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Research Article

From Bean to Biosphere: Vegetation Dynamics and Biodiversity in Arabica Coffee Agroforestry at Ijen Geopark

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ABSTRACT
This study evaluates vegetation biodiversity and ecological conditions at the Bondowoso Biosite of *Kebun Kopi*, Ijen Geopark, to support sustainable Arabica coffee production. Three agroforestry plots (KR1-3) and a plantation plot (PN) were analyzed for species composition. In KR1, *Acacia auriculiformis* (IVI=110) and *Trema orientalis* (IVI=190) are prominent. KR2 is dominated by *A. auriculiformis* (IVI=160) and *Ricinus communis* (IVI=80), while *Casuarina equisetifolia* is significant in KR3. The PN plot shows a more even IVI distribution between *Falcataria mollucana* and *Grevillea robusta*. Tukey's test reveals significant differences between KR1 and PN, and KR2 and PN plots (p-adj=0.001). The highest existence values are Anisoptera marginata (66.67 %) in KR1, *T. orientalis* (53.33 %) in KR2, *C. equisetifolia* (46.67 %) in KR3, and *Toona sureni* (26.67 %) in PN. Results indicate significant variations in species diversity, evenness, and dominance across plots, influenced by ecological, geographical, and anthropogenic factors. Higher Shannon-Wiener and Evenness indices in KR1 and KR2 suggest diverse species compositions are vital for ecosystem health, while KR3's dominance of few species highlights the need for biodiversity conservation. This research recommends regenerative Arabica coffee farming practices and sustainable conservation strategies at the Bondowoso Biosite of *Kebun Kopi*.

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INTRODUCTION

Ijen Geopark (7°45'18.0756"S–8°46'49.296"S and 113°47'28.3632"E–114°36'18.1548"E.), a UNESCO world heritage site, has 21 Geosites, 6 Biosites, and 9 Cultursites, with cultural, biological, and geological significance (Hasan & Ningrum 2023; Permanadewi et al. 2024). Bondowoso Biosite in Ijen Geopark produces high-quality Arabica coffee. The area's diverse flora, including Chinese Mahogany (*Toona sinensis*), Dadap (*Erythrina variegata*), Cinnamon (*Cinnamomum verum*), Pine (*Pinus* spp.), and White Paperbark (*Melaleuca leucadendra*), supports coffee agroforestry as shade plants. Studies by Anhar et al. (2021) show that high shade intensity supports optimal productivity for Arabica coffee, while Andika and Wicaksono (2020) found that 50 % light intensity increases chlorophyll content in coffee leaves compared to plants exposed to full light (100 %). These facts indicate a strong potential relationship between the presence of native vegetation and coffee agroforestry at the Bondowoso Biosite of *Kebun Kopi*.

Biodiversity not only reflects the health of ecosystems and their resilience to environmental changes but also determines the quality and uniqueness of the Arabica coffee produced (Sandifer et al. 2015; Carvalho et al. 2016). Ecological conditions, including soil quality, water availability, and climate, directly affect the growth of coffee plants and the sustainability of habitats for other species interacting within the coffee agroforestry ecosystem (Cerda et al. 2017; Sauvadet et al. 2019). This study aims to evaluate vegetation diversity at Bondowoso Biosite of *Kebun Kopi*, providing data and recommendations to support Ijen Geopark's conservation efforts and the sustainability of Arabica coffee agroforestry.

MATERIALS AND METHODS

Methods

The research at Bondowoso Biosite of *Kebun Kopi*, Ijen Geopark, was conducted from July to December 2023. Using a single plot method (20x20 m), vegetation analysis focused on agroforestry plots owned by the Community (KR) and PT Perkebunan Nusantara (PN). Three KR plots were selected for diverse vegetation, while PN was represented by one plot due to uniform agroforestry. Each plot had three repetitions to ensure comprehensive analysis, with criteria based on management diversity (Figure 1).

The primary data collected include species names, number of individuals, diameter at breast height (DBH), and total height for trees and poles, as well as stakes and seedlings. Horizontal structure data (diameter, density, and number of individuals) were also collected. Vegetation analysis results show plant diversity, Important Value Index (IVI), and specific valuable species. Further analyses include Shannon-Wiener, Margalef, and Evenness indices to determine diversity.

Important Value Index

The importance and position of a species within the observation area can be determined through the Importance Value Index (IVI). The formula that can be used to calculate the IVI (Khan 2016) is:

$$\text{Density (D)} = \frac{\text{Number of individuals of each species}}{\text{Area of Plot}}$$

$$\text{Relative Density (RD)} = \frac{\text{K}}{\text{Total number of all species}} \text{ x } 100\%$$

$$\text{Frequency (F)} = \frac{\text{Number of type a species found in a plot}}{\text{Total frequency of all species}}$$

$$\text{Relative Frequency (RF)} = \frac{\text{F}}{\text{Total frequency of all species}} \text{ x } 100\%$$

