

Indigenous Agroforestry Systems as Climate-Smart Biodiversity Refuges: Evidence from Gimbi District, Western Ethiopia

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Abstract

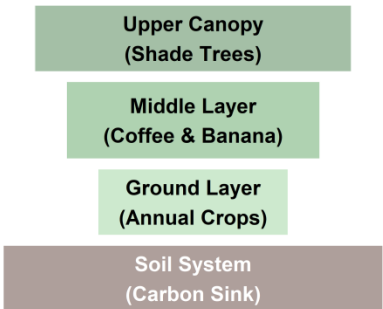
*Climate change is increasingly challenging the sustainability of smallholder agricultural systems, intensifying the need for land-use strategies that integrate production with biodiversity conservation. This study evaluates the species composition, structural characteristics, and diversity of indigenous agroforestry systems (IAFS) in Gimbi District, Western Ethiopia, to assess their potential role as biodiversity-conserving, climate-resilient production systems. Data were collected from 30 in 2020 systematically sampled vegetation plots (10m x 10) to quantify woody species composition, structure, and diversity. Key metrics calculated included the Shannon diversity index (H'), species richness, evenness, height, and diameter at breast height (DBH). The findings reveal a remarkable species base, documenting a total of 72 agroforestry plant species belonging to 43 distinct families. The system exhibited high diversity, reflected by a Shannon diversity index (H') of 3.16 and an evenness index of 0.74. Dominant indigenous species, such as *Cordia africana* and *Albizia gummifera*, serve critical functional roles in providing shade and fixing nitrogen. This high level of biodiversity confirms that IAFS not only enhance the stability and productivity of smallholder farms but also function as vital repositories for indigenous flora. This research supports the imperative for policy to formally recognize and integrate traditional agroforestry practices as cornerstone strategies for climate change adaptation and biodiversity conservation in Ethiopia and the wider Global South.*

Keywords: Biodiversity conservation, ecological stability, ecosystem services, *in-situ* conservation, climate-smart agriculture, Western Ethiopia

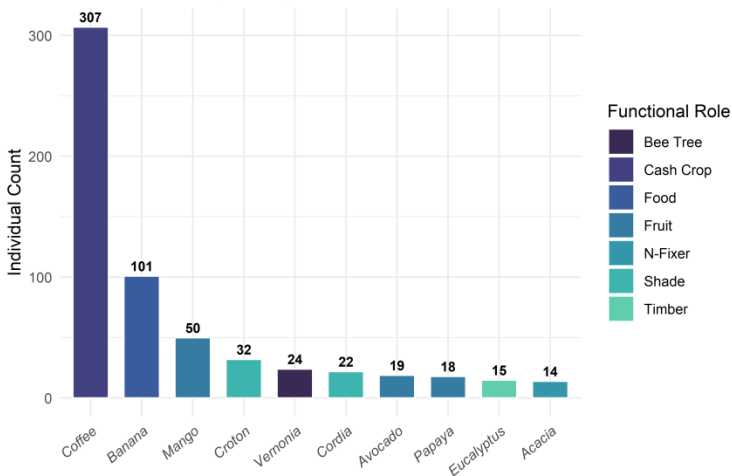
Indigenous Agroforestry Systems as Climate-Smart Biodiversity Refuges

Evidence from Gimbi District, Western Ethiopia | Total Species: 72 | Shannon Index (H'): 3.16

