et al. (2021).

Eventually, higher management intensities, particularly BMP, reduce canopy cover, increasing light penetration, which is essential for coffee photosynthesis (Tilden et al. 2024). This light availability is complemented by increased organic matter from organic fertilizer inputs, enhancing the soil's nutrient reservoir (Araujo et al. 2012). The physical quality of the soil under BMP also shows improvements, with lower bulk density, higher porosity, and better infiltration rates, creating a more favorable environment for root growth and water retention (Abu-hashim et al. 2023). Soil nutrient content, as evidenced by higher nitrogen (N-total) and organic carbon (C-organic) levels, further underscores BMP's effectiveness in maintaining soil fertility. These results align with existing studies on the benefits of intensive management practices in agroforestry systems, which show that optimized soil conditions support sustainable plant growth (Ekblad 2015). A broader review by Kiup et al. (2025) highlights that BMP strategies, such as organic matter-based fertilization, intercropping with nitrogen-fixing species, and proper canopy management, are effective at improving soil structure and nutrient cycling, key indicators of soil health and long-term system resilience.

Soil microbes abundance

Figure 5 presents the abundance of various soil microbes—cellulolytic bacteria, fungi, nitrobacter, and nitrosomonas—across different agroforestry management practices: Low coffee management (LC), medium coffee management (MC), high coffee management (HC), and best management practice (BMP). The results show that although BMP has advantages in terms of physical and chemical properties of

the soil, the facts in the field state that the BMP planting medium cannot support the growth and development of the population of microorganisms in the form of cellulolytic bacteria as cellulose decomposers, and nitrifying bacteria in the form of *Nitrosomonas* sp. and *Nitrobacter* sp. This is assumed to occur due to the routine application of inorganic herbicides for weed control. Differences in microbial abundance between the management practices were statistically analyzed using ANOVA and TukeyHSD, reinforcing the significance of management practices on microbial populations.

Figure 5 shows that overly intensive cultivation inputs on BMPs render the soil unable to provide a suitable habitat for cellulolytic and nitrifying bacteria (*Nitrosomonas* sp. and *Nitrobacter* sp.). Ecological disturbances that occur, such as the application of herbicides and inorganic fertilizers that are quite intensive in BMP, were the main cause of the unavailability of soil as a habitat for these microorganisms. This is in line with Barros-Rodríguez et al. (2021), indicating that temperature changes, decreased soil moisture, and vegetation removal due to intensive

inorganic inputs may eliminate microbes due to limited energy sources. Low levels of shade in BMP can increase air temperature and reduce humidity unexpectedly, thereby inhibiting succession.

The abundance of soil fungal populations in the BMP treatment is thought to be due to the agroclimatic characteristics resulting from the coffee cultivation management treatment that can support the growth of decomposer fungi more optimally than cellulolytic bacteria. This is in line with Kielak et al. (2016), who stated that cellulolytic bacteria and decomposing fungi play the same role in lignin decomposition and compete for carbon as an energy source. The high total population of microorganisms in MC management is thought to result from minimal crop intensification. The intermediate disturbance theory states that low-intensity disturbances can increase species diversity in an ecosystem by reducing the dominance of one species. Without disturbance, one species tends to dominate the habitat and suppress others, whereas low-level disturbances can limit this dominance and allow other species to thrive (Moi et al. 2020).

