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Full Length Research Article

Diversity and Ecophysiological Performance of Coffee under Dry-Field and Homegarden Agroforestry in Yogyakarta

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ABSTRACT

Coffee is commonly cultivated under agroforestry systems, including dry-field and homegarden. These systems were differentiated based on their proximity to the settlements, which might influence the species composition. This study aimed to observe plant composition, diversity, vegetation structure, and microclimate in coffee agroforestry systems and the physiological conditions of coffee. The experimental design was based on purposive sampling. A total of 100 nested plots were established in Glagaharjo and Balerante of Yogyakarta, each consisting of a dry-field and homegarden. Higher diversity and potential products were observed in dry-field agroforestry. There was no significant difference in microclimate between both systems. However, a significantly higher number of poles ($p < 0.001$) and trees ($p < 0.001$) in dry-field compared to homegarden contributed to lower light interception, higher humidity and temperature in dry-field, which could be associated with the higher physiological performance of coffee despite the non-significant difference between the systems ($p > 0.05$). Therefore, microclimate conditions under dry-fields were considered suitable for improving coffee growth performance.

1. Introduction

Coffee is the most traded commodity globally and the most consumed beverage worldwide (Samoggia and Riedel 2018). According to the USDA (2022), global coffee production reached 170 million bags in 2022–2023, each containing 60 kg. Indonesia is the fourth largest coffee producer in the world, following Brazil, Vietnam, and Colombia. The USDA also reports that Indonesia is the fourth largest exporter of coffee beans (6,600 bags) in 2022–2023. Small-scale farmers contribute the highest quantity (771,000 tons) to domestic coffee production in Indonesia compared to state (1,100 tons) and private (2,900 tons) enterprises (BPS 2023). Globally, 70% of global crop production relies on small-scale farmers, providing over 25 million livelihoods essential for food security and the rural economy (Jezeer et al. 2019). The international coffee trade involves 500 million people, from on-farm to off-farm management, including farmers, traders, processors, and retailers. These sectors' vast participation emphasizes their socioeconomic significance (Pancsira 2022).

Coffee cultivation on small-scale farms is commonly managed under an agroforestry system, considering that coffee is a species that requires shade to grow optimally (Meylan et al. 2017). Coffee cultivation under agroforestry systems also brings various benefits, including providing multiple economic functions for farmers (Roslinda et al. 2023), reducing the risk of losses caused by diseases (Cerda et al. 2020), maintaining carbon sequestration (Zaro et al. 2020), and conservation functions (Muñoz-Villers et al. 2020). However, various factors should be considered to establish a coffee-based agroforestry system, including plant composition, to allow optimal growth for coffee to avoid plant competition (Zewdie et al. 2022). Besides, appropriate plant composition in agroforestry also provides optimal light availability and temperature for coffee to ensure sensory quality and yield (Kath et al. 2020; Worku et al. 2015) and water availability, which influences physiological processes and the quality of coffee (Martinez et al. 2020). Even though coffee is classified as a C3 plant typically sensitive to high light intensity, there should be appropriate shading management, especially under agroforestry systems, such as pruning, to avoid continuous shading detrimental to plants. Various classifications of agroforestry systems include its production system, which is divided into homegarden and dry-field systems. A notable distinction between both systems is their distance from the residential area. Homegarden is commonly practiced near residential areas and is dominated by food crops or fruit trees. In contrast, the dry-field system is located away from the main house and is commonly composed of timber commodities.

Different plant compositions in the homegarden and dry-field systems can determine the crown structure, microclimate condition, and physiological response of coffee as the main crop. Assessing the potential products of each plant composition within both systems can also provide essential references for further evaluation of the ecological and socioeconomic benefits. Therefore, this research aimed to compare plant composition, diversity, vegetation structure, and microclimate in coffee agroforestry systems and the physiological conditions of coffee.