A. Multi-Layered Structure



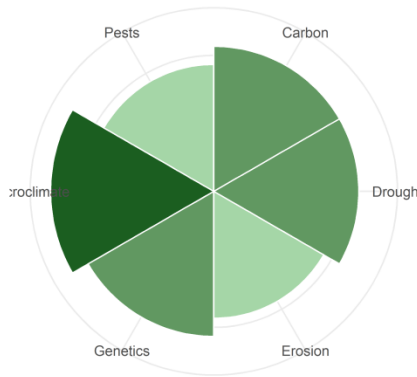
B. Top 10 Species Dominance



C. Ecosystem Services Value



D. Climate Resilience



Contact: [Your Name/University] | Statistical Significance: $p < 0.05$

Figure 1. Graphical Abstract

1. Introduction

Forest ecosystems provide essential ecological, economic, and social services globally, including climate regulation, biodiversity support, and critical livelihoods for over 1.6 billion people (FAO, 2020; IPCC, 2022; Pearce, 2001). Yet, these indispensable natural capitals face persistent degradation across Sub-Saharan Africa, where intense anthropogenic pressures drive large-scale forest conversion (Olorunfemi et al. 2022). Weak governance systems, institutional fragmentation, insecure land tenure, and the escalating demand for agricultural land continue to accelerate deforestation and forest degradation (Geist & Lambin, 2002; Lan, C. C. 2019), undermining both ecosystem integrity and human wellbeing.

Ethiopia exemplifies this alarming trajectory, experiencing one of the most pronounced declines in forest cover on the continent from historical estimates exceeding 40% to merely 2.36% by the early 2000s (Reusing, M. 2000.; Dessie, G. 2007; Sisay, G., & Gitima, G. 2020). This persistent decline is driven by a complex interplay of demographic expansion, state-led agricultural development, and short-term economic policies that overlook long-term ecological sustainability (Regassa, B. T. 2022). Localized climate shifts, including observed warming and decreasing rainfall (Gemedu et al., 2021), further exacerbate land degradation and ecosystem vulnerability, underscoring the urgent need for nature-based, climate-resilient governance strategies. Recent meteorological analysis in Gimbi District confirms a significant temperature increase of 0.31°C per decade and a decline in main rainy season rainfall by 69 mm per decade, intensifying the need for climate-resilient farming systems. In response, local farmers are increasingly adopting agroforestry as an adaptation strategy (Chemeda et al., 2025).

Within this context, indigenous agroforestry systems (IAFS) have emerged as critical nature-based solutions for reconciling biodiversity conservation with agricultural production (Telwala, 2023; Gupta et al., 2024). Rooted in traditional ecological knowledge, these systems integrate trees with crops and/or livestock, enhancing ecological resilience and farmer livelihoods. By combining production and conservation functions, indigenous agroforestry serves as a climate-smart refuge, particularly as rain-fed farming systems struggle under mounting climatic stress (Chemeda et al., 2025). Globally, agroforestry landscapes are recognized as multifunctional bio-cultural systems that harmonize agricultural productivity with biodiversity conservation and climate change mitigation (Tsiakiris et al., 2024).

In Ethiopia, IAFS in the western highlands demonstrate this potential vividly. They conserve a high proportion of native woody species comparable to natural forests while simultaneously enhancing carbon sequestration and sustaining local livelihoods (Chemeda et al., 2022). The presence of perennial

trees in such systems improves carbon sequestration more effectively than conventional monocultures, while conserving soil and water resources (Gemechu, 2025). This biodiversity-enhancing functions such as providing microhabitats, protecting soil organisms, and promoting ecological balance enable agroforestry systems to operate as biodiversity refuges within human-managed landscapes (Montagnini & del Fierro, 2024; Chemed et al., 2025). Beyond biodiversity, these systems also enhance food security by enabling year-round production of diverse crops, including fruits, vegetables, and cereals, thereby improving dietary diversity among smallholder households (Chemed et al., 2024).