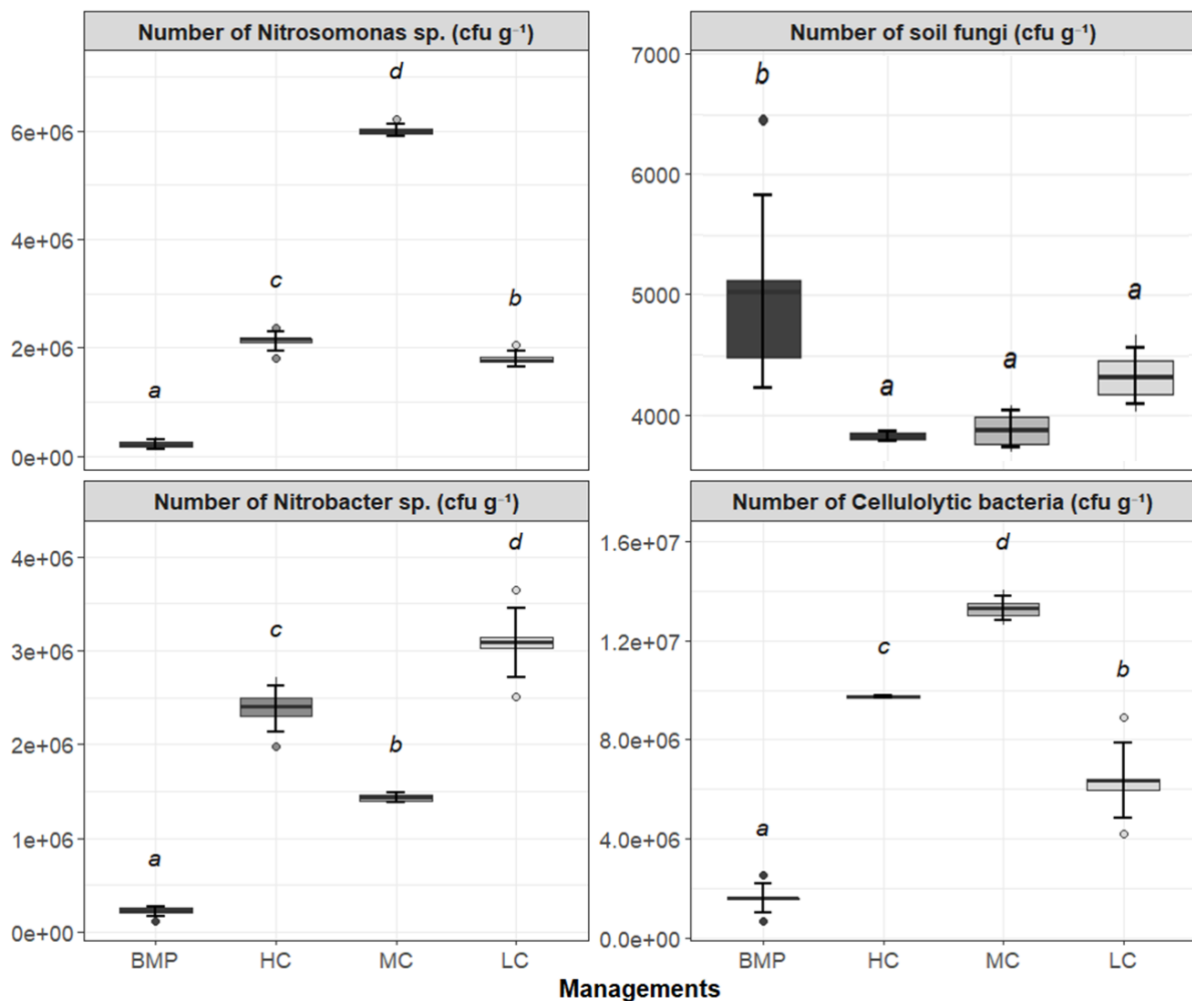


Figure 5. Differences in soil microbe abundance (cellulolytic bacteria, fungi, *Nitrobacter*, and *Nitrosomonas*) across different conditions of the agroforestry system. The same letter on each boxplot diagram showed no significant difference based on the TukeyHSD at $\alpha=0.05$

