BIODIVERSITAS
Volume 27, Number 5, May 2026
Pages: 16

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270509

Tree diversity, structure and composition in coffee agroforestry with varying shade systems, coffee species, and landscape settings in Malang, Indonesia

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Manuscript received: 15 November 2025. Revision accepted: 5 May 2026.

Abstract. *Hakim L, Yusuf M, Wiratantra FD, Rahardi B, Sunarharum WB, Nurrofik A. 2026. Tree diversity, structure and composition in coffee agroforestry with varying shade systems, coffee species, and landscape settings in Malang, Indonesia. Biodiversitas 27 (5): d270509. https://doi.org/10.13057/biodiv/d270509*. Coffee agroforestry in Malang Region, East Java, Indonesia has been widely recognized as a multifunctional land-use system that integrates economic, and social benefits; however, its comprehensive ecological characteristics remain poorly documented. This study examines tree diversity and ecological indicators in coffee agroforestry systems in Malang, East Java, across four landscape settings, three coffee species (arabica, robusta, and liberica) and shade systems typology (shaded monoculture, commercial polyculture, traditional polyculture and rustic). Field surveys were conducted at 64 sites to document shade-tree diversity, composition (Important Value Index) and ecological indices (Shannon-Wiener Diversity Index (H'), Evenness Index (E), and Simpson Dominance Index (D')). In total, there were 40 species of shade trees across all sites and primarily composed of Fabaceae and Malvaceae which contribute to soil fertility, habitat provision, and raw material resources. Results indicated that among shaded systems in averages includes, rustic-type exhibited the highest tree species diversity, high evenness, and low dominance (H' = 2.02, E = 0.97, D = 0.19), followed by traditional polyculture systems (H' = 1.23, E = 0.91, and D = 0.3), commercial polyculture (H' = 0.8, E = 0.89, D = 0.46), and shaded monoculture (H' = 0.17, E = 0.29, and D = 0.83). Liberica coffee agroforestry tended to show higher diversity index of shade trees with less dominance of few species compared to the other two. However, although its diversity assessments belong low to moderate scores, the presence of shade tree diversity has been shown to have a practical impact on the dynamics of coffee agroforestry, allowing farmers to increase food security while generating additional income beyond coffee. Therefore, to support ecological sustainability and community well-being in the Malang Region, conservation strategies and policy frameworks should prioritize biodiversity-friendly agroforestry management.

Keywords: Biodiversity, coffee agroforestry, ecological assessment, Malang Region, shade tree

INTRODUCTION

Agroforestry has been increasingly recognized as a sustainable land-use system that integrates trees with agricultural crops or livestock, providing ecological, economic, and social benefits simultaneously (Leakey 1996). According to Nair (1993), agroforestry systems could help reduce pressure on natural forests by promoting diversified and resilient agricultural landscapes. In tropical regions, where the conversion of forests to monoculture plantations has led to environmental degradation, agroforestry can help maintain biodiversity and ecosystem services (Torquebiau 2000; Jose 2009). Among agroforestry types, coffee agroforestry systems are predominantly grown in tropical countries known by its high biodiversity level including Indonesia. According to the Indonesian Coffee and Cocoa Research Institute, the extent of coffee agroforestry systems was estimated to have reached 1.26 million hectares in 2023 (Pusat Penelitian Kopi dan Kakao Indonesia 2023). This phenomenon has led to the significant development of coffee (*Coffea* spp.), not only as a key export commodity but also as a major source of agricultural income. In 2022, coffee contributed US$ 1.15 billion to Indonesia's foreign exchange by exporting 437.56 thousand tonnes (Kementerian Pertanian 2023).

Coffee agroforestry is typically managed under multistrata shade systems that resemble forest structure, suggesting its potential to support ecological functions alongside crop production. These shade-grown coffee systems could support flora and fauna diversity, improve soil quality, regulate microclimates, and enhance carbon sequestration, but, the impacts of shade-trees on such ecosystem benefits depend on shading type and species (Perfecto et al. 1996; Kutos et al. 2024). Understanding the vegetation structure and characteristics, such as species richness, canopy cover, basal area, and vertical stratification in coffee agroforestry systems, is critical to evaluate ecological health, biodiversity potential, and management sustainability as key indicators of ecological complexity and functionality (Soto-Pinto et al. 2000; Tscharntke et al. 2011; Atkins et al. 2023). Profiling shade trees based on their functional traits, such as nitrogen

fixation, litter quality, and crown architecture, provides critical insights into how they contribute to carbon storage, habitat provision, and hydrological regulation (Schroth et al. 2004; Cerda et al. 2017).

Despite Indonesia's global significance as a major coffee producer and the country's long history of shade-grown coffee, systematic research on how different types of shade systems influence ecological outcomes remains limited (Evizal et al. 2016). Furthermore, little is known about the detailed profiling of shade trees and how their structural and functional traits contribute to ecosystem services within coffee landscapes although some research in Indonesia has observed differences in basal area and species diversity between simple and complex systems (Raymundo et al. 2018). Therefore, applying the coffee agroforestry typology proposed by Toledo and Moguel provides a useful step for characterizing variation in shade structure and composition, thereby offering a foundational basis for future evaluations of their potential influence on ecosystem services and sustainable management (Toledo and Moguel 2012).

Malang Region in East Java Province represents a dynamic agroecological region where coffee agroforestry has been practiced for a long time in both mountainous and coastal areas. With several subdistricts known for their coffee production, either robusta (*Coffea canephora* Pierre ex A.Froehner), arabica (*Coffea arabica* L.), or (*Coffea liberica* W.Bull), it reflects the region's long-standing role as a center of cultivation (BPS Kabupaten Malang 2020; Abdelzaher 2025). However, increased land-use pressure as the impact of massive population growth, market demand, and agricultural intensification causes a concern that could alter the vegetation structure in many coffee-producing landscapes. These changes may lead to simplification of canopy layers, reduction in tree diversity, and loss of ecological functions (Rembold et al. 2017).

This study aims to investigate tree vegetation diversity, structure and composition of coffee agroforestry systems in varying coffee species (i.e. arabica, robusta, and liberica), shade systems (type and configuration) and landscape settings in Malang. The results are expected to provide baseline data that strengthens the long-term resilience of coffee agroforestry and contributes to a deeper understanding of agroforestry dynamics and offers insights into coffee shade management and sustainable land management in tropical agricultural landscapes.

MATERIALS AND METHODS

Study area

Field observation was conducted in Malang Region, East Java Province, Indonesia, from January 2025 to July 2025. This region is administratively comprised Malang District and Batu City, which have extensive coffee agroforestry systems spanning across four ecoregions, including three volcanic mountainous (Tengger, Arjuno, and Kawi) and hilly slopes along the coast in southern Malang (Figure 1).

Detailed descriptions of each ecoregion according to Suprayogo et al. (2023): (i) Tengger Mountainous Area, located on the eastern side of Malang. Within the area, there is Bromo-Tengger-Semeru National Park (BTSNP) as protected area. This area was formed from an ancient caldera, with recent volcanic activity occurring on Bromo (2,329 m asl) and Semeru/Mahameru (3,676 m asl), the highest peak. This mountainous area has a high level of soil fertility because it was formed from a combination of two soil types (andosol and entisol), which are associated with highly volcanic activities and the biomass generated from rainforest. The community includes the indigenous Tengger tribes and some of them practicing coffee agroforestry. (ii) Arjuno Mountainous Area, located on the northern side of Malang. Within the area, there is Raden Soerjo Grand Forest Park as protected area. This area consisted of two peaks with fewer volcanic activities, including Arjuno (3,339 m asl, dormant) and Welirang (3,156 m asl, normally active). The soil type in this area belongs to an inceptisol, with several properties that resemble those of an andic-like soil, making it suitable for coffee-agroforestry practices. Despite coffee agroforestry, there were other land use types, including natural forests, built-up areas, mixed gardens (orchards), barren land/rock outcrops, rice fields, shrubs, and dry fields.