Despite these proven ecological and socioeconomic benefits, the ecological contribution and biodiversity-refuge capacity of IAFS in the climate-sensitive Gimbi District of Western Ethiopia remain insufficiently quantified. While studies highlight their role in conserving native tree species and storing substantial carbon stocks, empirical evidence is still lacking on how these traditional systems function across different ecological gradients and socio-economic contexts (Chemed et al., 2022; Gemechu, 2025). In particular, there is limited scientific understanding of their carbon sequestration potential, biodiversity conservation value, and livelihood contributions under changing climatic conditions (Wana et al., 2023). Although indigenous agroforestry and traditional land-use systems in the Wollega Zones have long enhanced food security, income diversification, and ecosystem resilience, they remain under-documented, under-supported by policy, and undervalued in national climate and biodiversity frameworks (Montagnini & del Fierro, 2024; Tsiakiris et al., 2024). The absence of empirical quantification and policy integration limits their recognition as legitimate climate-smart biodiversity refuges within Ethiopia's sustainable development and climate adaptation strategies.

Accordingly, the present study addresses this knowledge gap by assessing the structure, composition, and diversity of woody species within the IAFS of Gimbi District. Specifically, this study aims to (i) determine the woody species composition, structure, and diversity within these systems; (ii) quantify their ecological significance using key diversity indices (H', Evenness, Richness); (iii) identify dominant indigenous species and their functional roles in system resilience; and (iv) provide policy-relevant conclusions on the role of IAFS as climate-smart biodiversity refuges. The findings provide empirical evidence supporting the integration of these traditional systems into national climate-smart agricultural and biodiversity conservation strategies.

2. Description of the Study Area

2.1. Location and Physical Setting

The study was conducted in Gimbi District, located in the West Wollega Zone of the Oromia National Regional State, Western Ethiopia (Fig. 2). The district lies between 9°10'–9°17' N and 35°44'–36°09' E

and covers a total area of approximately 1,183.44 km², administratively divided into 32 rural *ganda* (lowest administrative units).