$$\text{IVI} = \text{Relative Density (RD)} + \text{Relative Frequency (RF)}$$

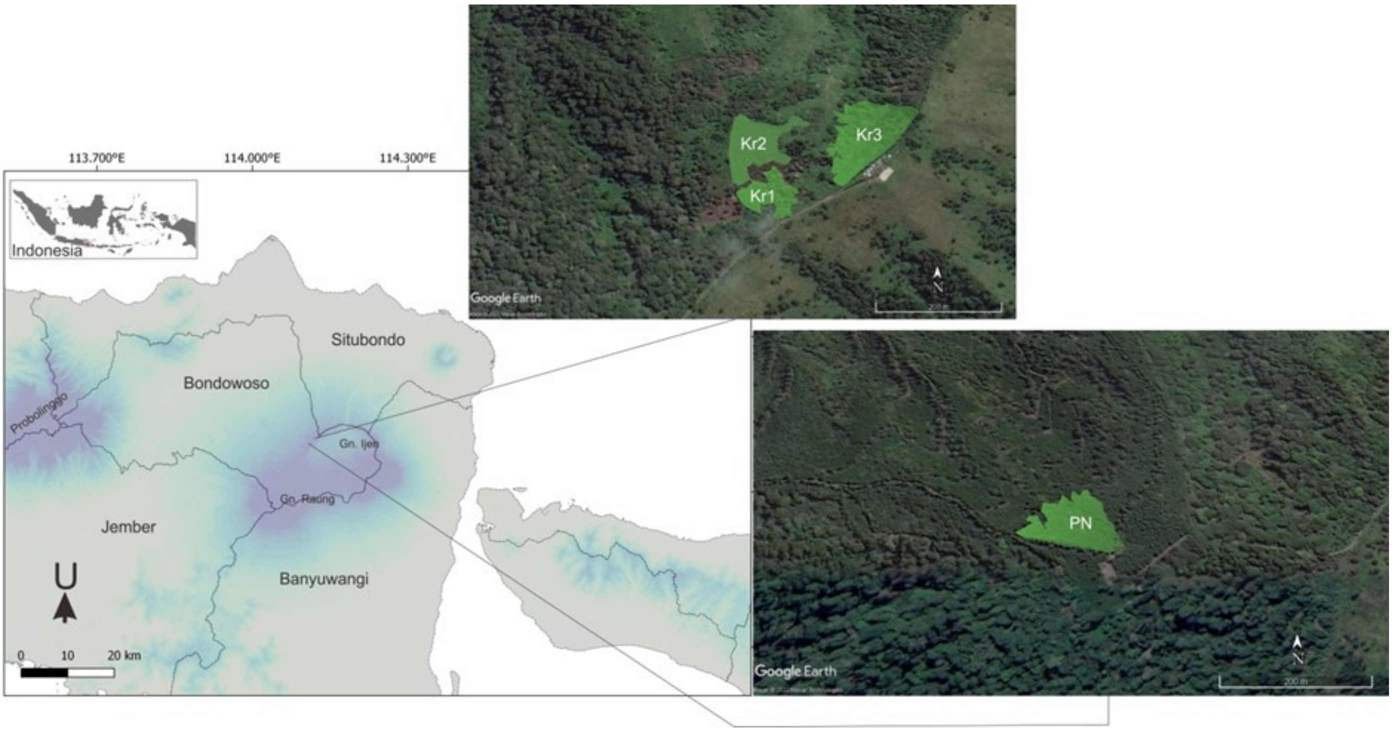

Figure 1. Map of the study area with area codes. KR is the agroforestry owned by the Community and PN is location owned by PT Perkebunan Nusantara, see methods for the details.

Shannon-Wiener Species Diversity Index (H')

The diversity of species in a region within an agroecosystem area can be determined through the Shannon-Wiener index. The formula used to calculate the Shannon-Wiener index value (Strong 2016) is as follows:

$$H' = \sum \frac{ni}{N} \mathrm{In}\left(\frac{ni}{N}\right)$$

Keys:
H'= The Shannon-Wiener index; ni= The number of individuals of the i-th species; N= Total number of individuals of all species.
The assessment criteria for the Shannon-Wiener diversity index are:
H' < 2 (Low diversity); 2 < H' < 3 (Moderate diversity); H' > 3 (High diversity)

The Evenness Index (E)

The evenness index can be used to calculate the evenness of the abundance of individuals for each species. The formula used to calculate the evenness index (Kvålseth 2015) is as follows:

$$E = \frac{H'}{\mathrm{In}\ S}$$

Keys:
E = Evenness Index; H' =Shannon-Wiener Diversity Index; S= The number of identified species
The assessment criteria for the Evenness Index are:
E > 0.6 (High evenness of species); 0.3 < E < 0.6 (Moderate evenness of species); E < 0.3 (Low evenness of species).

The Margalef Species Richness Index (DMg)

The species richness index can determine the species richness within an ecosystem compared to the total number of individuals. The formula used to calculate the Margalef species richness index (van Loon et al. 2018) is as follows:

$$DMg = \frac{(s-1)}{\mathrm{In}\ N}$$

Keys:
DMg=Margalef Species Richness Index; S=The number of identified species; N = The total number of individuals of all species.
The assessment criteria for the Margalef species richness index are: Dmg < 3.5 (Low level of species richness); 3.5 < Dmg < 5 (Moderate level of species richness); Dmg > 5 (High level of species richness).