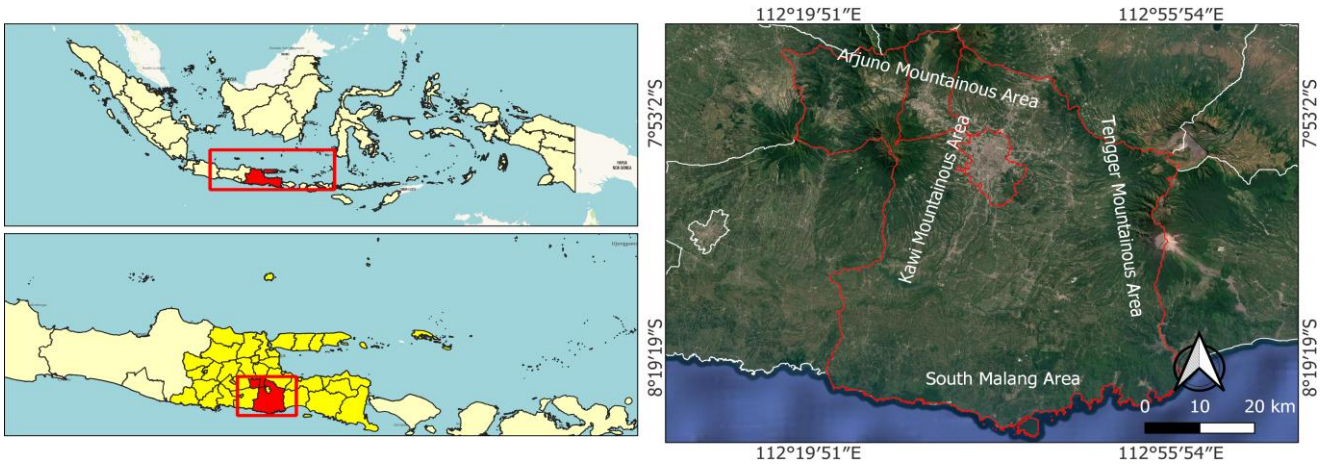

Figure 1. Map of the study area in Malang District and Batu City, East Java, Indonesia

(iii) Kawi Mountainous Area, located on the western side of Malang. Some areas are managed by Perhutani (state forestry company). This ancient volcanic complex, with its highest peak at Mount Buthak (2880 masl), offers unique microhabitats for coffee development, characterized by an inceptisol order soil type. Thus, according to its historical records during the colonial era, this area has been projected as the basis of coffee development in Malang Region (Cramer et al. 1957). Later, the current land uses are agroforestry, natural forests, built-up areas, orchards, vacant land/rock outcrops, rice fields, shrubs, and dry fields. (iv) South Malang Area, located on the southern side of Malang. This area consists of ancient volcanic slopes, hilly limestone areas, sandy coastal areas, and karst areas with elevations ranging from 0 to 700 masl. The types of soil orders present varied, depending on ecosystem types, including andosol and latosol orders on volcanic slopes, regosol in sandy coastal areas, and Mediterranean soils in karst areas.

Overall, within these ecoregions, we established 64 sampling sites of coffee agroforestry with a variation between transitional agroecological zones, ranging from lowland mixed gardens to upland montane forest systems. Each sampling site has been chosen for its unique soil characteristics, elevation, agroforestry type, shade variation, and coffee cultivation. All chosen sampling sites were outside of protected areas.

Field survey and data collection

Field surveys were conducted by teams of three to four trained researchers across the four ecoregions as explained above. Site selection followed a purposive sampling strategy, whereby coffee production systems representing a gradient of shade management intensities were deliberately targeted. Within each selected site, vegetation plots were established using random placement to minimize observer bias. This design, therefore, combines purposive site selection with random plot establishment. Each sampling site was spatially georeferenced and classified based on two explicit criteria: (i) coffee species planted, namely *C. canephora* (robusta), *C. arabica* (arabica), and *C. liberica* (liberica), (ii) shaded management systems, following the conceptual framework of Toledo and Moguel (2012). Shade systems (type and configuration) were classified into four categories: rustic (i.e. coffee plants are grown both under naturally growing trees and several multi-purposes tree plantations), traditional polyculture (i.e. coffee plants are shaded by a variety of tree species, which also serve as sources of fruits and/or hardwoods), commercial polyculture (i.e. coffee plants are grown under several selected shade trees that suited for coffee cultivation to maximize commercial value), and shaded monoculture (i.e. coffee plants are grown under a single tree species that is only used as shade, and the coffee are planted massively). Categorization were based on observable structural attributes, including the presence of shade trees and the diversity of woody species. Coffee fields lacking shade trees were categorized separately as unshaded coffee monoculture, which was treated as a non-agroforestry reference system, included solely for comparative purposes.

Vegetation surveys were conducted using a quadrant-based approach. At each site, three plots measuring 20 × 20 m were established to record all woody plants functioning as shade components with a Diameter at Breast Height (DBH) ≥ 20 cm. Species identification was initially carried out in the field with assistance from local farmers and community members, incorporating local ecological knowledge (LEK) of cultivated and spontaneous species. All shade vegetation was photographically documented using a Nikon P900 camera. The field identifications were subsequently verified through morphological examination of vegetative and reproductive characters (leaves, stems, fruits, and flowers). Identification was cross-validated using authoritative field guides (such as Flora Malesiana and Flora Pulau Sempu) (Rindyastuti et al. 2018) and online taxonomic databases, including The Plant List Ver 3.0 (www.theplantlist.org) (The Plant List 2013), and Plants of the World Online by the Royal Botanic Gardens, Kew (2017) (https://powo.science.kew.org). The global conservation status of each tree was confirmed using the International Union for Conservation of Nature (IUCN) Red List. No voucher specimens were collected due to ethical and permitting considerations associated with privately managed agricultural landscapes. This limitation is acknowledged, however, identification reliability was strengthened through triangulation of photographic records, multiple taxonomic references, and local expert knowledge. All field activities were non-invasive and observational, with no endangered or protected species collected. The resulting dataset provides a robust baseline for ecological assessment of coffee agroforestry systems in the Malang Region.

Data analysis

All sampling sites were spatially analyzed using Quantum GIS version 3.42.3 to examine the spatial distribution of coffee production systems, categorized by coffee species and shade management practices. Vegetation data from each site were tabulated by species and family to describe floristic composition across shade systems. Ecological indices were calculated for each sampling site, including the Shannon-Wiener Diversity Index (H') for measure diversity, the Evenness Index (E) for measuring distribution/dispersion of species in vegetation community, the Simpson Dominance Index (D'), and the Important Value Index (IVI), following standard ecological methodologies (Odum 1971; Fox et al. 2015; Majeed et al. 2022). These indices were used to characterize patterns of species diversity, dominance, and structural importance within each coffee production system. The formulas were described below:

Density

$$Di = ni / A$$

$$RDi = ni / N \times 100\%$$

Where, D_i is the density of species i, n_i is the number of individuals of species i, A is the total sampled area or total number of plots, RD_i is the relative density of species i, and N is the total number of individuals of all species.

Frequency

$F_i = P_i / P$

$RF_i = F_i / \Sigma F \times 100\%$

Where, F_i is the frequency of species i, P_i is the number of plots in which species i occurs, P is the total number of plots, RF_i is the relative frequency of species i, and ΣF is the total frequency of all species.

Dominance

$Do_i = BA_i / A$

$RDo_i = Do_i / \Sigma Do \times 100\%$

Where, Do_i is the dominance of species i, BA_i is the total basal area of species i, A is the total sampled area, RDo_i is the relative dominance of species i, and ΣDo is the total dominance of all species.

Important Value Index (IVI)

$IVI = RD_i + RF_i + RDo_i$

Where, IVI is the Important Value Index, RD_i is the relative density of species i, RF_i is the relative frequency of species i, and RDo_i is the relative dominance of species i.

*Diversity Index Shannon-Wiener (*H′*)*

$H' = -\Sigma\, p_i \ln p_i$

$p_i = n_i / N$

Where, H' is the Shannon-Wiener Diversity Index, p_i is the proportion of individuals belonging to species i, n_i is the number of individuals of species i, and N is the total number of individuals of all species.

Evenness Index (E)

$E = H' / \ln S$

Where, E is the Evenness Index, H' is the Shannon-Wiener Diversity Index, and S is the total number of species.

*Simpson Dominance Index (*D′*)*

$D = \Sigma\, p_i^2$

$p_i = n_i / N$

Where, D is the Simpson Dominance Index, p_i is the proportion of individuals belonging to species i, n_i is the number of individuals of species i, and N is the total number of individuals of all species.

Differences in ecological indices among agroforestry shade types were assessed using non-parametric statistics. Shannon diversity (H'), evenness, and dominance were compared across five agroforestry shade types. Because the sample sizes were unequal among groups and some classes contained limited observations, the Kruskal–Wallis rank-sum test was used to evaluate overall differences among shade types. When significant differences were detected, pairwise comparisons were further examined using Dunn's post hoc test with Holm-adjusted p-values. All statistical analyses were conducted in RStudio Ver 2025.01.

RESULTS AND DISCUSSION

Spatial distribution of coffee agroforestry's shaded system

According to our comprehensive survey, a total of 64 sampling sites were collected from the four landscapes in Malang at elevations ranging from 20 m asl (the lowest point) to 1,557 m asl (the highest point) (Figure 2). Specifically, 19 sites were situated in the Tengger mountainous area, 12 in the Arjuno mountainous area, 12 in the Kawi mountainous area, and 21 in the South Malang Region. The sampling sites were also categorized based on coffee species, comprising 21 sites for arabica (397 to 1,557 m asl), 24 sites for robusta (43 to 1,018 m asl), and 19 sites for liberica (20 to 879 m asl). This suggests that arabica predominantly occupies mountainous regions, robusta appears in both mountainous and coastal areas, while liberica predominantly inhabits coastal zones. All four types of shaded coffee systems identified in our surveys showed variations, with shaded systems comprising 62 sites and unshaded coffee representing 2 sites (highlighted in red in Figure 2). Specifically, the number of shaded monoculture systems was 18 sites, commercial polyculture was 20 sites, traditional polyculture was 22 sites, and rustic system was 2 sites. Based on soil characterization at the study sites, coffee agroforestry is cultivated on various soil types, including andosol, entisol, inceptisol, latosol, and Mediterranean soils. A detailed profile of each type of agroforestry system, along with the corresponding planted coffee varieties, is presented in Table 1, while the corresponding documentation is illustrated in Figure 3. Based on soil characterization at the study sites, coffee agroforestry is cultivated on various soil types, including andosol, entisol, inceptisol, latosol, and Mediterranean soils. A detailed profile of each type of agroforestry system, along with the corresponding planted coffee varieties, is presented in Table 1, while the corresponding documentation is illustrated in Figure 3.