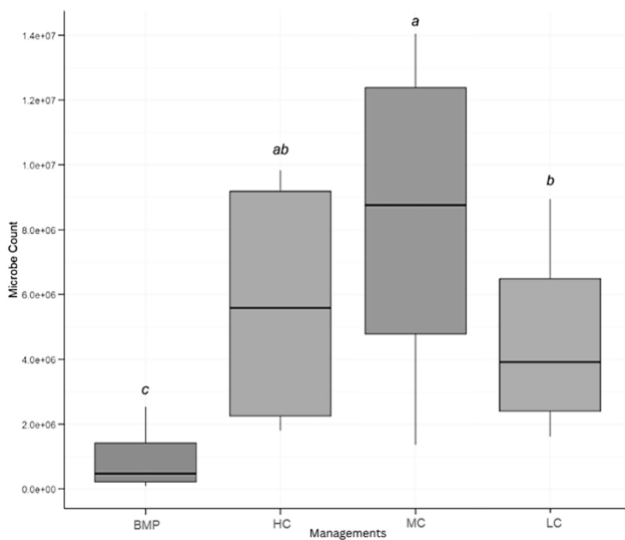


Figure 6. Differences between different management of the agroforestry system based on total microbe abundance (*Nitrosomonas* sp., *Nitrobacter* sp., and cellulolytic bacteria (CFU g⁻¹)). The same letter on the boxplot diagram showed a no-significant between conditions based on TukeyHSD at $\alpha=0.05$

The high level of shade and minimal environmental disturbance in less managed treatments creates a more stable ecosystem, supporting the succession of microorganisms within it. High input of shade tree litter is also a factor in maintaining microclimate stability, along with infrequent or absent weeding of understory plants. The abundance of microbial populations in each pine coffee agroforestry management indicates biologically active soil environment, enhancing ecosystem resilience and nutrient availability. These findings reinforce the idea that soil microbial health is integral to agroforestry productivity and align with research demonstrating the role of organic amendments in stimulating microbial populations (Araujo et al. 2012).

Figure 6 illustrates the total abundance of soil microbes under the different management intensities. Similar to Figure 6, MC exhibits a significantly higher total microbial abundance, indicating that intermediate intensification fosters a biologically active soil environment that may aid nutrient cycling. The ANOVA and TukeyHSD analyses confirm that these differences in microbial abundance are significant, underscoring the impact of intensive management on soil biology. This finding aligns with Araujo et al. (2012), Schmidt et al. (2019), and Suman et al. (2022), who found that organic amendments and careful management practices in agroforestry systems boost microbial populations and soil nutrient levels. The statistical significance of differences observed across management types underscores the impact of these practices on soil biology.

The trend in Figure 6 showing increasing total microbial abundance in MC underscores the role of medium-scale management in maintaining a biologically active soil environment. Jurburg et al. (2020), Lee et al. (2020), and Wang et al. (2024) also demonstrated that agroforestry systems with more closed nutrient cycles encourage higher microbial abundances, improving nutrient turnover and soil fertility. Furthermore, Lee et al. (2020) found that diverse

land-use practices, particularly those incorporating agroforestry, significantly impacted microbial community composition, further reinforcing the importance of management intensity in soil biological health. A similar study by Colombo et al. (2023) showed that shade trees in agroforestry systems moderate temperature extremes and increase soil water content, thereby increasing microbial biomass and soil enzymatic activity.

Productivity of coffee

The productivity of Arabica coffee branches varies significantly with management intensity, as detailed in Figure 7. Under BMP management, coffee branches achieve 100% node productivity, significantly outperforming HC (71.52%), MC (66.30%), and LC (64.32%). This trend suggests that the BMP approach not only enhances overall plant vigor but also maximizes the fruit-bearing potential of each branch, thereby directly affecting yield quality and quantity.

The number of productive nodes per branch increases significantly under BMP management. This productivity gain can be attributed to optimized pruning and nutrient management, which are known to enhance fruiting potential. Effective pruning under BMP management helps to direct energy toward productive branches, maximizing yield. De Beenhouwer et al. (2013) support this approach, noting that well-managed branches contribute substantially to the overall productivity of coffee plants in agroforestry systems.

Increased productive nodes per branch in BMP indicate a strategic use of resources toward fruit-bearing branches. Araujo et al. (2024) demonstrated that well-managed coffee plants with targeted pruning and adequate nutrient supply enhance yield potential through improved branch productivity, a trend consistent with the increased productivity observed under BMP conditions.

Relationship between fruit and bean weight of coffee

Figure 8 shows a regression analysis between the weight of 100 coffee beans and 100 coffee berries, providing insight into the relationship between fruit and bean weight. The positive regression trend suggests that as berry weight increases, bean weight also tends to increase, indicating that larger berries generally produce heavier beans. Management practices may influence this relationship, as higher intensity management (e.g., BMP) typically results in larger berries (Table 4), potentially leading to higher bean weights. This correlation highlights the potential for yield improvements through practices that enhance berry growth.