Ecological Status Assessment

Subsequently, an ecological status assessment is conducted to examine the existence factors of species within the agroecosystem. The formula used is (Sulistyowati 2008):

$$Ex = \left(\frac{Fr\ status + Cs\ status\ + Gd\ status}{3\ \times 5}\right) \times 100$$

Where:
Ex = Existence value; Fr status = Frequency status level of the spe cies; Cs status = Conservation status level of the species; Gd status = Geographic distribution status level.

Fr status is obtained from analysis of vegetation results. Cs and Gd status were obtained from IUCN (https://www.iucnredlist.org/_). Below are some conversion tables for Fr, Cs, and Gd status (Table 1-3, Sulistyowati 2008):

Table 1. Frequency status level (Fr, Sulistyowati 2008)

Percentage	Fr Status
81-100	1
61-80	2
41-60	3
21-40	4
0-20	5

Table 2. Conservation status level (Cs, Sulistyowati 2008)

Cs	Cs Status
CR = *Critically Endangered*	5
EN = *Endangered*	4
VU = *Vulnerable*	3
NT = *Near Threatened*	2
LC = *Least Concern*	1

Table 3. Geographic distribution status level (Gd, Sulistyowati 2008)

Geographic Distribution (Area)	Gd status
Distributes in certain local area (dl)	5
Distributed in region/island within country (dr)	4
Distributed in Indonesia country (di)	3
Distributed in continental Asia (da)	2
Distributed throughout the world (dw)	1

Existence value differences were analyzed using ANOVA and Tukey's HSD test, visualized with PCA graphs using matplotlib, Seaborn, and KDE, and described descriptively.

RESULTS AND DISCUSSION

Results

Important Value Index

The Important Value Index (IVI) visualization highlights key species roles in KR1, KR2, KR3, and PN plots (Figure 2). In KR1, *Acacia auriculiformis* (IVI=110) and *Trema orientalis* (IVI=190) show high ecological significance. KR2 is dominated by *Acacia auriculiformis* (IVI=160) and *Ricinus communis* (IVI=80, Figure 6C). KR3's dominant species is *Casuarina equisetifolia.* In the PN plot, *Falcataria mollucana* and *Grevillea robusta* show a more balanced IVI distribution, indicating greater ecological diversity and balance.

Shannon Diversity Index, Evenness, and Simpson Dominance

The Shannon index shows KR1 and KR2 have higher species diversity and more even distribution than KR3 (Figure 3). High Evenness in KR2 indicates balanced distribution. The Simpson dominance index reveals KR1 and KR2 have lower dominance, while KR3 has higher dominance, needing more biodiversity conservation and management.

Biodiversity Value

The Analysis of Variance (ANOVA) on Ex values (%) shows a significant difference between locations (p-adj = 0.00036), below the 0.05 threshold. This indicates substantial variation in species existence due to ecological, geographical, or anthropogenic factors. Post-hoc Tukey's HSD test identifies significant differences between certain pairs, notably KR1 and PN, and KR2 and PN (p-adj=0.001), marked by double asterisks (**) for high significance (Table 4).

Table 4. Tukey test analysis result (p-adj) indicating vegetation differences between locations. See methods for detailed abbreviation codes.

Location	KR2	KR3	PN	KR1
KR1	0.9	0.4498	0.001**	-
KR 2		0.4297	0.001**	0.9
KR 3			0.1355	0.4498
PN				