Traditional polyculture shade system (22 sites) consisted of robusta (9 sites), liberica (3 sites), and arabica (10 sites) coffee varieties. In traditional polyculture systems, coffee plants were mostly shaded by coconuts (*Cocos nucifera* L.), sengon (*Albizia falcataria* (L.) Fosberg), waru (*Hibiscus tiliaceus* L.), and jackfruit (*Artocarpus heterophyllus* Lam.) (Figure 3.D). Additionally, coffee were cultivated alongside timber species and/or other agricultural crops such as banana (*Musa* sp.), cassava (*Manihot esculenta* Crantz), chilli (*Capsicum* sp.), and porang (*Amorphophallus muelleri* Blume). It is noteworthy that traditional polyculture systems often incorporate the practice of mixed stratum that locally called "tumpang sari" in their planting arrangements. This approach is typically employed by local farmers on private land to meet diverse resource needs for food (Habibah et al. 2024). Consequently, this management strategy enhances overall land productivity.

In commercial polyculture shade systems (20 sites) there were 4 sites for arabica, 7 sites for robusta, and 9 sites for liberica. Even though these systems may resemble traditional polyculture systems, they differ in having a smaller number of shade species and the extensive planting for commercial purposes. Depending on their management, these systems can be privately owned or in collaboration between coffee farmers with Perhutani, a state-owned forestry company. It can also be distinguished from tree species used as shade, where privately-owned commercial polyculture mostly uses a combination of two species, such as coconuts (*C. nucifera*), and lamtoro (*Leucaena leucocephala* (Lam.) de Wit) (Figure 3.C), while commercial polyculture with Perhutani collaboration used a combination of eucalyptus (*Eucalyptus* sp.), mahogany (*Swietenia mahagoni* (L.) Jacq.), and pine (*Pinus merkusii* Jungh. & de Vriese). Based on its location, commercial polyculture with Perhutani collaboration tends to be found in buffer zones of protected areas (e.g. Bromo Tengger Semeru National Park, R. Soerjo Grand Forest Park, and Perhutani's protection forest). This buffer zone falls into production zone according to its zonation (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia 2020).

Shaded monoculture sites (18) were only found at the production zone of Perhutani's forest, divided into 7 sites for robusta, 6 sites for arabica, and 5 sites for liberica. The single species of shade found consisted of pine, eucalyptus, and mahogany, which could contribute in the microclimate's stability and protect coffee cultivation from excessive evaporation and light stress (Koutouleas et al. 2022). The prospect of these shade types still holds coffee yield as the main priority, and the landscape documentation is shown in Figure 3.B.

A contrasting condition was shown between unshaded coffee (Figure 3.A) and rustic coffee agroforestry (Figure 3.E), which had the same number of 2 sites. Based on our surveys, unshaded coffee consisted of a specialized monoculture plantation that focuses on providing the highest coffee yields. In other hands, in the rustic system occurred only for liberica coffee, the floristic structure was complex because it depended on long-term interaction between the age of coffee plantation and previous forest types (lowland forest on the coastal limestone). Rustic coffee agroforestry harbours higher biodiversity and may provide minimal disturbance to the ecosystems but sacrifice high-intensity coffee productivity, intensive yield management, due to the high tendency of competition among shades (Bandeira et al. 2005). In unshaded coffee system, the absence of shade reduces structural complexity and limiting ecological roles. Besides that, this system depends on improved varieties, heavy agrochemical inputs, photoinhibition, intensive labor throughout the year, and consist of lower soil bioproductivity (Alves et al. 2016; Avelino et al. 2023; Manson et al. 2024).

The diversity of locations supported by the elevation range and soil types illustrates the heterogeneity of ecological factors in which coffee agroforestry was established. The spatial distribution (Figure 2) explains whether coffee agroforestry in each sampling site might reflect complex responses towards various environmental characteristics (i.e., microclimates, soil types, and natural vegetation), original stand cover, and the asynchrony in the development stage of different plantations, which also shape shaded types. These findings are still in line with basic characteristics for each coffee species where arabica were still found at high elevations, aligning with its ecological requirement for cooler climates (Morais et al. 2006). Meanwhile, robusta and liberica occupied low to middle elevation areas (Hasyim et al. 2024).

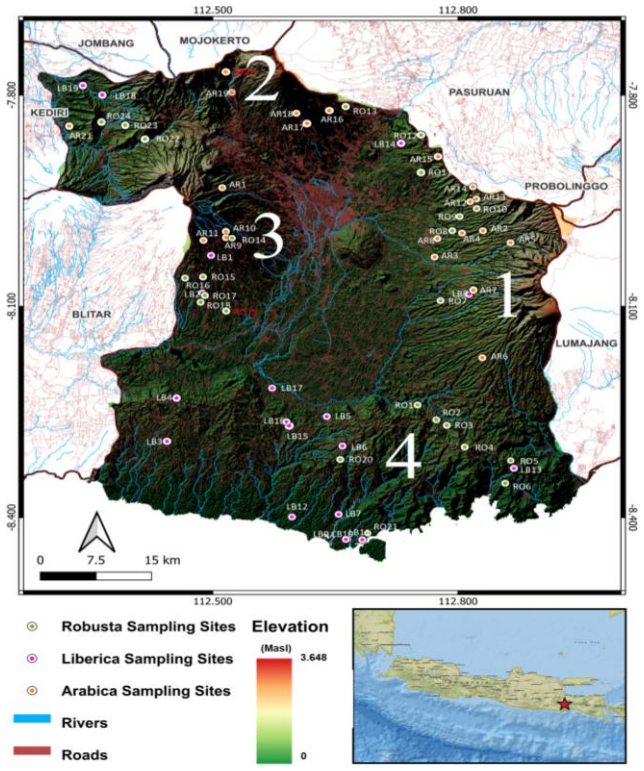

Figure 2. Spatial distribution of coffee agroforestry sampling sites in Malang Region based on coffee species planted: arabica (AR), robusta (RO), and liberica (LB). Red labels indicate unshaded coffee systems

Figure 3. Photographic examples of coffee agroforestry shade systems. A. Unshaded monoculture, B. Shaded monoculture, C. Commercial polyculture, D. Traditional polyculture, E. Rustic

Table 1. Detailed profiles of sampling sites of coffee agroforestry in Malang Region, Indonesia, including shade system (according to Toledo and Moguel 2012), and soil types (according to Suprayogo et al. 2023)