2. Materials and Methods

2.1. Study Area

The study was conducted in two villages viz. Glagaharjo and Balerante are located on the southern slope of Merapi Mountain, Yogyakarta (**Fig. 1**). Glagaharjo and Balerante were located in 700 and 900 masl, respectively. According to Schmidt and Ferguson classification, the mean annual temperature was recorded at 20–30°C, with a yearly rainfall of 875–2,527 mm/year, with a type C climate. Rainfall intensity during the study period was classified as very low (0.3 mm), with the highest intensity recorded at 13.9 mm, and the highest duration of daylight was 10 hours (**Fig. 2**). The study area was 0–3 km from Merapi National Park and was significantly affected by Merapi eruption in 2010. Generally, the study locations have fertile volcanic soil and relatively good land cover. The study sites were established based on agroforestry commonly practiced by the villagers, viz. homegarden and dry-field, which were differentiated by distance from residential areas. Homegarden is an agroforestry practice established around residential areas and planted with various timber and multi-purpose trees along with annual crops. Conversely, dry-field is an agroforestry practice established separately from residential areas and predominantly planted with trees and perennial crops. Hence, it is managed less intensively than homegarden (Suryanto et al. 2012). Coffee becomes the primary crop in both villages.

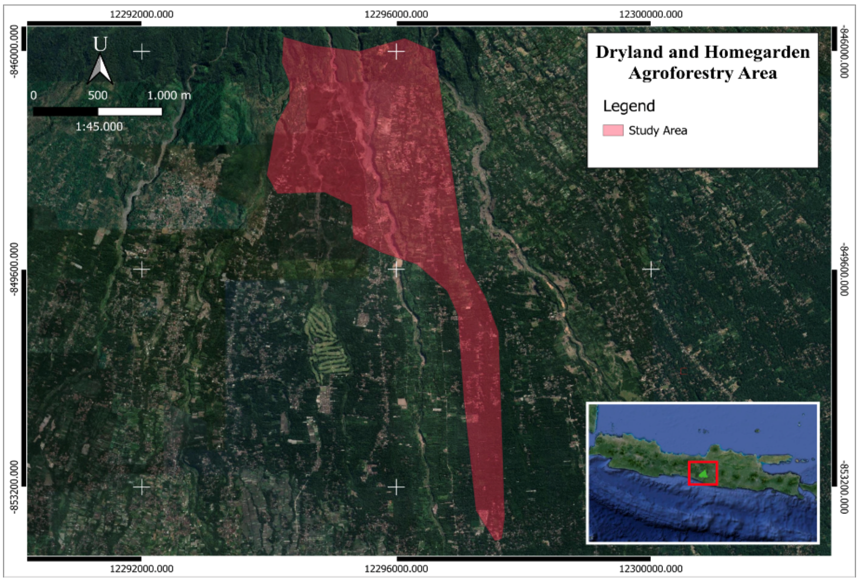

Fig. 1. Map showing collection data of study sites in Glagaharjo and Balerante, Yogyakarta (study location is indicated by red zone).

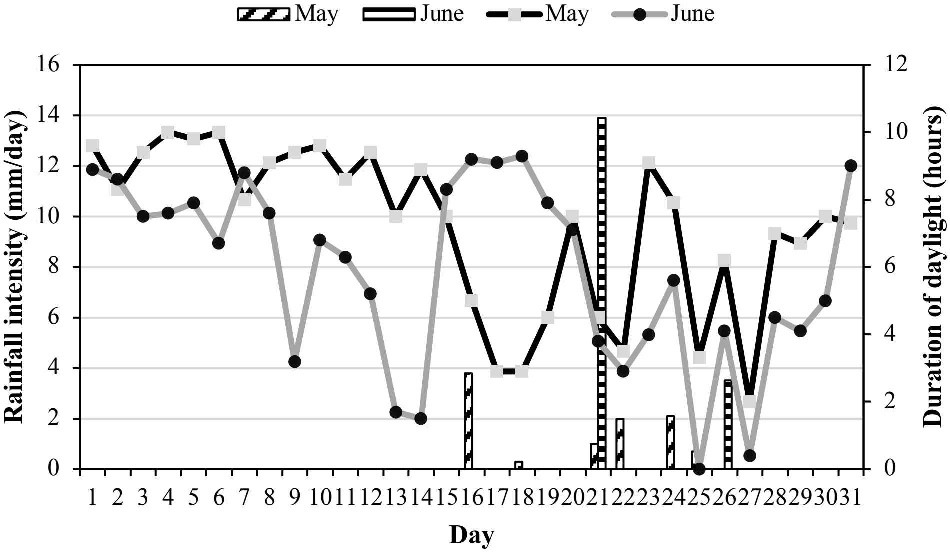

Fig. 2. Rainfall intensity and duration of daylight during the study period in Glagaharjo and Balerante of Yogyakarta.