The positive regression trend indicates that larger berries generally yield heavier beans (Figure 8). This correlation aligns with findings by Wright et al. (2024), who reported that nutrient and water management improve fruit size and quality in coffee agroforestry, thereby affecting bean weight. The trend also underscores the potential for higher yield through practices that enhance berry growth, as observed under BMP. The positive regression between berry and bean weight suggests that larger berries, often fostered by BMP practices, yield heavier beans. Xu et al. (2022) observed similar correlations, attributing higher

bean weights to increased nutrient availability and fruit development, further supporting the benefits of intensive management in coffee production.

Refractive index of coffee berries

Figure 9 compares the refractive index of coffee berries under different management intensities (LC, MC, HC, BMP). The refractive index, which is related to the sugar content in the berries, is highest under BMP conditions, indicating better fruit quality and ripeness. In contrast, LC management shows the lowest refractive index, which could be attributed to lower nutrient availability and suboptimal growth conditions. ANOVA and TukeyHSD analyses confirmed significant differences in refractive index across management practices, with BMP management yielding superior fruit quality attributes.

The refractive index, which indicates sugar content and fruit quality, was highest under BMP conditions, suggesting superior ripeness and quality. This is consistent with Osorio Pérez et al. (2023), who noted that nutrient-rich management practices improve coffee fruit quality, including sugar concentration. ANOVA and TukeyHSD confirm significant differences in management practices, with BMP showing the highest quality, underscoring the benefits of high-intensity management for enhancing fruit quality. The highest refractive index in BMP berries suggests improved sugar content, enhancing coffee quality. Xu et al. (2022) found that well-fertilized coffee plants in agroforestry systems exhibit higher sugar levels, linking intensive management to better coffee flavor profiles and market value.

Physical quality of coffee

Table 4 shows the physical quality of Arabica coffee fruit across different management practices. BMP management yields the heaviest berries, with an average weight of 239.00 g per 100 berries, as well as the largest berry diameter (16.85 mm) and length (17.73 mm). In contrast, LC management yields smaller berries, with significantly lower weights (163.88 g per 100 berries) and smaller dimensions (diameter of 11.69 mm and length of 13.32 mm). The weight of coffee beans per 100 berries follows a similar trend, with BMP management producing the heaviest beans, suggesting that higher management intensity improves both berry size and bean quality.

Higher management intensity improves the physical quality of Arabica coffee berries and beans, with BMP showing the most substantial results in terms of berry weight, diameter, and length. Quality improvement under BMP can be linked to adequate nutrient supply and pruning, which focuses plant resources on fewer, healthier berries. This observation aligns with the findings by Schmidt et al. (2023), who reported that nutrient and water availability, along with management practices, significantly affect the physical and biochemical quality of coffee fruits. Additionally, BMP practices that enhance soil fertility and moisture retention are crucial in supporting larger fruit sizes and better bean development.

BMP's impact on coffee berries and bean size, as observed in Table 4, reinforces the link between nutrient

management and fruit development. Balanced fertilization and moisture-retention practices in agroforestry enhance coffee berry size, suggesting that these practices can improve both yield and marketable quality of coffee by promoting healthier fruit development (Rakocevic et al. 2023). The increased productivity observed in coffee plants under BMP, with a higher number of productive nodes per branch, larger berry size, and greater bean weight, emphasizes the importance of intensive management practices (Vaast et al. 2006). BMP management optimizes nutrient delivery and pruning practices, directing resources to productive plant parts to enhance yield quality. Coffee berries grown under BMP exhibit higher refractive indices, indicating greater sugar content and improved flavor quality, a vital attribute in specialty coffee markets (Xu et al. 2023). The positive correlation between berry and bean weight further illustrates that larger, well-nourished berries produce heavier beans, resulting in greater overall yield per plant and per hectare (Cerda et al. 2020).