Coordinates	Landscape	Code	Shaded types	Elev (masl)	Soil types
8°0′35.30″S, 112°51′50.92″E	1	AR5	Shaded monoculture	1420	Andosol, entisol
7°55′13.20″S, 112°47′44.26″E	1	AR14	Commercial polyculture	1232	Andosol, entisol
7°57′7.14″S, 112°49′21.33″E	1	AR13	Commercial polyculture	1164	Andosol, entisol
7°57′39.05″S, 112°49′22.52″E	1	RO10	Shaded monoculture	1131	Andosol, entisol
7°57′25.62″S, 112°49′17.68″E	1	AR12	Traditional polyculture	1124	Andosol, entisol
7°59′32.30″S, 112°49′48.78″E	1	AR2	Shaded monoculture	1115	Andosol, entisol
7°57′26.02″S, 112°49′11.41″E	1	AR15	Traditional polyculture	1018	Andosol, entisol
8°10′23.04″S, 112°49′47.04″E	1	AR6	Traditional polyculture	798	Andosol, entisol
8°5′1.24″S, 112°48′45.19″E	1	AR7	Traditional polyculture	913	Andosol, entisol
8°5′13.48″S, 112°48′25.38″E	1	LB8	Traditional polyculture	910	Andosol, entisol
7°51′55.49″S, 112°45′26.82″E	1	RO12	Traditional polyculture	890	Andosol, entisol
8°0′2.13″S, 112°48′32.06″E	1	AR4	Traditional polyculture	854	Andosol, entisol
7°58′16.18″S, 112°48′31.29″E	1	RO9	Commercial polyculture	782	Andosol, entisol
8°6′37.69″S, 112°47′24.94″E	1	RO7	Traditional polyculture	777	Andosol, entisol
8°0′26.13″S, 112°47′6.47″E	1	RO8	Shaded monoculture	750	Andosol, entisol
8°1′47.86″S, 112°46′16.64″E	1	AR3	Traditional polyculture	695	Andosol, entisol
7°52′6.89″S, 112°43′52.43″E	1	LB14	Commercial polyculture	683	Andosol, entisol
7°58′21.33″S, 112°48′26.00″E	1	AR8	Traditional polyculture	666	Andosol, entisol
7°55′42.70″S, 112°45′18.59″E	1	RO11	Traditional polyculture	603	Andosol, entisol
7°46′43.92″S, 112°31′39.40″E	2	AR20	Unshaded monoculture	1557	Inceptisol
7°48′58.50″S, 112°32′50.62″E	2	AR19	Traditional polyculture	1275	Inceptisol
7°49′44.39″S, 112°34′30.44″E	2	AR18	Commercial polyculture	1191	Inceptisol
7°50′16.41″S, 112°35′59.20″E	2	AR16	Shaded monoculture	1098	Inceptisol
7°48′50.40″S, 112°37′34.11″E	2	AR17	Shaded monoculture	1078	Inceptisol
7°50′7.12″S, 112°39′4.61″E	2	RO13	Traditional polyculture	747	Inceptisol
7°51′36.98″S, 112°26′3.63″E	2	RO22	Shaded monoculture	742	Inceptisol
7°50′59.79″S, 112°22′26.54″E	2	RO23	Commercial polyculture	658	Inceptisol
7°48′35.60″S, 112°19′58.97″E	2	AR21	Commercial polyculture	546	Inceptisol
7°48′51.41″S, 112°21′44.88″E	2	RO24	Commercial polyculture	517	Inceptisol
7°46′19.95″S, 112°21′11.97″E	2	LB18	Shaded monoculture	514	Inceptisol
7°46′40.00″S, 112°18′55.89″E	2	LB19	Shaded monoculture	397	Inceptisol
7°55′55.44″S, 112°30′28.63″E	3	AR1	Traditional polyculture	1177	Inceptisol
8°0′25.22″S, 112°29′16.28″E	3	AR11	Traditional polyculture	1137	Inceptisol
7°59′38.38″S, 112°30′44.12″E	3	AR10	Shaded monoculture	1060	Inceptisol
8°0′7.75″S, 112°30′57.12″E	3	AR9	Shaded monoculture	998	Inceptisol
8°0′46.36″S, 112°33′48.22″E	3	RO14	Shaded monoculture	935	Inceptisol
8°1′41.75″S, 112°29′53.24″E	3	LB1	Shaded monoculture	879	Inceptisol
8°3′45.50″S, 112°29′29.87″E	3	RO15	Shaded monoculture	670	Inceptisol
8°3′53.51″S, 112°27′33.29″E	3	RO16	Commercial polyculture	660	Inceptisol
8°4′18.30″S, 112°27′33.82″E	3	LB2	Commercial polyculture	521	Inceptisol
8°5′5.33″S, 112°29′7.60″E	3	RO17	Commercial polyculture	520	Inceptisol
8°6′6.03″S, 112°28′17.10″E	3	RO18	Shaded monoculture	436	Inceptisol
8°5′42.52″S, 112°30′21.69″E	3	RO19	Unshaded monoculture	413	Inceptisol
8°19′46.58″S, 112°50′46.64″E	4	RO4	Traditional polyculture	834	Andosol, latosol
8°20′37.81″S, 112°51′29.89″E	4	RO5	Shaded monoculture	697	Andosol, latosol
8°21′4.53″S, 112°51′23.01″E	4	LB13	Shaded monoculture	639	Andosol, latosol
8°19′29.84″S, 112°37′58.99″E	4	RO20	Traditional polyculture	607	Andosol, latosol
8°20′29.26″S, 112°37′53.24″E	4	LB6	Commercial polyculture	564	Andosol, latosol
8°18′11.14″S, 112°24′54.46″E	4	LB3	Commercial polyculture	552	Andosol, latosol
8°17′22.21″S, 112°48′52.62″E	4	RO3	Traditional polyculture	534	Andosol, latosol
8°16′38.46″S, 112°47′39.23″E	4	RO2	Traditional polyculture	467	Andosol, latosol
8°20′50.00″S, 112°24′8.90″E	4	LB4	Shaded monoculture	463	Andosol, latosol
8°15′23.89″S, 12°45′2.15″E	4	RO1	Commercial polyculture	440	Andosol, latosol
8°17′23.53″S, 112°38′34.61″E	4	LB5	Commercial polyculture	433	Andosol, latosol
8°21′59.61″S, 112°51′15.36″E	4	RO6	Traditional polyculture	429	Andosol, latosol
8°15′24.35″S, 112°35′1.81″E	4	LB16	Rustic	403	Andosol, latosol
8°15′50.65″S, 112°35′24.47″E	4	LB15	Rustic	395	Andosol, latosol
8°12′55.37″S, 112°34′46.47″E	4	LB17	Commercial polyculture	306	Andosol, latosol
8°25′6.42″S, 112°38′29.81″E	4	LB7	Commercial polyculture	112	Andosol, latosol
8°24′5.33″S, 112°35′2.62″E	4	LB12	Traditional polyculture	75	Mediterranean
8°25′21.49″S, 112°41′23.19″E	4	RO21	Commercial polyculture	72	Mediterranean
8°25′33.88″S, 112°41′26.88″E	4	LB11	Traditional polyculture	65	Mediterranean
8°25′52.68″S, 112°39′59.85″E	4	LB9	Traditional polyculture	61	Mediterranean
8°26′4.70″S, 112°39′57.61″E	4	LB10	Traditional polyculture	43	Mediterranean

Overall, all combinations of shade type diversity make Malang an interesting site for a case study in agroforestry research. These field sites were selected to represent various ecosystem types and elevation gradients, ranging from lowland coffee plantations near valleys to complex multi-strata systems in upper montane zones. On the other hand, our observation highlights the potential role of coffee agroforestry: on one hand, as an economic livelihood for local communities, and on the other, as a land-use system that could support forest conservation by reducing pressure on strictly protected areas (Triwanto et al. 2022). The spread of coffee agroforestry into these buffer zones and rural areas underscores its importance as a socio-ecological compromise between conservation and production (Hidayat et al. 2021). Later, when linked to specialty coffee markets that appreciate origin-based differentiation, environmental factors can serve as a terroir aspect for future development. The integration of landscape diversity, agroforestry structure, and ecosystem functions contributes to distinct terroir characteristics that can increase the value of Malang coffee in specialty markets.

Species diversity of shade trees in coffee agroforestry

From 62 sampling sites, we recorded as many as 40 tree species, belonging to 18 families and 36 genera, where 24 species were found in arabica, 26 species in robusta, and 27 species in liberica. All of the tree species found have potential uses which 17 species as food resources, particularly fruits including kluwek (*Pangium edule* Reinw.), mango (*Mangifera indica* L.), coconut (*C. nucifera*), candlenut (*Aleurites moluccanus* (L.) Willd.), tamarind (*Tamarindus indica* L.), pete (*Parkia speciosa* Hassk.), lamtoro (*L. leucocephala*), avocado (*Persea americana* Mill.), durian (*Durio zibethinus* Murray), jackfruit (*A. heterophyllus*), sukun (*Artocarpus altilis* (Parkinson) Fosberg), bendo (*Artocarpus elasticus* Reinw. ex Blume), jambu air (*Syzygium aqueum* (Burm.fil.) Alston), matoa (*Pometia pinnata* J.R.Forst. & G.Forst.), sapodilla (*Manilkara zapota* (L.) P.Royen), and star apple (*Chrysophyllum cainito* L.), and one species as spices, i.e. clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry). There were also 9 legume species, showing their function as nitrogen fixers (Toledo and Miguel 2012).

The species assemblages revealed that 10 species were found on robusta, arabica, and liberica coffee agroforestry, 6 species were found on both arabica and robusta agroforestry, 2 species were found on both arabica and liberica agroforestry, and 5 species were found on both liberica and robusta agroforestry. In addition, 6 species were found only on liberica coffee agroforestry, 5 species were found only on arabica coffee agroforestry, and 2 species were found only on robusta coffee agroforestry. According to its distribution, most of the recorded trees are native species of Southeast Asia, and several species among them were introduced and domesticated, such as gamal (*Gliricidia sepium* (Jacq.) Kunth), mahogany (*S. mahagoni*), saman (*Samanea saman* (Jacq.) Merr.), tamarind (*T. indica*), avocado (*P. americana*), and balsa (*Ochroma pyramidale* (Cav.) Urb.).

Based on conservation status, 37 species are listed as Least Concern (LC), one species (*S. mahagoni*) is considered as Near Threatened (NT), and two species, including sonokeling (*Dalbergia latifolia* Roxb.) and pine (*P. merkusii*) were listed as Vulnerable (VU) according to IUCN assessment (IUCN Redlist 2025). We confirmed the absence of tree species considered as Endangered or Critically Endangered. Except that, comparison on species amount across each shade types (Figure 4) have been revealed that the traditional polyculture shown the highest tree composition in arabica (23 species from 10 sites) and robusta (26 species from 9 sites), meanwhile in liberica the highest composition was performed by rustic agriculture with 16 species from 2 sites. We assumed that higher tree diversity in the traditional polyculture system besides technically influences by amount of site, are still related towards management for sustainable livelihoods which is flexible to increase non-coffee products as active incomes. Meanwhile in rustic systems, it might relate towards for long term utilization for secondary choices or passive income, which is let the plantation randomly grown. Dude to compilation across shade systems, it was proven that the agroforestry systems of three coffee species have consistently utilized a combination of fruit trees, timber trees, and legume trees, which support the productivity and quality of the ecosystem. Overall, detailed checklist of all family, presence in coffee species, conservation status and its presence in each type of shade system were presented in Table 2.