2.2. Procedures

2.2.1. Vegetation survey

Sampling and data collection were carried out in May–June 2018. A vegetation survey was conducted using purposive sampling on coffee-based agroforestry practiced by the villagers in both villages. Experimental units were established using nested sampling consisting of a 20 m × 20 m plot for trees, 10 m × 10 m plot for pole, 5 m × 5 m for saplings, 2 m × 2 m for seedlings, and 1 m × 1 m for understorey plants (**Fig. 3**). Life stage classification was determined based on Soendjoto et al. (2014). There were 50 plots established in each village, and 25 plots were made for each agroforestry practice. Therefore, the total number of plots established in both villages was

100. Parameters observed in the vegetation survey were species, number of individuals of each species, and diameter.

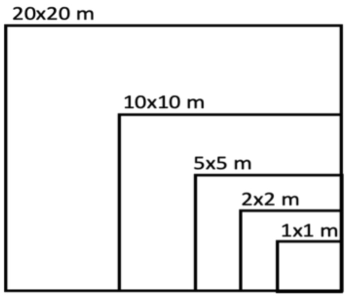

Fig. 3. Nested plot used in the research.

2.2.2. *Eco-physiology analysis of coffee*

Ecological parameters observed in the study were wind speed, relative humidity, temperature, and light intensity, each of which was observed in the midday. Physiological parameters observed in coffee were nitrate reductase activity, stomatal density and aperture, chlorophyll content, and leaf-relative water content (Salsinha et al. 2023). Plant sampling was determined by random sampling. Leaf samples were collected from healthy and active-grown plants, particularly from the middle part of the crown.

2.3. *Data Analysis*

Descriptive analysis was performed for the vegetation survey, and quantitative analysis was conducted to understand the eco-physiological difference between the two agroforestry practices. Data derived from vegetation surveys was used to assess species density, dominance, and frequency distribution (Eddy et al. 2019). These data were subsequently used to calculate each species' relative abundance, dominance, and frequency, following the methodology proposed by Kasim et al. (2019). Eventually, the Importance Value Index (IVI) was calculated using these three metrics to ascertain the significance of each species within the respective forest ecosystems, as detailed by Yuliana et al. (2019). However, the IVI for seedlings and saplings was solely calculated by relative abundance and frequency. The formula for calculating parameters is as follows:

$$Species\ density = \frac{number\ of\ individual}{size\ of\ sampling\ plot} \tag{1}$$

$$Species\ dominance = \frac{total\ basal\ area\ of\ species}{size\ of\ sampling\ plot} \tag{2}$$

$$Species\ frequency = \frac{number\ of\ plots\ of\ each\ species}{total\ sampling\ plot} \tag{3}$$

$$Relative\ density\ (RD) = \frac{species\ density}{total\ species\ density} \times 100 \tag{4}$$

$$\text{Relative dominance (RDom)} = \frac{\text{species dominance}}{\text{total species dominance}} \times 100 \tag{5}$$

$$\text{Relative frequency (RF)} = \frac{\text{species frequency}}{\text{total species frequency}} \times 100 \tag{6}$$

$$\text{Importance value index (IVI)} = RD + RDom + RF \tag{7}$$

The diversity of understorey plants was evaluated based on three fundamental parameters viz. species richness, determined using the Margalef Index (Dmg), species heterogeneity assessed with the Shannon-Wiener Index (H'), and species evenness evaluated based on the Pielou–Evenness Index (J') following the Equation 8–10 outlined by (Nugroho et al. 2022).

$$Dmg = \frac{S-1}{ln(N)} \tag{8}$$

$$H' = -\sum\left(\frac{n_i}{N} \times ln\frac{n_i}{N}\right) \tag{9}$$

$$J' = \frac{H'}{ln(S)} \tag{10}$$

where N is the total number of species, n_i is the number of certain species, and S is the number of species.

The ecophysiological difference between coffee agroforestry practices was analyzed using ANOVA and independent T-test at a confidence level of 95%. Data analysis for the number of individuals was conducted based on Kruskall-Wallis nonparametric analysis to determine whether there is a significant difference between both systems, followed by Mann-Whitney U test as nonparametric post-hoc analysis if both systems were significantly different. Data analysis was carried out using the ggplot2 package in R-Studio Ver. 2023.12.1+402 and Minitab Ver. 21.4 2023.