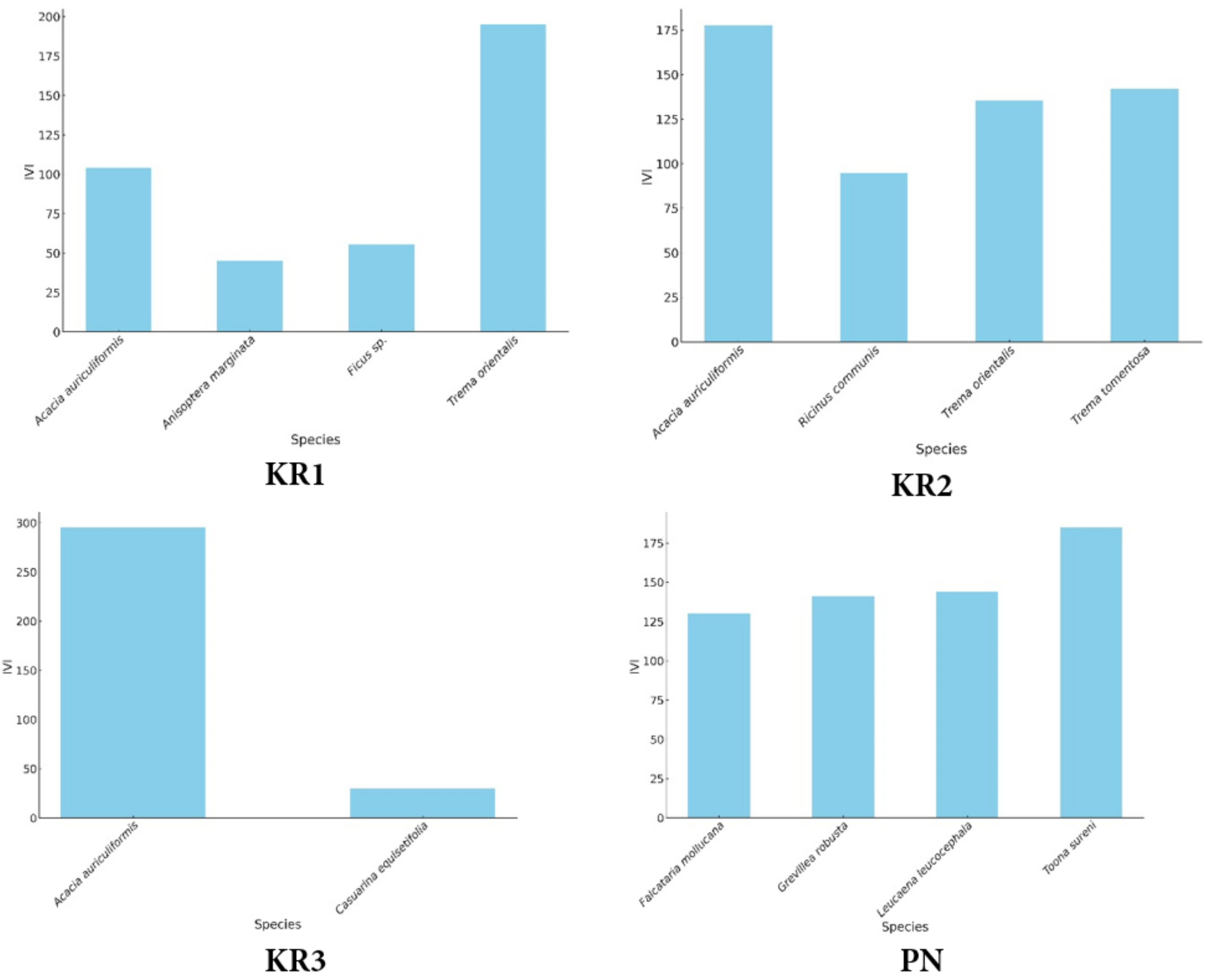

Figure 2. Important Value Index (IVI) graphs at 4 locations. See methods for detailed abbreviation codes.

The boxplot of Ex values (%) (Figure 4) shows significant variation in species existence across locations. Each location has species with the highest Ex values, indicating their prevalence, such as *T. orientalis*. PN and KR2 feature species with the lowest Ex values, indicating lesser dominance.

At KR1, *A. marginata* has the highest Ex value (66.67 %), while *A. auriculiformis* (Figure 6A) has the lowest (40 %, Figure 5). In KR2, the highest Ex value is 53.33 %, and *T. orientalis* (Figure 6B) the lowest (40 %). For KR3, *C. equisetifolia* is highest (46.67 %) and *A. auriculiformis* lowest (26.67 %). In PN, *Toona sureni* is highest (26.67 %) and *Leucaena leucocephala* lowest (20 %).

The PCA visualization displays a dataset that encompasses various locations (focusing on Ex (%) values). Each location is represented by a different color and plotted in a two-dimensional space generated by PCA. The size of each point on the graph is proportional, providing an overview of the biodiversity value at each location. Specifically, for the KR2 location, the more contrasting color highlights its extreme difference from other locations, facilitating the identification of its data distribution in PCA space, and indicating its distribution is much wider and larger compared to other locations.

The biplot lines in the graph, emanating from the center point, represent the features 'FR Status', 'Cs Status', and 'Gds' (Figure 7). Each arrow indicates the influence and contribution of these features to the variability in the dataset. The length and direction of the arrows show how significantly