Based on inventory species from Table 2, Fabaceae was the largest family with nine species, followed by Malvaceae with seven species. The presence of Fabaceae suggests beneficial value in maximizing land productivity, such as its ability to fix nitrogen, cause lower pH at topsoil, reduce soil acidification, and its litter can increase soil biomass (Misgana et al. 2024). Malvaceae was mostly planted as sources for building material and animal fodder, including waru gunung (*Talipariti simile* (Blume) Fryxell), bayur (*Pterospermum javanicum* Jungh.), balsa (*O. pyramidale*), kembang (*Scaphium linearicarpum* (Mast.) Pierre), trete (*Microcos tomentosa* Sm.), except for the single species, durian (*Durio zibethihus* Murray), that widely used for its fruits as food (Da-Costa-Rocha et al. 2014; Ketsa et al. 2020; Rahayu et al. 2023; Rumicha et al. 2025). Three species of monoculture of shade trees, such as pine (*P. merkusii*), eucalyptus (*Eucalyptus* sp.), and mahogany (*S. mahagoni*) were not only made dense canopy cover for coffee plantation, but also harvested for its timber and resin (Demko and Machava 2022; Budiaman and Hardjanto 2023). Thus, its occurrence in the production zone is expected to provide a natural barrier, preventing wildlife expansion, while coffee plantations also serve as additional habitats (Manson et al. 2024). The presence of crop trees, such as coconut (*C. nucifera*), and clove (*S. aromaticum*), also holds importance. The coconut tree was planted for its multiple benefits provided based on its parts (i.e., wood, leaves, and fruits), and the cloves also depended on its function as a main source of important spices (Kumar and Kunhamu 2022; Ullah et al. 2023; Habibah et al. 2024).

Table 2. Tree species in agroforestry system of three coffee species

Family	Tree Species	Coffee species			IUCN status	Shade systems (sites)
		Arabica (n=20)	Robusta (n=23)	Liberica (n=19)		
Achariaceae	Kluwek (*Pangium edule* Reinw.)	✓			LC	TP (1)
Anacardiaceae	Mango (*Mangifera indica* L.)			✓	LC	R (1)
Annonaceae	Kenanga (*Cananga odorata* (Lam.) Hook.f. & Thomson)	✓		✓	LC	TP (2), SM (1)
Arecaceae	Coconut (*Cocos nucifera* L.)	✓	✓	✓	LC	TP (9), SM (5), CP (6), R (1)
Cannabaceae	Anggrung (*Trema orientalis* (L.) Blume)	✓	✓	✓	LC	TP (3), CP (1), R (1)
Euphorbiaceae	Candlenut (*Aleurites moluccanus* (L.) Willd.)	✓			LC	TP (1)
Fabaceae	Angsana (*Pterocarpus indicus* Willd.)	✓	✓		LC	TP (4)
Fabaceae	Sengon (*Albizia falcataria* (L.) Fosberg)	✓	✓	✓	LC	TP (6), CP (3), R (1)
Fabaceae	Trembesi (*Samanea saman* (Jacq.) Merr.)		✓	✓	LC	TP (3), SM (1), CP (1), R (1)
Fabaceae	Gamal (*Gliricidia sepium* (Jacq.) Kunth)	✓			LC	TP (1)
Fabaceae	Tamarind (*Tamarindus indica* L.)			✓	LC	CP (3), R (1)
Fabaceae	Dadap (*Erythrina subumbrans* (Hassk.) Merr.)		✓		LC	TP (3), CP (1)
Fabaceae	Pete (*Parkia speciosa* Hassk.)	✓		✓	LC	TP (5), SM (1), CP (3)
Fabaceae	Sonokeling (*Dalbergia latifolia* Roxb.)	✓			VU	TP (2)
Fabaceae	Lamtoro (*Leucaena leucocephala* (Lam.) de Wit)	✓	✓	✓	LC	TP (5), SM (2), CP (5)
Lamiaceae	Teak (*Tectona grandis* L.f.)		✓	✓	LC	TP (3), CP (1)
Lamiaceae	Jati Putih (*Gmelina arborea* Roxb. ex Sm.)		✓	✓	LC	TP (3), CP (1), R (1)
Lauraceae	Avocado (*Persea americana* Mill.)	✓		✓	LC	TP (3), SM (1), CP (1)
Magnoliaceae	Cempaka (*Magnolia champaca* (L.) Baill. ex Pierre)			✓	LC	TP (2)
Malvaceae	Waru Gunung (*Talipariti simile* (Blume) Fryxell)	✓			LC	TP (5)
Malvaceae	Waru (*Hibiscus tiliaceus* L.)		✓	✓	LC	TP (3), CP (1), R (1)
Malvaceae	Durian (*Durio zibethinus* Murray)	✓	✓	✓	LC	TP (6), SM (1), CP (3), R (1)
Malvaceae	Bayur (*Pterospermum javanicum* Jungh.)			✓	LC	R (1)
Malvaceae	Balsa (*Ochroma pyramidale* (Cav.) Urb.)	✓	✓		LC	TP (1)
Malvaceae	Kembang (*Scaphium linearicarpum* (Mast.) Pierre)	✓	✓		LC	TP (2)
Malvaceae	Trete (*Microcos tomentosa* Sm.)		✓		LC	TP (1)
Malvaceae	Kapok (*Ceiba pentandra* (L.) Gaertn.)	✓	✓	✓	LC	TP (2)
Meliaceae	Mahogany (*Swietenia mahagoni* (L.) Jacq.)	✓	✓	✓	NT	TP (9), SM (4), CP (5), R (1)
Meliaceae	Suren (*Toona sinensis* (A.Juss.) M.Roem.)	✓	✓		LC	TP (3), CP (2), R (1)
Moraceae	Jackfruit (*Artocarpus heterophyllus* Lam.)	✓	✓	✓	LC	TP (4), SM (1), CP (3), R (1)
Moraceae	Sukun (*Artocarpus altilis* (Parkinson) Fosberg)	✓	✓	✓	LC	TP (2), R (1)
Moraceae	Bendo (*Artocarpus elasticus* Reinw. ex Blume)		✓	✓	LC	TP (4),
Myrtaceae	Eucalyptus (*Eucalyptus* sp.)	✓	✓		LC	TP (2), SM (1), CP (1)
Myrtaceae	Clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry)		✓	✓	LC	TP (1), SM (4)
Myrtaceae	Jambu air (*Syzygium aqueum* (Burm.fil.) Alston)		✓	✓	LC	TP (1)
Pinaceae	Pine (*Pinus merkusii* Jungh. & de Vriese)	✓	✓	✓	VU	TP (4), SM (5), CP (3)
Rubiaceae	Jabon (*Neolamarckia cadamba* (Roxb.) Bosser)	✓	✓		LC	TP (1)
Sapindaceae	Matoa (*Pometia pinnata* J.R.Forst. & G.Forst.)		✓	✓	LC	TP (1), R (1)
Sapotaceae	Sapodilla (*Manilkara zapota* (L.) P.Royen)			✓	LC	CP (1), R (1)
Sapotaceae	Star apple (*Chrysophyllum cainito* L.)			✓	LC	R (1)
Total		24	26	27		

Note: The "n" refers to the total sites. The IUCN Status, as referred to by the International Union for Conservation of Nature (IUCN), includes LC (Least Concern), NT (Near Threatened), and VU (Vulnerable). Code for Shade Systems: TP (Traditional Polyculture), SM (Shaded Monoculture), CP (Commercial Polyculture), R (Rustic)

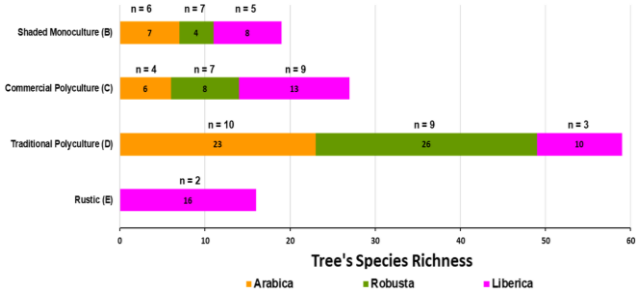

Figure 4. Comparison of tree's species richness on each coffee agroforestry's shaded types. Sign "n" revers to total coffee sites

Besides the mentioned species, other shade tree species also showed its crucial niches, both ecologically (such as serving wild animals' habitats, food resources, keeping microclimates, binding the soil, and carbon preservation) and economically (alternative incomes by timber and/or non-timber products, representing resilience adaptation for market fluctuation, and minimizing risk of coffee failure) (Lugo-Pérez et al. 2023; Nasiro 2024; Mihrete and Mihretu 2025). Therefore, the productivity at each sampling site depended on the tree composition and community structure that shape agroforestry types. Higher shade composition potentially supports more ecological services and increases land productivity based on the variation in its products. However, it also serves as evidence for promising local food security for further improvement.