3. Results and Discussion

3.1. Vegetation Structure, Composition, and Diversity

The total number of individuals in all life stages observed in dry-field and homegarden agroforestry was 254 and 101, respectively. The total number of individuals discovered in the dry-field was higher than homegarden for each life stage, except for the number of seedlings, which was similar between the two systems (**Fig. 4**). The number of understoreys (82.35%), saplings (51.61%), poles (66.25%) and trees (60.75%) were recorded more frequently in dry-field compared to homegarden. Conversely, the number of seedlings was 81.82% higher in the homegarden than in the dry-field. Despite the overall higher value of individuals in dry-field, the significant difference between both systems was only observed in poles and trees (**Table 1**; **Fig. 5**). Homegarden can be managed at various stages of succession, providing diversification of products and soil resting periods throughout the years (Bertsch 2017).

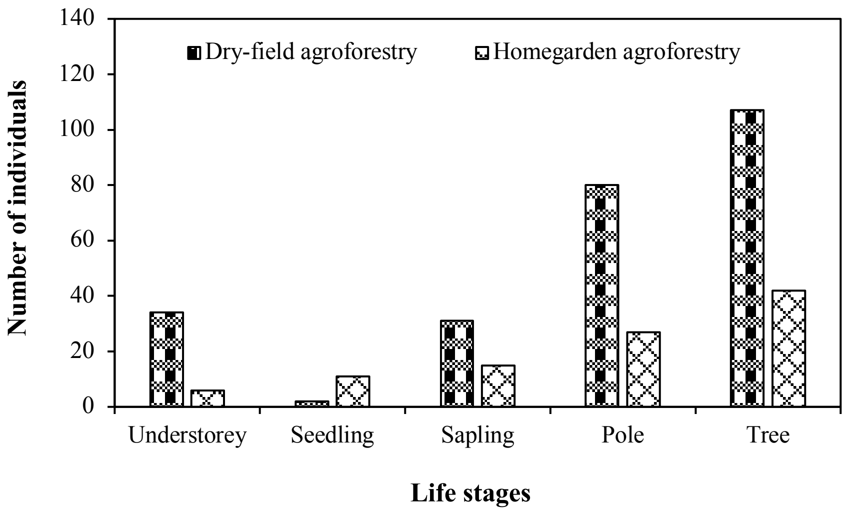

Fig. 4. Number of individuals in each life stage under dry-field and homegarden agroforestry.

Table 1. Comparison of median tree life stages in dry-field and homegarden agroforestry (between brackets, mean standard deviation)

Life stage	**Dry-field agroforestry**	**Homegarden agroforestry**	**Kruskall-Wallis**	***P*-Value**
Seedling	(1.47 ± 0.61) 1	(1.27 ± 0.44) 1	0.87	0.35
Sapling	(3.05 ± 1.82) 3	(3.13 ± 2.60) 3	0.33	0.57
Pole	(5.53 ± 2.85) 5	(3.34 ± 1.63) 3	15.81	< 0.001
Tree	(8.40 ± 3.64) 8	(5.98 ± 2.29) 6	13.14	< 0.001