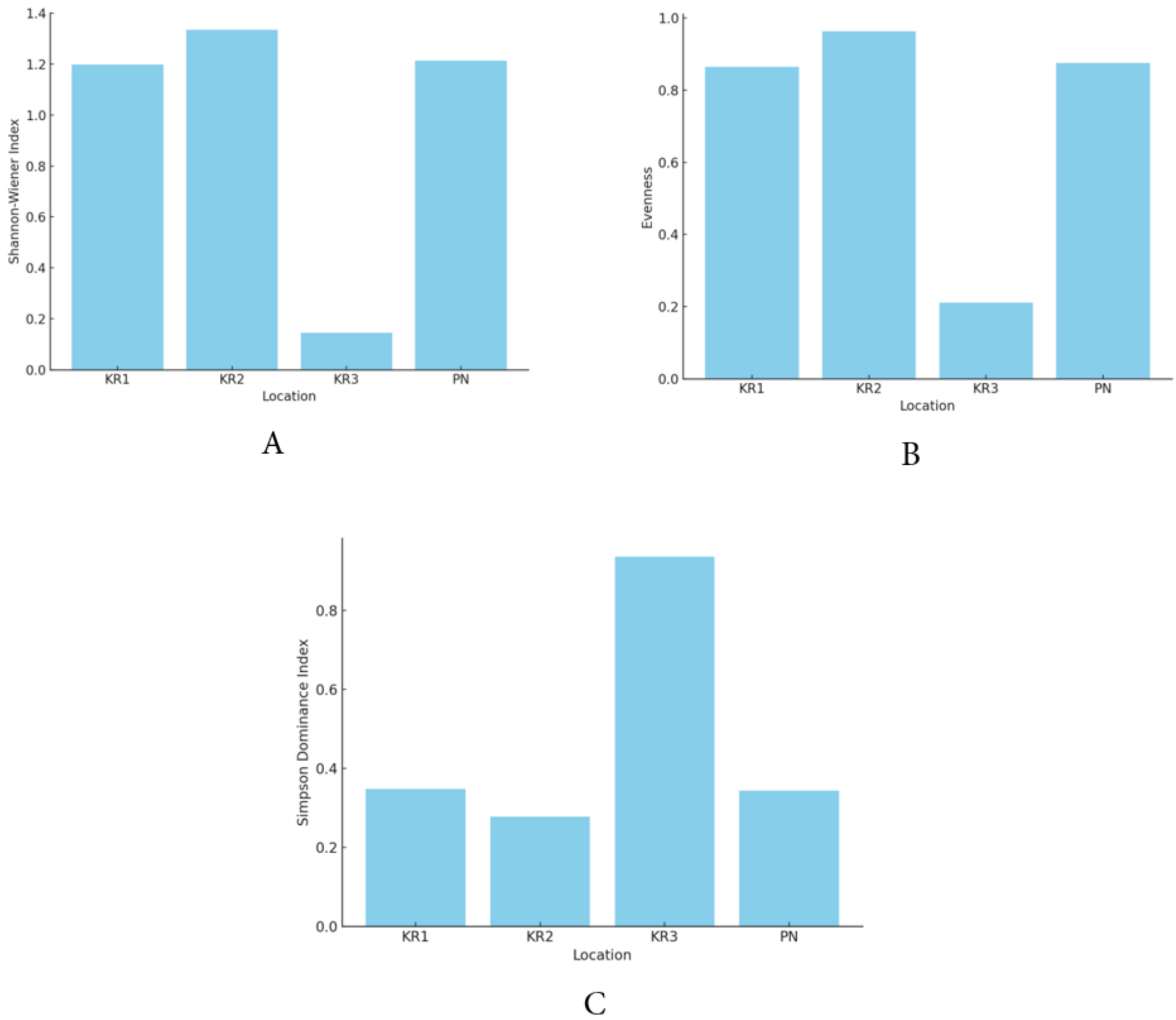

Figure 3. Ecological indexes of location. Keys=A. Shannon-Wiener; B=Evennes; C. Simpson Dominance. See methods for detailed abbreviation codes.

these features influence the formation of the principal components. The biplot helps to understand the relationship among all parameters: FR, Cs, and Gds, which interact with the overall KR2 distribution, and Cs and FR have a weak interaction with KR1.

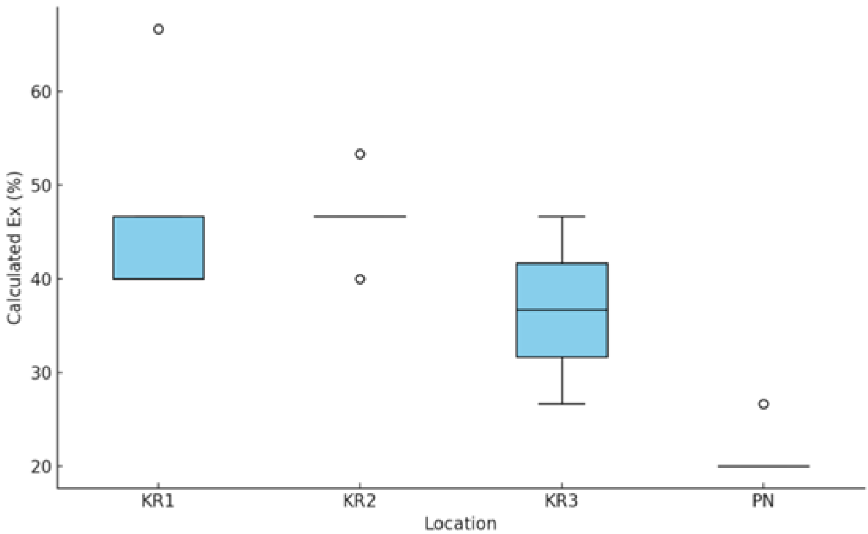

Figure 4. Boxplot graph of ex (%) across locations. This boxplot illustrates the different mean values and deviations across locations. See methods for detailed abbreviation codes.