Ecological indices

The assessment towards shade tree composition across sampling sites (Table 3) based on H' categorization, 10 coffee agroforestry sites exhibited very low diversity, 10 sites showed low diversity ($H' \leq 1$), and 42 sites ranged within the moderate category ($1 < H' < 3$) (Odum 1971), meanwhile based average calculations on coffee species, liberica exhibited the highest Shannon diversity (H' = 1.049), followed by arabica (H' = 0.713) and robusta (H' = 0.692). A similar pattern was observed for evenness, with liberica showing the highest value (E = 0.944), followed with robusta (E = 0.652) and arabica (E = 0.559). In contrast, dominance was lowest in liberica (D = 0.366), compared with robusta (D = 0.521) and arabica (D = 0.548) which is indicating that liberica-based coffee systems supported a more diverse and more evenly distributed ecological community than arabica and robusta systems. Meanwhile, within shaded coffee systems, rustic systems supported the highest diversity, characterized by high species evenness and low dominance (H′ = 2.02, E = 0.97, D = 0.19) followed by traditional polyculture (H′ = 1.23, E = 0.91, D = 0.30), and commercial polyculture (H′ = 0.80, E = 0.89, D = 0.46). In contrast, shaded monoculture exhibited the lowest diversity and evenness and the greatest dominance (H′ = 0.17, E = 0.29, D = 0.83). These results reflect biodiversity condition at each sampling site and highlight structural differences among shaded coffee agroforestry systems. IVI analysis further revealed distinct dominant shade-tree species across coffee types. In arabica coffee agroforestry (Table 3), *P. merkusii* was the most dominant shade species, achieving full dominance (IVI = 300) at four sites (AR2, AR9, AR10, AR16) and high dominance (IVI>150) at two additional sites (AR13, AR14). Other prominent shade species included *S. mahagoni*, which fully dominated site AR17 and was dominant at AR18 and AR21, and *Eucalyptus* sp., which fully dominated AR5 and was dominant at AR1. In robusta coffee agroforestry, a greater diversity of dominant shade species was observed. *C. nucifera* emerged as the primary shade species, fully dominating three sites (RO5, RO15, RO18) and showing high dominance at RO1, RO16, and RO20. This was followed by *S. aromaticum* (fully dominant at RO10 and RO14), *S. mahagoni* (fully dominant at RO8 and dominant at RO9), and *P. merkusii* (fully dominant at RO22). In contrast, liberica coffee agroforestry systems did not exhibit complete dominance by a single shade-tree species. Instead, five sites (LIB1, LIB4, LIB13, LIB18, LIB19) were characterized by co-dominance of two shade-tree species, indicating a more mixed canopy structure.

The ecological assessment of four coffee agroforestry shade types was evaluated using mean values, as presented in Table 4. Rustic coffee agroforestry and traditional polyculture showed higher shade-tree diversity and evenness and low dominance and might indicate prolonged human-landscape interactions that promote a balance between agricultural production and conservation objectives (Wynter et al. 2025). Meanwhile, commercial polyculture systems and shade monoculture systems showed markedly lower diversity and evenness with high dominance, reflecting limited variation in shade-tree composition and a strong tendency toward species dominance. This also tends to be associated with external drivers, including market demands and policy intervention, which often encourage simplified and homogenized shade structures (Muñoz-Villers et al. 2020). Although H' values across shade types may be categorized as low to moderate, these patterns reflect farmer's accumulated ecological knowledge developed through long-term land management practices. Such knowledge guides shade-tree selection, seasonal management, and the regulation of ecological interactions that help sustain productivity and biodiversity (Albertin and Nair 2004; Kusumawati et al. 2022). Overall, these findings highlight the importance of maintaining a balance between farmers' economic priorities and the ecological functions of coffee landscapes. Recognizing the ecological value of structurally diverse shade systems provides opportunities for more adaptive, inclusive, and sustainable coffee agroforestry management strategies.

Table 3. Comparison of ecological indices in coffee agroforestry sites with varying coffee species (arabica, robusta, and liberica) based on Shannon-wienner index (*H′*) Species evenness (*E*), dominance (*D′*) and tree composition using Important Value Index (IVI)

Site number	Shaded types	(*H′*)	(*E*)	(*D′*)	Tree composition (IVI)
AR1	Traditional polyculture	1.1	0.84	0.36	*Persea americana* Mill. (22.94), *Artocarpus heterophyllus* Lam. (47.67), *Eucalyptus* L'Hér. (140.41), *Pinus merkusii* Jungh. & de Vriese. (88.96)
AR2	Shaded monoculture	0	0	1	*Pinus merkusii* Jungh. & de Vriese. (300)
AR3	Traditional polyculture	1.6	0.95	0.2	*Chromolaena odorata* (L.) R.M.King & H.Rob. (23.92), *Trema orientale* (L.) Blume. (59.7), *Pterocarpus indicus* Willd. (69.33), *Albizia falcataria* (L.) Fosberg. (58.3), *Taliparitis simile (Blume) Fryxell* (67.4), *Durio zibethinus* L. (21.21)
AR4	Traditional polyculture	1.05	0.65	0.47	*Parkia speciosa* Hassk. (20.38), *Taliparitis simile* (Blume) Fryxell (26.9), *Durio zibethinus* L. (171.17), *Swietenia mahagoni* (L.) Jacq. (61.28), *Artocarpus heterophyllus* Lam. (20.24)
AR5	Shaded monoculture	0	0	1	*Eucalyptus* L'Hér. (300)
AR6	Traditional polyculture	1.4	0.91	0.26	*Pterocarpus indicus* Willd. (70.6), *Parkia speciosa* Hassk. (36.57), *Daviesia speciosa* Crisp (88.87), *Taliparitis simile (Blume) Fryxell* (69.51), *Ochroma pyramidale* (Cav. ex Lam.) Urb.(34.44)
AR7	Traditional polyculture	2.08	0.91	0.12	*Pangium edule* Reinw. (13.62), *Trema orientale* (L.) Blume (41.78), *Pterocarpus indicus* Willd. (42.74), *Daviesia speciosa* Crisp (33.26), *Leucaena leucocephala* (Lam.) de Wit (29.69), *Gliricidia sepium* (Jacq.) Kunth (12.99), *Persea americana* Mill. (13.46), *Taliparitis simile (Blume) Fryxell* (36.13), *Swietenia mahagoni* (L.) Jacq. (14.41), *Toona sinensis* (A.Juss.) M.Roem. (48.29), *Artocarpus heterophyllus* Lam. (13.58)
AR8	Traditional polyculture	1.3	0.95	0	*Cocos nucifera L.* (102.07), *Pterocarpus indicus* Willd. (43.02), *Durio zibethinus L.* (82.65), *Neolamarckia cadamba* (Roxb.) Bosser (72.24)
AR9	Shaded monoculture	0	0	1	*Pinus merkusii* Jungh. & de Vriese. (300)
AR10	Shaded monoculture	0	0	1	*Pinus merkusii* Jungh. & de Vriese. (300)
AR11	Traditional polyculture	0.5	0.86	0.59	*Swietenia mahagoni* (L.) Jacq. (197.4), *Pinus merkusii* Jungh. & de Vriese. (102.6)
AR12	Traditional polyculture	1.4	0.89	0.26	*Parkia speciosa* Hassk. (24.25), *Leucaena leucocephala* (Lam.) de Wit (26.32), *S. mahagoni* (69.01), *Toona sinensis* (A.Juss.) M.Roem. (82.51), *Pinus merkusii* Jungh. & de Vriese. (97.88)
AR13	Commercial polyculture	0.2	0.41	0.85	*Toona sinensis* (A.Juss.) M.Roem. (40.64), *Pinus merkusii* Jungh. & de Vriese. (259.36)
AR14	Commercial polyculture	0.56	0.52	0.71	*Solanum linearifolium* Geras. ex Symon (53.22), *Toona sinensis* (A.Juss.) M.Roem. (32.23), *Pinus merkusii* Jungh. & de Vriese. (214.54)
AR15	Traditional polyculture	1.01	0.92	0.46	*Ceiba pentandra* (L.) Gaertn. (30.9), *Swietenia mahagoni* (L.) Jacq. (148.21), *Pinus merkusii* Jungh. & de Vriese. (120.87)
AR16	Shaded monoculture	0	0	1	*Pinus merkusii* Jungh. & de Vriese. (300)
AR17	Shaded monoculture	0	0	1	*Swietenia mahagoni* (L.) Jacq. (300)
AR18	Commercial polyculture	0.6	0.97	0.52	*Swietenia mahagoni* (L.) Jacq. (169.8), *Pinus merkusii* Jungh. & de Vriese. (130.2)
AR19	Traditional polyculture	1.58	0.98	0.21	*Samanea saman (Jacq.) Merr.* (81.77), *Persea americana* Mill. (42.52), *Artocarpus heterophyllus* Lam. (38.47), *Artocarpus elasticus Reinw. ex Blume.* (53.94), *Pinus merkusii* Jungh. & de Vriese. (83.28)
AR20	Unshaded monoculture	0	0	0	(-)
AR21	Commercial polyculture	0.6	0.99	0.5	*Parkia speciosa* Hassk. (140.46), *Swietenia mahagoni* (L.) Jacq. (159.53)
LB1	Shaded monoculture	0.6	1	0.5	*Persea americana* Mill. (107.81), *Syzygium aromaticum* (L.) Merr. & L.M.Perry. (192.19)
LB2	Commercial polyculture	1.1	0.99	0.33	*Cocos nucifera* L. (105.25), *Tamarindus indica* L. (104.162), *Leucaena leucocephala* (Lam.) de Wit. (93.58)
LB3	Commercial polyculture	1.3	0.99	0.26	*Persea americana* Mill. (59.89), *Leucaena leucocephala* (Lam.) de Wit. (67.39), *Artocarpus heterophyllus* Lam. (80.1), *Manilkara zapota* (L.) P.Royen (92.6)
LB4	Shaded monoculture	0.7	0.86	0.51	*Cocos nucifera* L. (184.95), *Leucaena leucocephala* (Lam.) de Wit. (115.05)
LB5	Commercial polyculture	0.9	0.86	0.44	*Cocos nucifera* L. (68.37), *Albizia falcataria* (L.) Fosberg. (161.03), *Parkia speciosa* Hassk. (70.6)
LB6	Commercial polyculture	1.2	0.82	0.35	*Cocos nucifera* L. (130), *Albizia falcataria* (L.) Fosberg. (26.66), *Hibiscus tiliaceus L.* (63.3), *Swietenia mahagoni* (L.) Jacq. (80)