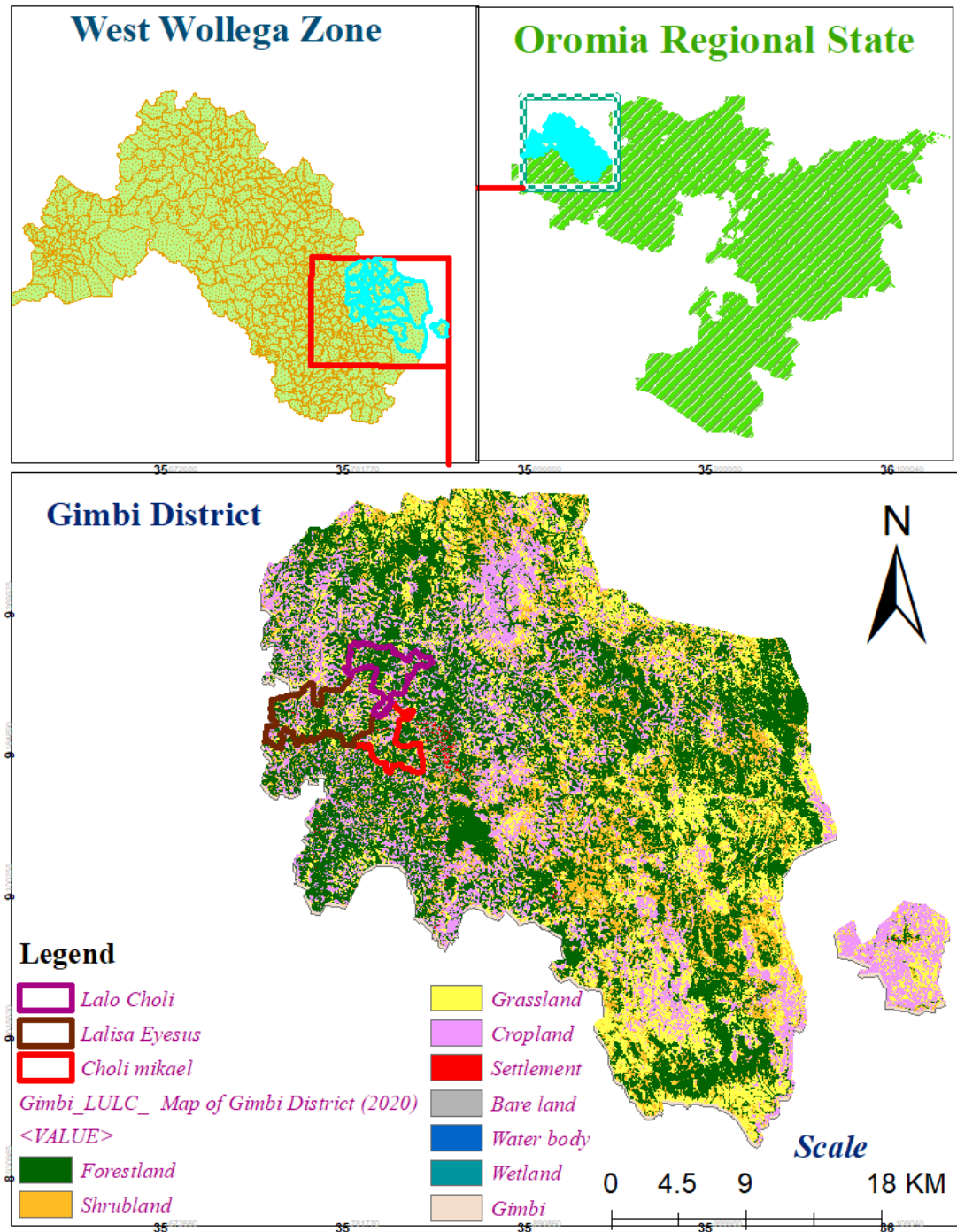


Figure 2. Study area map

Gimbi District exhibits a diverse physical geography, with an altitudinal range of 1,200 to 2,222 m above sea level, resulting in distinct agro-ecological zones (lowland, midland, and highland). These zones are largely classified by their suitability for perennial crops such as coffee. Agriculture in the district is predominantly mixed crop–livestock farming, with indigenous coffee-based agroforestry serving as the dominant land-use system, integrating perennial trees with crops and livestock to support

both livelihoods and ecosystem services.

2.2. Climate and Climate Vulnerability

Gimbi District is largely classified as a midland climate zone. The area receives an abundant mean annual rainfall ranging from 1400 to 1800 mm, with mean annual temperatures fluctuating between a minimum of 10 °C and a maximum of 30 °C. The rainfall follows a bimodal pattern: Main Rainy Season (Ganna): June to September, Small Rainy Season (Arfaasaa): March to May, and Major Dry Season (Bona): Extends from mid-October to April. Despite the relatively high rainfall, Gimbi District is highly vulnerable to climatic shifts, which necessitates the study of climate-resilient solutions. Recent meteorological analysis in Gimbi District confirms a significant temperature increase of 0.31°C per decade and a decline in main rainy season rainfall by 69 mm per decade, intensifying the need for climate-resilient farming systems (Chemeda, Senbeta & Birhane, 2025). In response, local farmers are increasingly adopting agroforestry as an adaptation strategy (Chemeda et al., 2025).

2.3. Socio-economic Context and Land Use

The economy of Gimbi District is overwhelmingly dependent on rain-fed small-scale agriculture. Approximately 90% of the district's land area is used for agricultural production, supporting a relatively high population density of 124.8 inhabitants per km². The average rural land holding size is small, estimated at about 1.2 hectares.

The principal cash and food crops include coffee, sesame, corn, beans, and bananas, varieties of vegetables. Critically, coffee farming predominates in the district's southwest. This socio-economic and ecological context characterized by small landholdings, high climate vulnerability, and a dominant shade-dependent cash crop provides the ideal setting for investigating the ecological function and biodiversity-refuge capacity of IAFS as a sustainable, climate-smart alternative.