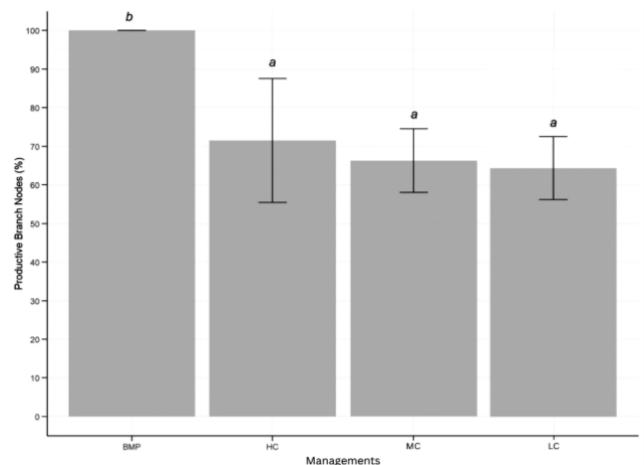


Figure 7. Differences between the four agroforestry management systems are based on the percentage of productive branch nodes. The same letter on the barplot diagram showed a no-significant between conditions based on TukeyHSD at $\alpha=0.05$

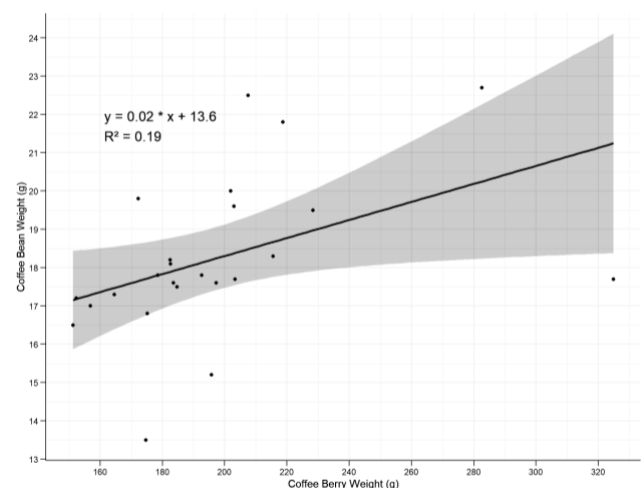


Figure 8. Regression analysis of the weight of 100 beans and berries

Yield quantity of coffee

The yield of Arabica coffee per plant and per hectare also varies with management intensity, as shown in Table 5. BMP management provides the highest yield, with 0.54 kg of berries per plant and 1.13 tons per ha, along with a significant coffee bean yield of 0.19 tons per ha. In contrast, LC management yields are much lower, with only 0.08 kg of berries per plant and 0.17 tons per ha. Although the extraction rate (percentage of beans from berries) is similar across management levels, BMP management produces a substantially higher absolute yield. These findings align with previous research indicating the efficacy of intensive management practices for maximizing coffee production (Ekblad 2015; Torrez et al. 2023).

Yield quantities per plant and per hectare were markedly higher in BMP-managed systems than in LC, MC, and HC. This increase in yield is primarily due to enhanced nutrient management, canopy optimization, and soil improvements that collectively promote plant growth and fruit production (Maharjan et al. 2024; Tilden et al. 2024). Studies by Xu et al. (2023) have shown that intensive agroforestry management significantly increases crop yields by improving resource use and enhancing microclimate conditions. The similarity in extraction rate across management types suggests that fruit-to-bean conversion efficiency remains stable, but the absolute yield gains from BMP highlight its potential for maximizing coffee production in agroforestry settings (Araujo et al. 2012; Suman et al. 2022).

The yield advantages of BMP highlight its potential to meet productivity goals within sustainable agroforestry frameworks. Higher yields with stable extraction rates across management types suggest that while fruit-to-bean conversion remains efficient, BMP maximizes absolute productivity (Maharjan et al. 2024). Additionally, Kurniawan et al. (2024) found that combining strategic pruning with the application of organic or mixed fertilizers resulted in

elevated levels of total soil nitrogen and microbial nitrogen biomass, while also improving coffee yields. This aligns with studies suggesting that effective management practices not only enhance ecological benefits but also provide substantial economic returns by optimizing coffee quality and yield (Torrez et al. 2023; Tilden et al. 2024). Higher yields in BMP systems highlight the importance of intensive agroforestry management. Ultimately, the gradient from low to intensive management practices, such as best management practices (BMP), positively affects various ecological and productivity-related parameters. Furthermore, light availability and soil physical properties are also positively enhanced coffee yield quality and quantity (Xu et al. 2023; Maharjan et al. 2024).