LB7	Commercial polyculture	0.8	0.92	0.46	*Cocos nucifera* L. (81.67), *Artocarpus heterophyllus* Lam. (34.56), *Syzygium aromaticum* (L.) Merr. & L.M.Perry (183.75)
LB8	Traditional polyculture	1.2	0.95	0.31	*Cocos nucifera* L. (94.92), *Samanea saman* (Jacq.) Merr. (58.95), *Pterospermum javanicum* Jungh. (101.8), *Artocarpus elasticus* Reinw. ex Blume. (44.3)
LB9	Traditional polyculture	1.3	0.98	0.28	*Chromolaena odorata* (L.) R.M.King & H.Rob. (58.34), *Cocos nucifera* L (101.46), *Parkia speciosa* Hassk. (81.8), *Pterospermum javanicum* Jungh. (58.69)
LB10	Traditional polyculture	1.1	1	0.35	*Samanea saman* (Jacq.) Merr (90.88), *Swietenia mahagoni* (L.) Jacq (107.7), *Artocarpus altilis* (Parkinson) Fosberg (101.42)
LB11	Traditional polyculture	1.3	1	0.25	*Chromolaena odorata* (L.) R.M.King & H.Rob. (68.02), *Cocos nucifera* L (96.3), *Parkia speciosa* Hassk (67.35), *Durio zibethinus L.* (68.34)
LB12	Traditional polyculture	0.3	1	0.33	*Pterocarpus indicus* Willd. (97.82), *Swietenia mahagoni* (L.) Jacq. (84.42), *Artocarpus elasticus* Reinw. ex Blume (117.53)
LB13	Shaded monoculture	0.7	0.99	0.5	*Pterospermum javanicum* Jungh (135.32), *Swietenia mahagoni* (L.) Jacq (164.68)
LB14	Commercial polyculture	1.1	0.97	0.34	*Trema orientale* (L.) Blume (86.4), *Gmelina arborea* Roxb. ex Sm. (122.7), *Pinus merkusii* Jungh. & de Vriese. (90.9)
LB15	Rustic	1.87	0.96	0.22	*Tectona grandis* L.f. (80.48), *Gmelina arborea* Roxb. ex Sm. (38.42), *Hibiscus tiliaceus* L. (23.8), *Ceiba pentandra* (L.) Gaertn. (23.91), *Pterospermum javanicum* Jungh (29.56), *Artocarpus altilis* (Parkinson) Fosberg (47.1), *Chrysophyllum cainito* L. (56.73)
LB16	Rustic	2.17	0.99	0.16	*Mangifera indica L.* (51.97), *Cocos nucifera* L (25.49), *Trema orientale* (L.) Blume (34.17), *Samanea saman* (Jacq.) Merr. (30.49), *Tamarindus indica* L. (28.19), *Swietenia mahagoni* (L.) Jacq (35.91), *Artocarpus elasticus* Reinw. ex Blume (37.80), *Pometia pinnata* J.R.Forst. & G.Forst. (33.97), *Manilkara zapota* (L.) P.Royen (21.97)
LB17	Commercial polyculture	1.1	0.97	0.34	*Hibiscus tiliaceus* L. (103.67), *Durio zibethinus* L. (117.57), *Artocarpus heterophyllus* Lam. (78.74)
LB18	Shaded monoculture	0.6	1	0.52	*Tectona grandis* L.f. (152.18), *Durio zibethinus* L (147.81)
LB19	Shaded monoculture	0.6	0.69	0.5	*Parkia speciosa* Hassk (132.49), *Artocarpus heterophyllus* Lam. (167.51)
RO1	Commercial polyculture	0.9	0.91	0.4	*Cocos nucifera* L. (150.43), *Albizia falcataria* (L.) Fosberg. (68.91), *Erythrina subumbrans* (Hassk.) Merr. (80.65)
RO2	Traditional polyculture	1.3	0.81	0.36	*Cocos nucifera* L. (118.48), *Tectona grandis* L.f. (60.78), *Gmelina arborea* Roxb. ex Sm. (41.4), *Durio zibethinus* L. (41.5), *Toona sinensis* (A.Juss.) M.Roem. (37.8)
RO3	Traditional polyculture	1.5	0.95	0.23	*Cocos nucifera* L. (62.92), *Albizia falcataria* (L.) Fosberg. (33.92), *Microcos tomentosa* Sm. (33.99), *Syzygium aqueum* (Burm.f.) Alston (49.66), *Pometia pinnata* J.R.Forst. & G.Forst. (119.48)
RO4	Traditional polyculture	1.5	0.93	0.25	*Cocos nucifera* L. (37), *Magnolia champaca* (L.) Baill. ex Pierre (104.4), *Swietenia mahagoni* (L.) Jacq (80.63), *Artocarpus heterophyllus* Lam. (37.43), *Artocarpus altilis* (Parkinson) Fosberg (40.54)
RO5	Shaded monoculture	0	0	1	*Cocos nucifera* L. (300)
RO6	Traditional polyculture	1.1	0.7	0.45	*Albizia falcataria* (L.) Fosberg. (32.83), *Magnolia champaca* (L.) Baill. ex Pierre (33.85), *Hibiscus tiliaceus* L. (67.95), *Ceiba pentandra* (L.) Gaertn. (40.83), *Syzygium aromaticum* (L.) Merr. & L.M.Perry (124.5)
RO7	Traditional polyculture	1.8	0.96	0.17	*Trema orientale* (L.) Blume (24.74), *Albizia falcataria* (L.) Fosberg. (103.27), *Leucaena leucocephala* (Lam.) de Wit (41.88), *Tectona grandis* L.f. (36.45), *Persea americana* Mill. (36.56), *Solanum linearifolium* Geras. ex Symon (32.47), *S. mahagoni* (24.58)
RO8	Shaded monoculture	0	0.82	0.46	*Swietenia mahagoni* (L.) Jacq (300)
RO9	Commercial polyculture	0.8	0.82	0.46	*Cocos nucifera* L. (75.44), *Leucaena leucocephala* (Lam.) de Wit (76.45), *Toona sinensis* (A.Juss.) M.Roem. (148.1)
RO10	Shaded monoculture	0	0	1	*Syzygium aromaticum* (L.) Merr. & L.M.Perry (300)
RO11	Traditional polyculture	1.2	0.92	0.3	*Leucaena leucocephala* (Lam.) de Wit (63.91), *Eucalyptus* L'Hér. (109.75), *Syzygium aromaticum* (L.) Merr. & L.M.Perry (83.91), *Pinus merkusii* Jungh. & de Vriese. (42.4)
RO12	Traditional polyculture	1.3	1	0.25	*Pterocarpus indicus* Willd. (63.15), *Albizia falcataria (L.) Fosberg*. (101.02), *Leucaena leucocephala* (Lam.) de Wit (65.1), *Hibiscus tiliaceus* L. (70.72)
RO13	Traditional polyculture	1.2	0.93	0.3	*Albizia falcataria (L.) Fosberg*. (62.05), *Leucaena leucocephala* (Lam.) de Wit (70.61), *Tectona grandis* L.f. (74.8), *Taliparitis simile* (Blume) Fryxell (92.53)
RO14	Shaded	0	0	1	*Syzygium aromaticum* (L.) Merr. & L.M.Perry (300)

	monoculture				
RO15	Shaded monoculture	0	0	1	*Cocos nucifera* L. (300)
RO16	Commercial polyculture	0.6	1	0.5	*Cocos nucifera* L. (179.54), *Leucaena leucocephala* (Lam.) de Wit (120.45)
RO17	Commercial polyculture	0.6	0.97	0.52	*Tectona grandis* L.f. (123.51), *Gmelina arborea* Roxb. ex Sm (176.48)
RO18	Shaded monoculture	0	0	1	*Cocos nucifera* L. (300)
RO19	Unshaded monoculture	0	0	0	(-)
RO20	Traditional polyculture	0.6	1	0.5	*Cocos nucifera* L. (175.12), *Swietenia mahagoni* (L.) Jacq (124.87)
RO21	Commercial polyculture	1	0.96	0.36	*Samanea saman* (Jacq.) Merr (96.9), *Toona sinensis* (A.Juss.) M.Roem. (121.4), *Swietenia mahagoni* (L.) Jacq (81.7)
RO22	Shaded monoculture	0	0	1	*Pinus merkusii* Jungh. & de Vriese. (300)
RO23	Commercial polyculture	0.6	0.99	0.5	*Leucaena leucocephala* (Lam.) de Wit (119.96), *Durio zibethinus* L. (180.03)
RO24	Commercial polyculture	0.6	1	0.5	*Leucaena leucocephala* (Lam.) de Wit (143.63), *Durio zibethinus* L. (156.36)

Table 4. Comparison of ecological indices among agroforestry shade types based on Kruskal–Wallis followed by Dunn's post hoc test