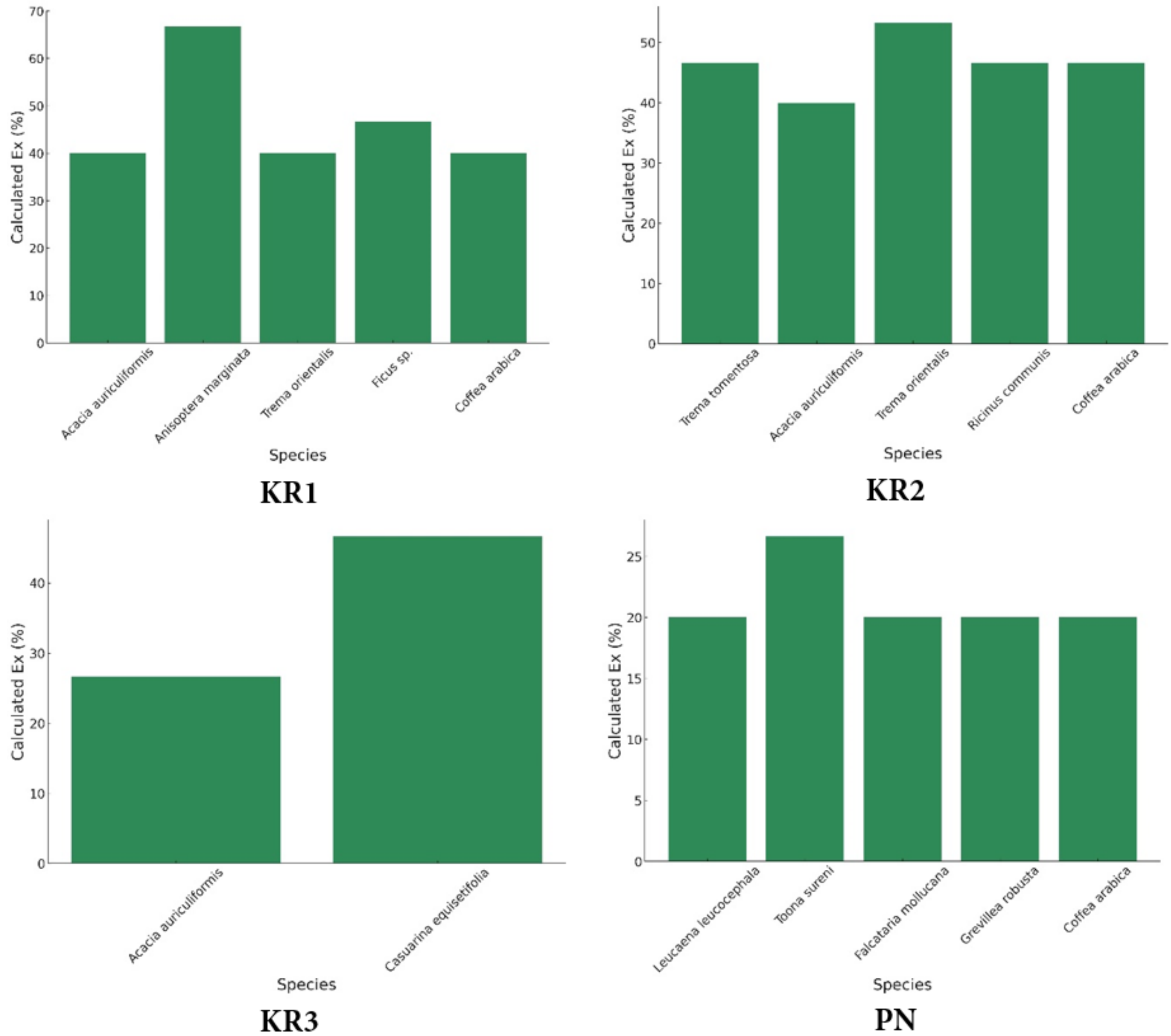

Figure 5. Comparison of Ex values at each location with different plant types.