2.4. Vegetation Sampling and Data Collection

A purposive sampling approach was employed to assess the ecological characteristics of the IAFS in three localities due to their convenience; namely; Lalo Choli, Lalisa Eyesus, Choli Mikael. A total of 30 sample plots (quadrats), each measuring 10 m × 10 m, were established across the study site to capture representative areas of indigenous home garden agroforestry practices (key informant review). Within each plot, all woody species with a DBH $\geq$ 2.5 cm and a height $\geq$ 2.5 m were recorded. Species identification was carried out using local knowledge, and confirmed with standard floral guides. For each species, the following data were collected: scientific name, family, and primary functional role (e.g., shade, fruit, timber, medicinal).

2.5. Data Analysis

Ecological data were analyzed using the following diversity and evenness metrics:

1. Species Richness (S): The total count of all unique woody species recorded across the 30 plots.
2. Shannon Diversity Index (H'): Used to account for both the number of species and their relative abundance, calculated as:

$H' = -\sum_{i=1}^S (P_i \ln P_i)$, where S is the number of species and P_i is the proportion of individuals belonging to the i^{th} species.

3. Pielou's Evenness Index (E): Used to measure the equality of species abundance, calculated as:

$$E = \ln H' / \ln S$$

Descriptive statistics were applied to summarize the species composition and their corresponding functional uses.

SPSS V.23 and R 4.5 were used to analyze the data.

3. Results

3.1. Species Composition and System Structure

The inventory of woody perennials (DBH > 2.5 cm, height > 2.5 m) defined the structural foundation of the IAFS (Table 1). The system was numerically dominated by *Coffea arabica* (307 individuals) and *Musa acuminata* (101 individuals), whose frequent integration formed a definitive coffee-banana intercropping layer (Fig. 2). Other prevalent components included fruit trees (*Mangifera indica*, *Persea americana*, *Carica papaya*) and multipurpose shade trees (*Croton macrostachyus*, *Cordia africana*, *Acacia abyssinica*).

Table 1. Top 10 Most Frequent Structural Species in the IAFS

Rank	Scientific Name	Family	Total Abundance (No.spp)	Primary Functional Role
1	<i>Coffea Arabica</i>	Rubiaceae	307	Cash Crop / Shade Dependent
2	<i>Musa acuminata</i>	Musaceae	101	Food / Microclimate Regulator
3	<i>Mangifera indica</i>	Anacardiaceae	50	Fruit Tree / Cash Crop/bee forage
4	<i>Croton macrostachyus</i>	Euphorbiaceae	32	Shade / Timber / Medicinal, bee forage
5	<i>Vernonia rueppellii</i>	Asteraceae	24	Bee forage / Wood / Fodder
6	<i>Cordia Africana</i>	Boraginaceae	22	Shade / Timber / Soil Fertility/bee forage
7	<i>Persea</i>	Lauraceae	19	Fruit Tree / Food

<i>Americana</i>				
Rank	Scientific Name	Family	Total Abundance (No.spp)	Primary Functional Role
8	<i>Carica papaya</i>	Caricaceae	18	Fruit Tree / Food
9	<i>Eucalyptus globulus</i>	Myrtaceae	15	Construction / Timber/fire wood/ bee forage
10	<i>Acacia abyssinica</i>	Fabaceae	14	Shade / Timber / charcoal /Nitrogen Fixation

The vertical structure was characterized by three primary layers: a scattered canopy of timber/fuelwood species (e.g., *Cordia africana*, *Eucalyptus globulus*), an intermediate layer of coffee and banana, and a diverse ground layer (Fig. 2).



Figure 2. Multi-layered structure of a coffee–banana home garden agroforestry system showing species arrangement and microclimate benefits

Footnote: While botanically herbaceous, *Musa acuminata* was included in structural metrics as a perennial component exceeding the minimum height (> 2.5 m) and pseudo-stem diameter (> 2.5cm) criteria.