Agroforestry shade type	n	Shannon diversity (*H′*)	Evenness (*E*)	Dominance (*D′*)
Rustic	2	2.02 ± 0.21^{a}	0.98 ± 0.01^{a}	0.19 ± 0.04^{bc}
Traditional polyculture	24	1.24 ± 0.39^{a}	0.92 ± 0.10^{a}	0.30 ± 0.13^{c}
Commercial polyculture	18	0.81 ± 0.29^{b}	0.89 ± 0.08^{a}	0.46 ± 0.14^{b}
Shaded monoculture	18	0.18 ± 0.30^{c}	0.30 ± 0.25^{b}	0.83 ± 0.24^{a}
Unshaded monoculture	2	0.00 ± 0.00^{bc}	0.00 ± 0.00^{ab}	0.00 ± 0.00^{bc}

Note: Values are presented as mean ± SD. The significant differences among agroforestry shade types based on Dunn's post hoc test with Holm-adjusted p-values following Kruskal–Wallis analysis at $p < 0.05$ were shown by superscript letters

Implication and recommendations

This study comprehensively shows the detailed characteristics of coffee agroforestry in Malang Region in varying landscapes, elevations, shade types and coffee species. In light of this finding, we emphasize that coffee agroforestry becomes one of the primary landscapes shaping Malang Region, particularly in rural areas and buffer zones that span three mountainous areas and the coastal area. Coffee agroforestry not only provides a unique ecological mosaic, but also summarizes various socio-cultural practices, ecological knowledge, and land management against coffee as the main commodity (Urugo et al. 2025). Coffee productivity in Malang Region in 2024 reached 15.236,57 tons from 21,100 ha of area with Malang District produced over 15.000 tons, significantly higher than Batu City which produced the rest (BPS Kabupaten Malang 2025; BPS Kota Batu 2025). We assumed each type of coffee agroforestry shaded system in our study sites might show its contribution in determining productivity across the region through distinct shade-tree compositions and ecological conditions. Nevertheless, to inform management implications, future research is recommended to determine the influence of variables such as microclimates, farmers' agroforestry management, and agronomy characters selecting which agroforestry shaded system to choose (Waktola and Fekadu 2021; Konaté et al. 2024).

Several recommendations are proposed in agroforestry planning, such as biodiversity enhancement, soil management, sustainable pest control, food security, and carbon stock improvement. For biodiversity enhancement, although several sites have been confirmed to have complex vegetation shades (such as those found in rustic and polyculture systems), the overall scores from ecological assessments still need to be improved. Therefore, efforts to increase the diversity of shade species are crucial for creating more balanced microclimate conditions. Planting shade trees is crucial in suppressing the intensity of direct light, reducing excess temperature, and lowering the rate of photorespiration (Hairiah et al. 2002). Beyond biodiversity outcomes, improved shade complexity can also enhance the resilience of coffee agroforestry systems to climate variability by regulating microclimate and supporting key soil processes, such as moisture retention, organic matter accumulation, and nutrient cycling (Albertin and Nair 2004; Misgana et al. 2024). Consequently, biodiversity-oriented shade management provides a foundation for climate-adaptive agroforestry practices that strengthen system durability and long-term sustainability, aligned with the Sustainable Development Goals on climate action (SDG 13) (Küfeoğlu 2022). In addition, to maintain the sustainability of coffee productivity and ecosystem stability in the context of soil management, one necessary approach is site-specific soil management. This approach consists of a strategy that increases soil resiliency, particularly in

several areas with unstable rainfall patterns. In its practice, this approach could easily be adjusted by the specific characteristics of each soil type in each ecoregion (Tham-Agyekum et al. 2023).

As a recommendation for sustainable pest control and management in coffee plantations, one potential approach is utilizing shade trees as predator houseplants (Góngora et al. 2023). This concept refers to the primary ecological functions of shade trees, which provide natural microhabitats and enhance food-web complexity, particularly by involving ants and birds that act as natural predators and biocontrollers (Moura et al. 2025). Several key pests, such as *Hypothenemus hampei* (Ferrari, 1867) (coffee berry borer) and *Xylosandrus compactus* Wood & Bright, 1992 (branch borer), which are known to cause severe damage in coffee systems, can be better regulated when predator-supporting shade trees are present. Evidence from studies conducted in South America, India, and other coffee producers in tropical regions shows that higher shade-tree species richness and structural complexity significantly improve predator activity, with certain species functioning specifically as effective houseplants for predatory ants and insectivorous birds (Escobar-Ramírez et al. 2019; Sinu et al. 2021).

Meanwhile, in the context of food security improvement, the observed diversity of shade trees may indicate a potential contribution to household food security by supplying culturally significant edible plants and multifunctional resources that support local livelihoods. However, it should be noted that the contribution of shade tree diversity to household food security was not directly measured in this study, as household-level food security surveys and quantitative assessments of shade tree product use were not conducted. Consequently, interpretations presented here are inferred from shade tree species composition and supported by ethnobotanical evidence from comparable agroforestry systems reported in the literature. From an ethnobotanical perspective, traditional shade species are intentionally selected not only for their ecological functions but also for their provision of fruits, leaves, medicines, animal fodder, and firewood that reflect long-standing cultural knowledge and subsistence strategies (Toledo and Barrera-Bassols 2008; Bharucha and Pretty 2010; Reza et al. 2025). The integration of these ethnobotanically valuable species reduces dependence on external food markets, enhances dietary diversity, and preserves traditional culinary practices that contribute to community well-being around Malang ecoregions (Santhyami and Yunita 2024). Furthermore, maintaining diverse shade-tree assemblages reinforces intergenerational knowledge transfer regarding plant use, harvesting cycles, and seasonal food availability, which were often overlooked but constitute an essential social dimension of food security (Tesfa et al. 2025).

From a carbon-stocks perspective, shade trees exhibit high photosynthetic capacity, rapid growth rates, and substantial wood density, as these traits enable efficient CO_2 sequestration within tree trunks, branches, and root systems (Soto-Pinto et al. 2010; Haggar et al. 2011). In addition, continuous inputs of litterfall, fine-root turnover, and rhizodeposition further enhance soil-carbon stabilization through microbial transformation and humification processes (Noponen et al. 2013). Our study sites on shaded coffee potentially represent substantial carbon reservoirs, contributing to both aboveground and belowground carbon pools through long-term biomass accumulation and the formation of organic matter, as observed during the shade system, compared with unshaded coffee. Furthermore, evidence from studies across Latin America and Southeast Asia shows that diversified shade canopies significantly increase total carbon stocks, often by 40-60% compared to full-sun monocultures due to their multilayered vertical structure and greater stand structural complexity (De Beenhouwer et al. 2013; Cerda et al. 2020). Consequently, species-rich shade compositions not only enhance overall ecosystem functioning but also strengthen the role of coffee agroforestry as an effective nature-based climate mitigation strategy through improved carbon sequestration and long-term carbon storage.

In future development, coffee agroforestry with higher biodiversity, food web, and biomass compound provides higher sustainability against climate issues, requiring consistent management strategies that integrate biodiversity conservation with farmers' socio-economic realities. This is because the socio-cultural dimension of coffee agroforestry should be recognized as a core element in conservation strategies (Gillison et al. 2004; Valencia et al. 2015). At the policy and management level, acknowledging these multifunctional roles is crucial for designing incentive-based mechanisms, including eco-certification schemes and payments for ecosystem services, that not only reward biodiversity-friendly practices but also improve local livelihoods (Triwanto et al. 2022). Thus, embedding local knowledge into broader policy frameworks can reinforce conservation outcomes while ensuring that coffee agroforestry remains both ecologically resilient and socially equitable (Hakim 2011; Hidayat et al. 2021; Sudomo et al. 2023; Habibah et al. 2024). In this sense, future research is expected to bridge ecological assessments with participatory approaches, thereby producing comprehensive guidelines that strengthen the resilience and multifunctionality of coffee agroforestry in Malang Region.

In conclusion, this study describes that coffee agroforestry systems in Malang Region was structured by interactions among landscape settings across four ecoregions with elevation ranged from 43-1557 m. asl, types of shade systems, and its tree species composition, resulting in heterogeneous ecological mosaics. Ecological assessments based on diversity, evenness, and dominance indices indicate that rustic and traditional polyculture systems consistently support higher shade-tree diversity, greater structural complexity, and lower species dominance compared to commercial polyculture and shaded monoculture systems. These patterns highlight the ecological advantages of more complex shade systems in sustaining ecosystem functions such as biodiversity conservation, microclimate regulation, and long-term land productivity, while also supporting farmers' livelihoods. In contrast, simplified shade monoculture systems exhibit reduced ecological performance and higher species

dominance, reflecting management strategies that prioritize short-term productivity over multifunctionality. From a management and policy perspective, the findings underscore the importance of maintaining and promoting diverse shade systems through conservation-oriented agroforestry strategies. Future research and policy efforts should prioritize continuous ecological monitoring and participatory approaches that integrate local ecological knowledge with adaptive management frameworks, thereby strengthening the resilience and sustainability of coffee agroforestry landscapes in Malang Region.

ACKNOWLEDGEMENTS

We gratefully thank Elfaskhosyi S. Gunawan, Arya Bimantara, Roza Anggelina, Hamdan Yuwafi, and Danniary Ismail Faronny, for their support while conducting field observation. We also thank local farmers around the Malang Region, East Java, Indonesia, for their contribution and support in collecting field data. We are grateful to Universitas Brawijaya, Malang, for supporting this research with *Hibah Ekosistem Guru Besar* 2024/2025. We also thank the anonymous reviewer and editor for their constructive comments and reviews.

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