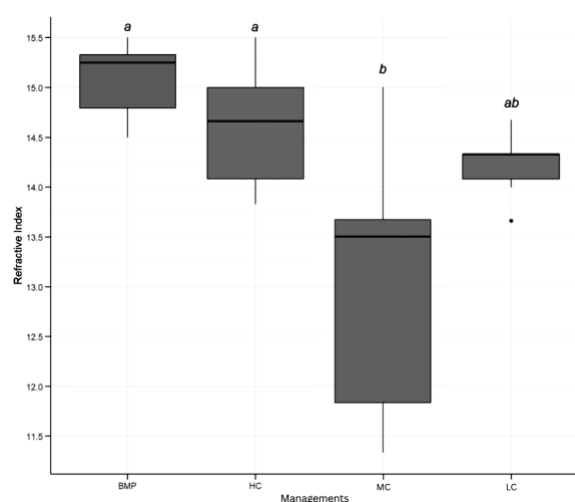


Figure 9. Differences between each management of the agroforestry system based on the refractive indexes of coffee berries. The same letter on the boxplot diagram showed a no-significant between conditions based on TukeyHSD at $\alpha=0.05$

Table 4. Effect of management on the physical quality of coffee

Managements	Weight of 100 berries (g)	Diameter of berry (mm)	Length of berry (mm)	Weight of 100 coffee beans (g)
BMP	239.00±53.25 b	16.85±0.75 c	17.73±0.57 c	20.08±2.49 b
HC	202.73±14.82 ab	15.07±0.66 b	15.96±0.73 b	18.77±1.06 ab
MC	182.83±9.50 a	14.39±1.26 b	15.54±0.44 b	17.58±1.52 ab
LC	163.88±12.99 a	11.69±0.92 a	13.32±1.28 a	16.52±1.52 a
TukeyHSD (5%)	47.80	1.61	1.45	2.97

Note: Numbers followed by the same letter in the same column showed no significant difference based on the TukeyHSD at the 5% level

Table 5. Effect of management on the coffee yield quantities

Managements	Weight of berries per plant (kg plant ⁻¹)	Weight berries per hectare (t ha ⁻¹)	Weight of coffee beans per hectare (t ha ⁻¹)	Bean extraction rate (%)
BMP	0.54±1.08 c	1.13±0.26 c	0.19±0.03 c	17.42±3.78
HC	0.24±0.26 b	0.47±0.07 b	0.09±0.01 b	18.57±1.27
MC	0.20±0.39 b	0.40±0.07 ab	0.08±0.01 b	19.32±2.41
LC	0.08±0.27 a	0.17±0.06 a	0.03±0.01 a	20.29±2.63
TukeyHSD (5%)	0.95	0.71	0.12	ns

Note: Numbers followed by the same letter in the same column showed no significant difference based on the TukeyHSD at the 5% level, and ns means not significant

In conclusion, this study evaluated the effects of varying management intensities on soil quality, microbial populations, and coffee productivity within a pine-coffee agroforestry system. The findings support the hypothesis that higher management intensities, specifically best management practices (BMP), positively enhanced soil physical and chemical properties, thereby directly improving coffee yield and quality. The result revealed that BMP management effectively reduced soil bulk density and increased porosity and infiltration rates, creating an optimal environment for coffee plant growth. BMP can offer soil media with good physical characteristics and high nutrient content. However, MC management can provide a more favorable ecosystem for the growth of soil microbial populations. The more stable abiotic factors of the ecosystem under non-intensive management can support the development of microorganisms through succession. It was also observed that BMP practices led to larger berry sizes, heavier bean weights, and higher sugar content in coffee beans, which are critical quality indicators. This research contributes valuable insights for future strategies in sustainable coffee production and highlights the broader environmental benefits of well-managed agroforestry systems.

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