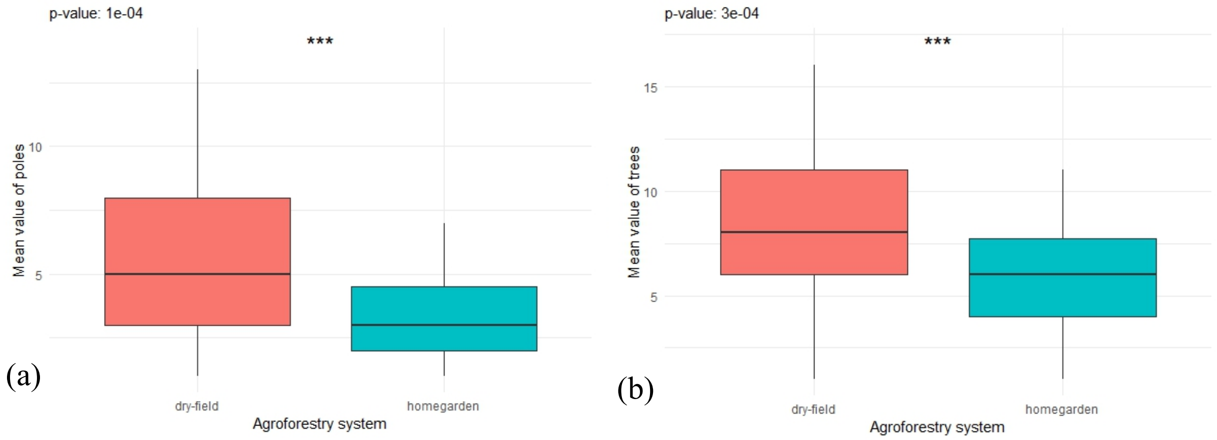

Fig. 5. Mean value of poles (a) and trees (b) under dry-field and homegarden agroforestry. The significance of the paired Mann-Whitney U test is indicated by ***$p < 0.001$.

There were 18 species belonging to 13 families identified in both coffee-based agroforestry systems. Fabaceae was the most dominant family observed in both systems, followed by Lamiaceae and Meliaceae, covering approximately 11% of all species, and others made up only 5% of both systems. Coffee, the main commodity, showed the highest IVI value at the seedling stage and ranked second at the sapling stage in the homegarden system (**Table 2**). In the dry-field system, coffee can also be found at the seedling and sapling stages but with relatively lower IVI values.

The species with high IVI values at seedling and sapling in the dry-field were *Leucaena leucocephala* and *Artocarpus heterophyllus*, respectively. Lastly, the understory stage in the homegarden was dominated by *Colocasia esculenta*, a carbohydrate-rich food crop. In contrast, the dry-field was dominated by *Penisetum purpureum.* Plant species discovered under dry-field were predominantly classified as tolerant and pioneer species with considerable economic value, such as *L. leucocepha*, *Melia azedarach* and *Gmelina arborea.* Dry-field is less intensively managed due to its great distance from residential areas. Therefore, less-managed perennial plants with tolerant traits are considered suitable species (Triwiyanto et al. 2015). In contrast, homegarden is in close proximity to the house, in turn intensively managed plants are used in the system (Sharma et al. 2022).

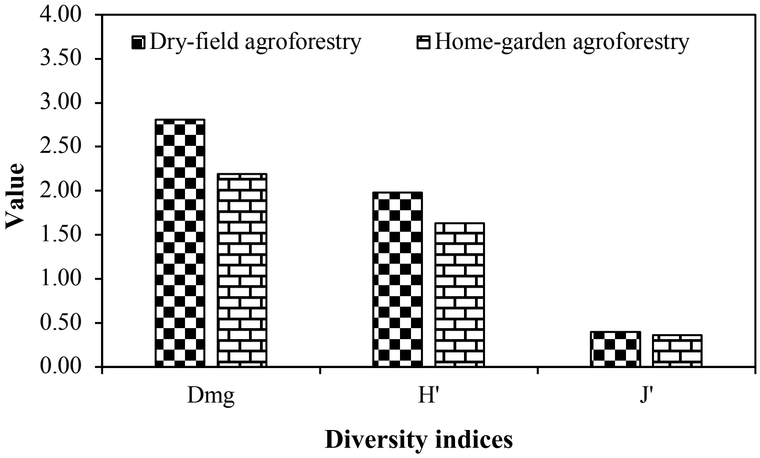

Fig. 6. Diversity indices of dry-field and homegarden agroforestry.

The values of dmg (2.81), H' (1.98), and J' (0.4) indices of dry-field agroforestry showed higher results than homegarden agroforestry. In terms of heterogeneity and evenness indicators, the dry-field system recorded higher values compared to the homegarden system (**Fig. 6**). Referring to Bullecer et al. (2014), the richness (abundance) values in both systems are relatively low (dmg < 3.5). In contrast, the heterogeneity in both agroforestry systems was classified as moderate (H' > 1). In ecosystem management, these criteria are important for measuring ecosystem stability (De Boeck et al. 2018). An ecosystem will exhibit good and healthy stability when all diversity indicators have high values (Zhang et al. 2018). However, this relationship cannot always be generalized to every type of ecosystem or specific stand, including in agroforestry systems. The selection of agroforestry species considers various factors, including economic aspects and market availability, so the species encountered in an agroforestry system may be limited. There were 10 species discovered in both agroforestry systems, mostly consisting of multi-purpose tree species such as *A. heterophyllus*, *Coffea arabica*, *Durio* sp., *Mangifera indica*, and *Persea americana*. Other similar species were timber trees (*Swietenia mahagony* and *F. moluccana*), food crops (*C. esculenta*), and ground cover (*Mimosa pudica* and *P. purpureum*). Out of 18 species, only 7 species were discovered in dry-fields, mostly identified as timber trees, whereas Cocos nucifera was only observed in home gardens.