3.2. Integration of Traditional Food Crops

Beyond the perennial structure, the home gardens incorporated a variety of traditional food crops. The ground layer contained herbs, tubers, and roots such as cabbage, "Anchote" (*Coccinia abyssinica*), and "Goodarree" (*Colocasia esculenta*). *Coccinia abyssinica*, a preferred local food of Wollega, was recorded sparsely. Climbing beans ("Abbaa bonaa", *Phaseolus lunatus*) were also observed, typically planted along fences.

3.3. Vegetation Structure and Size-Class Distribution

The diameter distribution of trees (DBH > 2.5 cm) in the IAFS exhibited a reverse J-shaped pattern (Fig. 3), with a high density of individuals in the smallest diameter classes (2.5-10 cm) and a rapid decline towards larger classes. The larger diameter classes (>30 cm DBH) were predominantly composed of *Albizia gummifera* and *Cordia africana*.

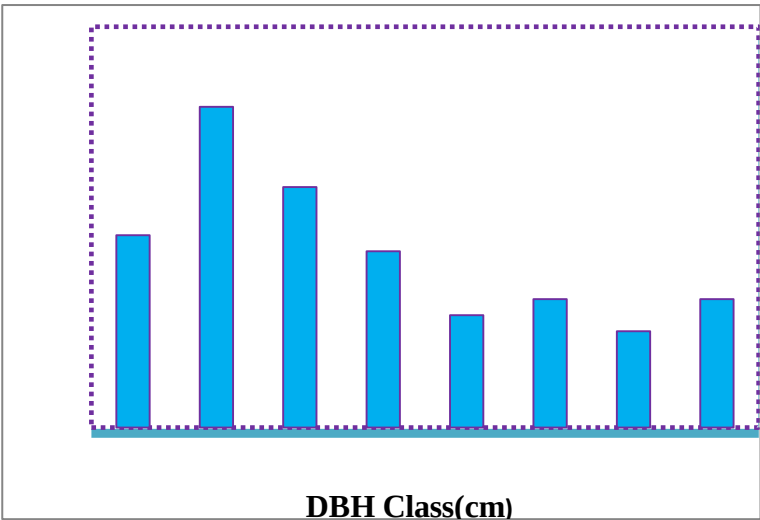


Figure 3. Diameter-class distribution of recorded tree species in the IAFS

3.4. Species Diversity and Evenness

A total of 72 agroforestry plant species belonging to 43 distinct families were documented. Quantitative analysis yielded a Shannon Diversity Index (H') of 3.16 and a Pielou's Evenness Index (J') of 0.74 (Table 2).

Table 2.Agroforestry species composition and diversity (N=30)

Shannon diversity Index	3.16*
Pielou's Evenness index	0.74
Species richness	72

Survey, 2020

4. Discussions

4.1 Whole-System Biodiversity in Indigenous Agroforestry Systems

The present study demonstrates that IAFS in Gimbi District harbor substantial whole-system plant biodiversity, encompassing woody perennials, perennial non-woody crops, annual food plants, root and tuber crops, and climbing legumes. The documentation of 72 cultivated plant species belonging to 43 families reflects a level of biological diversity comparable to, and in some cases exceeding, which reported for other traditional agroforestry systems in southwestern Ethiopia (Negash, 2014; Seid & Kebebew, 2022; Kebebew et al., 2024).

Importantly, this diversity should not be interpreted solely through a forestry lens. Rather, it represents intentional agroecosystem design, in which farmers integrate multiple life forms and functional groups

within limited landholdings. Such system-level biodiversity contrasts sharply with simplified monocropping systems and reinforces the role of IAFS as managed biodiversity reservoirs within agricultural landscapes (De Beenhouwer et al., 2016; Montagnini & del Fierro, 2024).