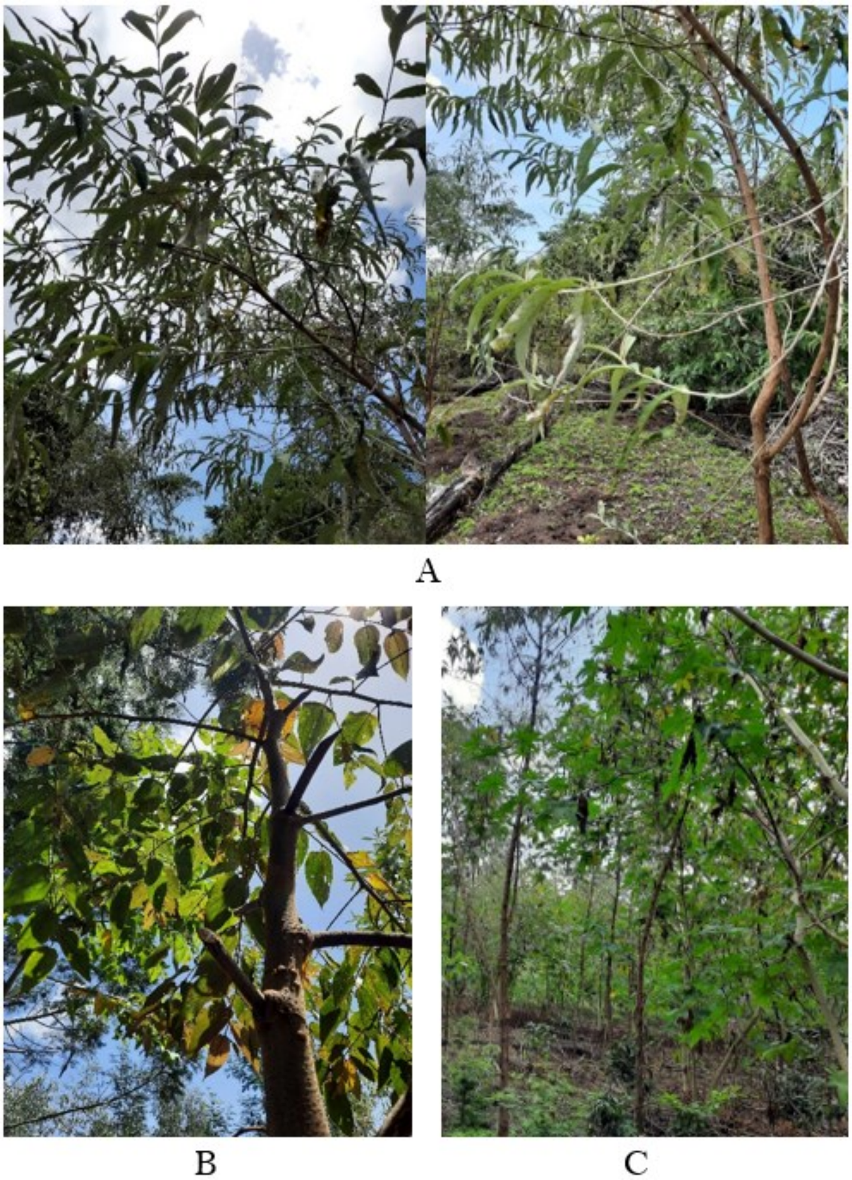

Figure 6. various vegetations at The Ijen Coffee Biosite. Keys=A. *Acacia auriculiformis*; B. *Trema orientalis*; C. *Ricinnus communis.*

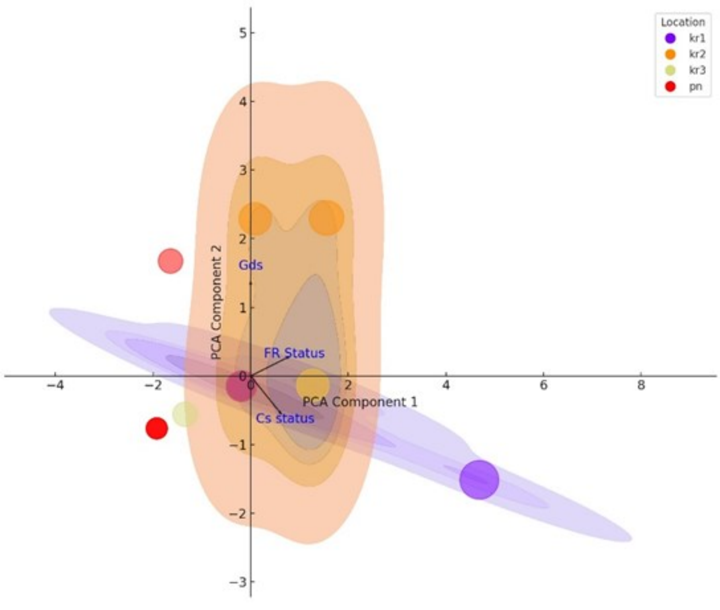

Figure 7. PCA graph of biodiversity value preference found at each location, linked to supporting components Gds, FR, and Cs Status. The size of the circles indicates the data density at each location.

Discussion

The IVI analysis reveals dominant species in each plot. In KR1, *A. auriculiformis* (IVI=110) and *T. orientalis* (IVI=190) are most dominant, indicating their ecological importance. KR2 shows high IVI scores for *A. auriculiformis* (IVI=160) and *R. communis* (IVI=80), reflecting their competitive advantages. *A. auriculiformis* dominates the vertical and horizontal structure, influencing other species' composition due to intense competition. (Azad & Sumon 2016; Ngoan et al. 2023; Sikuzani et al. 2024). Additionally, *A. auriculiformis* is a nitrogen-fixing plant that can increase soil nitrogen content. Furthermore, its dominance provides suitable habitats for many birds, small mammals, and insects. Its canopy also creates a favorable microclimate, particularly beneficial for coffee.

In KR3, *C. equisetifolia* holds a dominant role, possibly reflecting its unique adaptation to the plot's conditions. This plant has an extensive root system and needle-like leaves, providing considerable biomass and covering large areas, which can fundamentally influence the microclimate, such as light, water, and nutrients. *C. equisetifolia* has the ability to enhance soil fertility through nitrogen fixation (Atangana et al. 2014). The PN plot shows a balanced IVI distribution among species like *F. mollucana* and *G. robusta*, indicating greater ecological diversity. *F. moluccana*, known for rapid growth and nitrogen fixation, improves soil fertility and supports other plants. Its extensive canopy moderates light, temperature, and humidity, benefiting the ecosystem (Ambas et al. 2024). *G. robusta* is valued for its resilience, versatile canopy providing shade, maintaining soil moisture, attracting pollinators, and is used for timber, windbreaks, and shade in coffee plantation (Nesper et al. 2019; Sharma et al. 2023).