Table 2. Importance Value Index (IVI) of plant species under dry-field and homegarden agroforestry

Species	**Family**	**Dry-field agroforestry**					**Homegarden agroforestry**				
		U	**Sd**	**Sp**	**P**	**T**	**U**	**Sd**	**Sp**	**P**	**T**
Artocarpus heterophyllus	*Moraceae*			**58.11**	26.19	49.69			23.33	56.31	6.08
Cocos nucifera	*Arecaceae*										57.19
Coffea arabica	*Rubiaceae*		83.33	17.69				**113.64**	56.67		
Colocasia esculenta	*Araceae*	42.16					**100.00**				
Durio sp.	*Malvaceae*			7.91	14.99	21.34				35.19	
Falcataria moluccana	*Fabaceae*			59.43	**110.66**	**113.89**		86.36	**76.67**	**123.73**	**134.94**
Gmelina arborea	*Lamiaceae*			15.73		11.28					
Gnetum gnemon	*Gnetaceae*					7.86					
Leucaena leucocephala	*Fabaceae*		**116.67**								
Mangifera indica	*Anacardiaceae*			4.79	10.66					21.99	
Melia azedarach	*Meliaceae*				10.36	5.30					
Mimosa pudica	*Fabaceae*	36.27					50.00				
Parkia speciosa	*Fabaceae*				7.71	7.46					
Pennisetum purpureum	*Poaceae*	**121.57**					50.00				
Persea americana	*Lauraceae*			12.60	37.85	28.93					10.92
Swietenia mahagoni	*Meliaceae*			17.39	81.58	42.67			43.33	62.78	90.87
Syzygium polyanthum	*Myrtaceae*			6.35							
Tectona grandis	*Lamiaceae*					11.57					
IVI		200	200	200	300	300	200	200	200	300	300

Notes: U= understorey; Sd= seedling; Sp= sapling; P= pole; T= tree.

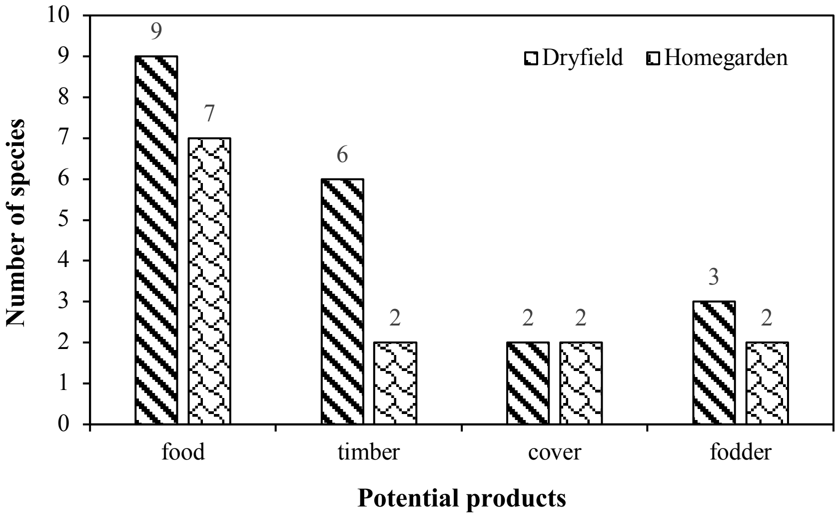

Fig. 7. Potential products of each species in dry-field and homegarden agroforestry.