4.2 Contribution of Non-Woody Crops to Biodiversity Refuge Function

Non-woody cultivated species formed a critical component of system diversity and functionality. Perennial crops such as *Musa acuminata* and *Carica papaya*, along with annual vegetables, legumes, and root and tuber crops (e.g., *Coccinia abyssinica* and *Colocasia esculenta*), contributed substantially to species richness and functional heterogeneity. Banana (*Musa acuminata*), although botanically herbaceous, played a key structural and microclimatic role within the system, occupying an intermediate vertical layer and buffering temperature and moisture conditions for understory crops such as coffee. Root and tuber crops, particularly *Coccinia abyssinica* (“Anchote”), represent culturally valued food sources with high nutritional importance and resilience under variable climatic conditions. Their presence underscores the role of IAFS as biocultural refuges, safeguarding both biodiversity and indigenous food systems (Seid & Kebebew, 2022; Chemed et al., 2024).

4.3 Structural Complementarity between Woody and Non-Woody Components

The multi-layered structure observed in the IAFS (Fig. 2) reflects a high degree of vertical and functional complementarity between woody and non-woody species. Upper canopy trees such as *Cordia africana* and *Albizia gummifera* provide shade, reduce solar radiation, and contribute organic matter through litter fall. The intermediate layer, dominated by coffee and banana, optimizes light use while moderating microclimatic extremes. The ground layer, composed of herbs, legumes, vegetables, and tuber crops, ensures continuous soil cover and diversified production. This stratification enhances overall resource-use efficiency and ecological stability, consistent with findings from other tropical agroforestry systems where layered vegetation reduces evapotranspiration, improves soil moisture retention, and supports diverse microhabitats (Hailu et al., 2021; Tsiakiris et al., 2024). The observed structure supports the interpretation of these systems as functionally integrated agroecosystems, rather than assemblages of independent crop components.

4.4 Population Structure and Regeneration Dynamics

The reverse J-shaped diameter distribution of woody species (Fig. 3) indicates continuous recruitment and sustained regeneration within the agroforestry systems. Such patterns are characteristic of actively managed landscapes where selective retention, planting, and protection of younger individuals are embedded within traditional management practices (Negash, 2014; Kebebew et al., 2024). Unlike natural forests, regeneration in IAFS is not solely ecological but also socio-ecological, shaped by farmers’ decisions regarding species selection, spacing, and replacement. This combination of natural regeneration and human management

contributes to long-term system persistence and supports the maintenance of structural complexity under ongoing land-use pressure.

4.5 Functional Diversity and Ecosystem Service Provision

The high species richness observed translated into substantial functional diversity, underpinning a range of ecosystem services. Shade provision, soil fertility enhancement, food production, fuelwood supply, and medicinal use were distributed across multiple species and functional groups (Table 1). This functional redundancy enhances resilience by reducing dependence on any single species or crop. Increased litter inputs from diverse perennial components contribute to soil organic matter accumulation and improved soil structure, which are particularly important in erosion-prone landscapes of western Ethiopia (Ararsa & Endalamaw, 2024; Keprate et al., 2025). Moreover, biologically complex systems can reduce pest and disease outbreaks through habitat diversification, aligning with broader agro-ecological principles (Sileshi et al., 2012; IPCC, 2022).

4.6 Indigenous Knowledge and Species Selection Logic

The composition of the IAFS reflects deeply embedded indigenous ecological knowledge, where species are selected and managed based on multiple criteria, including productivity, resilience, cultural value, and ecosystem function. The retention of indigenous tree species alongside exotic fruit and cash crops illustrates adaptive decision-making rather than static tradition. Home-garden management, often involving women, plays a central role in maintaining non-woody crop diversity and traditional food species. This knowledge-driven management enhances dietary diversity and strengthens household-level resilience to climate variability, reinforcing findings from other Ethiopian agroforestry contexts (Hika Wana et al., 2024; Chemedet et al., 2024).