R. communis is capable of thriving at high densities due to its remarkable competition with other plants, a result of its production of allelopathic toxins that inhibit the growth of other plants (Saddiqe et al. 2020). It is also planted as a boundary marker (Boğan et al. 2020). Consequently, it becomes a new dominant regime, highlighting its importance in a location. The differences in diversity values indicate that the factors influencing species presence at these locations differ substantially, providing important insights for further research on the management and conservation of biodiversity in these areas (Udawatta et al. 2019). Locations KR1 and KR2 exhibit high diversity and significant biodiversity value, with *T. orientalis* and *A. auriculiformis* being key species. Variations in diversity, evenness, and dominance are influenced by species-specific interactions. Nitrogen-fixing *A. auriculiformis* in KR1 and KR2 enhances soil fertility, supporting higher diversity and evenness (Azad & Sumon 2016; Sikuzani et al. 2024). Conversely, the dominance of *C. equisetifolia* in KR3, with its extensive root system and needle-like leaves, may create a microenvironment that suppresses other species, resulting in lower diversity and higher dominance. Soil quality and fertility, microclimatic conditions such as light intensity and humidity, and human management practices, including land use intensity and agroforestry techniques, also contribute to these ecological differences (Atangana et al. 2014). The balanced IVI distribution in the PN plot, with species like *F. moluccana* and *G. robusta*, reflects greater ecological diversity and balance, likely due to effective management and favorable environmental conditions (Nesper et al. 2019; Sharma et al. 2023; Ambas et al. 2024).

The ANOVA results demonstrate substantial differences in species presence across various locations, likely resulting from a combination of ecological, geographical, and human-induced factors that influence species distribution and prevalence (Aronson et al. 2014; Ellis 2015). High Ex (%) values at KR1 indicate species play critical roles in ecosystem structure and function, such as providing habitats or food sources. Low Ex (%) values suggest species face high competition or are unsuited to the environment, requiring special conservation attention if important for biodiversity. PN shows strong human -plant interaction. On the other hand, plantations are managed more for economic gain than for conservation (Haggar et al. 2017). Overall, Ex (%) values help identify key species in ecosystems and provide important insights for habitat management and conservation strategies (Sulistyowati 2008). Again, this highlights the importance of community-developed agroforestry for the well-being of communities around the Bondowoso Biosite of *Kebun Kopi*, while also serving as a protector in its conservation strength. This dual role makes agroforestry a promising sustainable agricultural system in the modern era (Wilson & Lovell 2016).

High Ex (%) values, such as for *A. marginata* in KR1 and *T. orientalis* in KR2, indicate the dominance or greater presence of these species at those locations, as well as their critical role in the ecosystem. *A. marginata*, a member of the Dipterocarpaceae family, which is characteristic of the Indonesian tropical region, signifies areas with good forest conservation (Brearley et al. 2016). However, many members of the Dipterocarpaceae are now severely damaged due to forest land conversion and the demand for high-quality building wood (Widiyono 2021). *T. orientalis*, or locally known as 'Mengkirai', is a species with high intolerance levels but capable of coping with high heavy metal content, making it suitable for restoration of former mining lands with high Ni content (Rodrigues & Rodrigues 2014). Its significant presence in the Ijen Biosite of *Kebun Kopi* highlights the importance of preserving species with high environmental sensitivities.

Conversely, species with low Ex values, like *L. leucocephala* in PN, may face higher competition or be less suited to the environmental conditions, indicating the importance of more specific conservation or management strategies for these species. The competition arises because this plant is intentionally provided as the primary shade in coffee agroforestry. This reflects how Ex values can provide insights into the ecological and conservation importance of various species within their local contexts.

CONCLUSIONS

The IVI highlights dominant species in each plot: *A. auriculiformis* (IVI=110) and T. *orientalis* (IVI=190) in KR1; *A. auriculiformis* (IVI=160) and *R. communis* (IVI=80) in KR2; *C. equisetifolia* in KR3. PN shows a balanced IVI among species like *F. mollucana* and *G. robusta*. Shannon Diversity, Evenness, and Simpson Dominance indices reveal KR1 (H'=1.20, E=0.86, D=0.35) and KR2 (H'=1.33, E=0.96, D=0.28) have higher diversity than KR3 (H'=0.15, E=0.21, D=0.94). This research affirms the comprehension of biological diversity and natural ecological conditions at the Bondowoso Biosite of *Kebun Kopi* with the sustainability of Arabica coffee production.

AUTHOR CONTRIBUTION

N.D. designed the research and was responsible for overseeing the entire research process. A.S.K. collected data and wrote the manuscript.

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CONFLICT OF INTEREST

All authors declare that there is no conflict of interest with any party, concerning the data collection, writing, and the forthcoming publication of this manuscript.

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