Several potential products were identified in agroforestry systems: food, timber, ground cover and fodder (**Fig. 7**). Species potentially utilized as food and timber sources were mostly observed in dry-field agroforestry. Even though the number of species in homegarden for food, timber, ground cover, and fodder was lower than that of dry-field, there were more species as potential food sources than other possible products. Three species were identified as multi-purpose based on potential products, whether for timber, fodder, or ground cover. *Falcataria moluccana*, *L. leucocephala*, *P. purpureum*, *F. moluccana* and *L. leucocephala* were potential timber and fodder sources. *F. moluccana* was more favored as livestock feed than *L. leucocephala* at the foot of Mount Kelud, Malang, Indonesia (Kusumawati et al. 2022). Hence, it was reasonable that *F. moluccana* was more frequently observed in homegarden because it was easier for the farmers to access fodder for their cattle. Additionally, the growth rate and biomass production of *P. purpureum*, known as Napier grass, prevails over other tropical grasses due to higher dry matter production and nutritional quality (Negawo et al. 2017). Comparatively, the homegarden agroforestry system in Terai, located in warmer regions, recorded higher plant composition of ornamental, cereals and pulses, medicinal and religious purposes, and vegetable/pickle compared to colder regions (Pandey et al. 2021).

3.2. Ecophysiological Characteristics of Coffee Under Dry-Field and Homegarden Agroforestry

The ecological conditions, such as light interception, relative humidity, temperature, and wind speed at the three locations were not significantly different (**Table 3**). Light interception in dry-field agroforestry was higher than homegarden regardless of its non-significant difference. It could be attributed to the higher density of understorey, seedlings, saplings, and poles, which accounted for 147 individuals, compared to trees which only accounted for 107 individuals (**Fig. 4**) in the dry-field despite higher species observed in this agroforestry than that of homegarden. Consequently, there was less shading in the dry-field than homegarden. However, tree density in homegarden was higher than in other life stages, resulting in higher shading indicated by higher light intercept by De Mattos et al. (2020), who concluded that light interception positively correlated with canopy coverage. Similarly, cacao cultivated under rubber plantations recorded 3°C higher than cacao intercropped with various shading trees in the cabruca agroforestry system

(Heming et al. 2022). Temperature and relative humidity in this study were deemed uncommon because they were not contradictory, as recorded by many studies.

Despite the high temperature recorded in dry-field agroforestry, the relative humidity in this system was also high. Conversely, homegarden showed lower temperature and relative humidity. It might be attributed to higher plant density forming a more complex multi-strata system, promoting higher transpiration, eventually leading to higher humidity in the dry-field than homegarden. Additionally, a higher temperature could result from higher light interception in the dry-field than in the homegarden. As confirmed by Wright and Francia (2024), vegetation can affect microclimate, including temperature, vapor pressure deficit, and humidity through evapotranspiration and the mobilization of water within the system. The wind speed in the dry-field agroforestry system is relatively higher (average 23.05 km/h) than the homegarden agroforestry system (average 20.2 km/h). The difference in wind speed was presumed to be due to the proximity of the homegarden to settlements, which may cause a decrease in wind speed due to the presence of houses. On the contrary, the wind speed was more unrestricted in the dry-field system located farther from settlements even though more vegetation was observed in the dry-field. Generally, the environmental conditions (temperature, light interception, humidity, and temperature) already meet the criteria for optimal coffee growth, according to Merle et al. (2022). **Table 3** shows that the microclimatic values between dry-field and homegarden agroforestry are insignificant. This explains that the agroforestry system maintains the balance of the microclimate of the two systems (Abebe and Asfaw 2023).

Table 3. Microclimate condition of dry-field and homegarden agroforestry

Parameters	Dry-field agroforestry	Homegarden agroforestry	*P*-value
Light interception (%)	65.55 ± 1.34 a	66.56 ± 0.33 a	0.41
Relative humidity (%)	76.50 ± 0.71 a	76.00 ± 1.41 a	0.70
Wind speed (km h^{-1})	23.05 ± 1.34 a	20.20 ± 1.13 a	0.70
Temperature (°C)	25.50 ± 0.71 a	25.25 ± 0.35 a	0.15

Notes: value indicated mean ± standard deviation; values with the same letter do not significantly differ according to independent T-test ($p > 0.05$).

The physiological conditions of coffee plants generally exhibited similarities with their ecological conditions. All measured parameters showed no significant differences (**Table 4**). The physiological condition of plants is usually influenced by similar environmental conditions, leading to similar physiological conditions (Singh et al. 2020). Higher stomatal opening of coffee leaves under dry-field agroforestry could be associated with higher relative water content. The relationship between leaf water content is synergistic with stomatal apertures. Declining leaf water status can promote lower stomatal apertures and vice versa (Buckley 2019).