4.7 Climate-Smart Attributes beyond Carbon Sequestration

While agroforestry systems are frequently highlighted for their carbon sequestration potential, the climate-smart attributes of the IAFS documented here extend beyond carbon storage. The integration of perennial and annual crops ensures year-round food availability, spreads climatic risk across multiple species, and buffers households against seasonal crop failure. Structural complexity moderates temperature extremes and reduces moisture stress for shade-sensitive crops such as coffee, supporting adaptive capacity under observed warming and rainfall variability in Gimbi District (Gemedet et al., 2021; Chemedet et al., 2025). These attributes align with climate-smart agriculture principles emphasizing adaptation, resilience, and livelihood security (FAO, 2013; Mbow et al., 2014).

4.8 Comparison with Similar Agroforestry Systems

The diversity values recorded in this study ($H' = 3.16$; $J' = 0.74$) are comparable to or higher than those reported for coffee-based agroforestry systems in Yayu and other parts of southwestern Ethiopia (Negash, 2014; Seid & Kebebew, 2022; De Beenhouwer et al., 2016). Importantly, the inclusion of non-woody cultivated species broadens the biodiversity assessment beyond tree-focused inventories, highlighting the added value of whole-system approaches. This comparison reinforces the generalizability of the findings and supports the argument that indigenous agroforestry systems across similar agro-ecological zones function as biodiversity-rich production landscapes rather than transitional or degraded land uses.

4.9 Indigenous Agroforestry Systems as Climate-Smart Biodiversity Refuges

Taken together, the high species richness, functional diversity, vertical stratification, and integration of culturally important food crops support the interpretation of IAFS in Gimbi District as climate-smart biodiversity refuges within human-managed landscapes. These systems conserve indigenous plant diversity, maintain ecological processes, and sustain livelihoods under increasing climatic stress. Rather than relics of pre-modern agriculture, the findings indicate that IAFS represent dynamic, adaptive land-use strategies with relevance for contemporary climate adaptation and biodiversity conservation agendas (Montagnini & del Fierro, 2024; Tsiakiris et al., 2024).

5. CONCLUSIONS

This study provides empirical evidence that IAFS in Gimbi District, Western Ethiopia, support high whole-system plant biodiversity, encompassing woody perennials, perennial non-woody crops, annual food species, root and tuber crops, and climbing legumes. The documented richness of 72 cultivated plant species across 43 families highlights the capacity of these systems to function as biodiversity-rich production landscapes, even under conditions of small landholdings and increasing climatic stress.

The observed vertical stratification, functional complementarity, and continuous regeneration of woody components indicate that these systems are structurally complex and dynamically managed, rather than residual or degraded land uses. The integration of non-woody crops—particularly banana, traditional root and tuber species, and annual vegetables—plays a critical role in enhancing dietary diversity, buffering climatic risk, and sustaining year-round food availability. These attributes reinforce the interpretation of IAFS as biocultural systems, where biodiversity conservation is inseparable from indigenous knowledge and livelihood strategies.

From a climate-smart perspective, the findings demonstrate that the resilience of IAFS extends beyond carbon-related benefits. Structural complexity, species diversity, and functional redundancy collectively enhance adaptive capacity by moderating microclimatic conditions, reducing vulnerability to crop failure, and stabilizing production under variable rainfall and warming trends. These characteristics are consistent

with climate-smart agriculture principles emphasizing adaptation, resilience, and food security in smallholder contexts.

Overall, the study supports the recognition of IAFS as climate-smart biodiversity refuges within human-managed landscapes. Integrating these systems into national climate adaptation, biodiversity conservation, and sustainable land-use policies—such as Ethiopia’s Climate Resilient Green Economy strategy—offers a cost-effective and socially grounded pathway to address interconnected challenges of climate change, biodiversity loss, and rural livelihood insecurity. Future research should build on this foundation by exploring functional diversity metrics, ecosystem service trade-offs, and scaling pathways for indigenous agroforestry across comparable agroecological zones.

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