The chlorophyll content of coffee leaves in this study was low for all agroforestry systems because coffee was cultivated under shade trees (Corzo-Bacallao et al. 2023). Coffee is classified as a C3 plant, indicating its need to shade trees to avoid photoinhibition (Chatterjee et al. 2020; Chiarawipa et al. 2021). One of the physiological characteristics commonly observed in C3 plants such as coffee or tea is higher chlorophyll content but a lower ratio of chlorophyll a and b compared to unshaded plants (Chen et al. 2021; Liu et al. 2020). A similar result was also observed in this study. It is associated with lower light intensity under a shaded environment, resulting in the downregulation of NOL gene expression, hindering the transformation of chlorophyll b to chlorophyll a, which decreases chlorophyll a/b (Li et al. 2024).

Nevertheless, the chlorophyll content of coffee under a dry-field was higher (0.481 mg/g) than that of homegarden (0.476 mg/g), resulting in a higher ratio of chlorophyll a and b. It was attributed to lower light interception in dry-field agroforestry, indicating lower shading intensity than homegarden agroforestry (**Table 3**). Additionally, the nitrate reductase activity of coffee under dry-field agroforestry was also higher, indicating higher efficiency of nitrate assimilation and amino acids production, which eventually can contribute to chlorophyll biosynthesis. Nitrate reductase is an important indicator of nitrogen mobilization within the plant, and its deficiency can result in decreasing plant viability (Bittner 2014).

Ecophysiological conditions positively correlate with coffee yield (Melke and Fetene 2014). The ecophysiological condition of coffee plants, including photosynthesis, carbon allocation, nitrogen metabolism, defense mechanisms against oxidative stress, and others, plays a crucial role in adapting coffee plants to unfavorable environmental conditions. Moreover, ecophysiological conditions also affect coffee beans' sensory quality, such as aroma, taste, acidity, and others (Ferreira et al. 2021). Furthermore, we obtained coffee yield data from interviews conducted with landowners. The interviews showed that the average coffee yield in the dry-field was 5.5 kg/tree/harvest, and in homegarden was 4.5 kg/tree/harvest (Source: personal communication).

Table 4. Physiological performance of coffee under dry-field and homegarden agroforestry

Parameters	Dry-field agroforestry	Homegarden agroforestry	***P*-value**
Leaf relative water content (%)	76.28 ± 2.43 a	76.09 ± 2.23 a	0.94
Stomatal density (mm^2)	190.50 ± 2.12 a	198.50 ± 12.02 a	0.45
Stomatal opening (mm)	20.50 ± 0.71 a	19.00 ± 1.41 a	0.31
Chlorophyll a ($mg\ g^{-1}$)	0.48 ± 0.06 a	0.48 ± 0.04 a	0.93
Chlorophyll b ($mg\ g^{-1}$)	0.56 ± 0.08 a	0.56 ± 0.06 a	0.98
Chlorophyll a/b	0.86 ± 0.03 a	0.85 ± 0.02 a	0.85
Total chlorophyll ($mg\ g^{-1}$)	1.04 ± 0.14 a	1.04 ± 0.09 a	0.96
Nitrate reductase activity (μ mol NO^{2-} g^{-1} $hour^{-1}$)	2.72 ± 1.71 a	2.50 ± 1.39 a	0.90

Notes: value indicated mean±standard deviation; values with the same letter do not significantly differ according to independent T-test ($p > 0.05$).

4. Conclusions

Coffee cultivation is commonly practiced under agroforestry systems, including dry-field and homegarden agroforestry. The higher number of species and diversity under dry-field, particularly those classified as an understorey, seedling, sapling and pole, contributed to distinctive microclimate modification compared to homegarden agroforestry system, including lower light interception, higher humidity and temperature. However, there was no significant difference in microclimate between these systems, leading to a non-significant difference in the physiological performance of coffee cultivated within the systems. Despite the non-significant difference in both microclimate and physiological performance of coffee within the systems, the higher physiological parameters under dry-field indicated that this system might be considered a suitable agroforestry system for coffee. Pruning management of shade trees is imperative to manage the shading intensity for a suitable growth environment for coffee.

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