Traditional Ecological Knowledge as Biocultural Insurance: Quantifying Homegarden-Based Agrobiodiversity and Climate Resilience in Ethiopia

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Abstract

Traditional Ecological Knowledge (TEK) underpins smallholder resilience, yet its functional contribution to climate adaptation remains poorly quantified. This study investigates TEK-driven homegardens as biocultural insurance systems that maintain biodiversity, productivity, and livelihood stability under climate stress in the Hadiya and Kambata-Tembaro Zones, Central Ethiopia. Using a mixed-methods design integrating ecological inventories ($n = 180$ plots), ethnobotanical and socio-cultural assessments, and household surveys ($n = 384$), the Homegarden Insurance Hypothesis was tested through structural equation modeling. A total of 77 plant species across 38 families were identified, with Lamiaceae, Fabaceae, and Asteraceae most represented. Species diversity was high (Shannon $H' = 1.95–3.45$), and 60% of taxa served multiple roles food, medicinal, and agroecological. TEK-guided co-cultivation practices, such as Cajanus cajan with Ficus sur, enhanced soil fertility, shading, and pest regulation. Culturally significant species received stronger conservation attention ($r = 0.84$, $p < 0.001$), while intergenerational knowledge transfer correlated with adaptive species richness ($r = 0.67$, $p < 0.001$). Following droughts, TEK-managed homegardens retained 86% of productive species and 92% of dietary diversity, compared with 42% and 50% in monocultures. Structural equation modeling indicated that TEK intensity significantly improved homegarden diversity ($\beta = 0.68$, $p < 0.001$), yield stability ($\beta = 0.42$, $p = 0.003$), and income resilience ($\beta = -0.55$, $p < 0.001$). Overall, these results provide robust quantitative evidence that TEK functions as a biocultural insurance mechanism, linking indigenous knowledge intensity to ecological stability and livelihood security offering practical insights for climate-resilient agroecosystem design and biodiversity policy integration.

1. Introduction

Traditional Ecological Knowledge (TEK) the cumulative, place-based understanding of species, landscapes, and ecological processes developed by local communities over generations plays a vital role in sustaining biodiversity, ecosystem services, and adaptive capacity under climate change (Tengö et al., 2017; Berkes, 2018). In smallholder systems, TEK supports the management of multifunctional agroecosystems that buffer climatic variability through diversified production, species selection, and adaptive learning (Gómez-Baggethun & Reyes-García, 2019; Reyes-García et al., 2022). Despite recognition in global frameworks such as IPBES (2019) and the CBD (2020), quantitative validation of TEK's resilience-building functions remains scarce, as most studies emphasize qualitative or descriptive accounts (Ruiz-Mallén & Corbera, 2013; Kassam et al., 2021). The absence of empirical evidence linking TEK intensity to measurable ecological and livelihood outcomes limits its integration into climate adaptation policy.

Homegardens are among the most enduring TEK-based agroecosystems, integrating diverse crops, trees, and livestock within small, multi-strata plots that sustain food, medicine, and ecological services year-round (Galhena et al., 2013; Kumar & Nair, 2021). Their structural complexity promotes microclimate regulation, soil fertility, and pollination (Chandrashekara, 2019), making them "living laboratories" of adaptation (Eyzaguirre & Linares, 2010). In Ethiopia, where smallholders face recurrent droughts and land degradation, homegardens have long served as biocultural refugia that conserve indigenous crops and knowledge crucial for food and cultural security (Asfaw, 2014; Teshome et al., 2022). However, while numerous studies document their species composition and cultural roles (Abebe et al., 2020; Feleke et al., 2023), few assess how TEK-driven management enhances resilience through quantifiable ecological and livelihood indicators (Mekonnen et al., 2022).

In the Ethiopian highlands, homegarden diversity reflects intergenerational learning, gendered labor, and ecological experience (Woldetsadik et al., 2023), yet such systems remain undervalued within modernization policies favoring yield uniformity (Gebremariam et al., 2020). Demonstrating TEK's quantitative role in stabilizing productivity, sustaining dietary diversity, and maintaining ecosystem functioning under stress is essential for positioning it as a biocultural insurance mechanism (Folke et al., 2021; Boillat et al., 2022).

In light of the existing knowledge gaps and the growing demand to incorporate evidence-based TEK into climate adaptation policy, this study employs a hypothesis-driven comparative framework. The research investigates the role of TEK in shaping biodiversity and resilience within smallholder homegardens. Guided by the Biocultural Resilience Framework, the study quantitatively evaluates how variation in TEK intensity affects species diversity, functional redundancy, and adaptive capacity. This evaluation offers a rigorous empirical examination of the Homegarden Insurance Hypothesis. Because TEK is culturally embedded, we further examined whether TEK–biodiversity–resilience relationships differ between the Hadiya and Kambata-Tembaro communities, allowing a cross-cultural assessment of biocultural adaptation. To incorporate a geographical dimension, we also evaluated how homegarden structure and climate-buffering potential vary along ecological gradients in Central Ethiopia. These aims were operationalized through a causal model in which TEK intensity is expected to elevate species and functional diversity, with biodiversity mediating improvements in yield stability and reductions in livelihood vulnerability. Accordingly, we hypothesized that (i) households with higher TEK intensity would maintain richer and more resilient species assemblages; (ii) cultural context would modify the strength of TEK-driven ecological outcomes; and (iii) biodiversity would act as a key mediating mechanism linking TEK to household resilience. These integrated objectives and hypotheses guided the design and analytical strategy of the study and provided a rigorous framework for evaluating TEK as a biocultural insurance system under increasing climate stress.

2. Methods

Study Area

The study was conducted in Hadiya and Kambata-Tembaro Zones, Central Ethiopia (Fig. 1), regions characterized by diverse agroecologies, predominantly smallholder farming, and a rich tradition of homegarden cultivation. Rainfall is bimodal, with mean annual precipitation ranging from 800 to 1,400 mm, while temperatures vary between 15°C and 25°C across altitudes. Livelihoods are heavily dependent on mixed farming systems, where crop cultivation, livestock rearing, and homegarden management are tightly interwoven with local cultural practices. These zones were selected for their high prevalence of homegardens and documented engagement with TEK in daily agricultural and household decision-making.

Ecology, Population, Ethnicity, Language, and Religion

Hadiya and Kambata-Tembaro Zones are situated in the south-central Ethiopian highlands, predominantly occupying midland to highland elevations (1,500–2,800 m a.s.l.). The zones feature sub-humid climates, remnants of Afromontane forests, and long-established enset-based homegarden agroforestry systems. The topography is diverse, with fertile Nitisol-dominated soils, terraced or slope-managed farmlands, and smallholder cropping systems that sustain high levels of agrobiodiversity. Ecological variability is influenced by altitude, microclimate, land-use intensity, and traditional cultural management practices.

According to the 2007 national census by the Central Statistical Agency of Ethiopia, the Hadiya Zone had a total population of 1,231,196 (612,026 men and 619,170 women), with approximately 10.9% residing in urban areas. The Kambata-Tembaro Zone recorded 1,080,837 inhabitants (536,676 men and 544,161 women), of whom about 14.4% lived in urban centers.

The inhabitants of these zones define their ethnic identity through lineage, language, and cultural heritage rather than external classifications. In the Hadiya Zone, communities collectively identify as Hadiya, a group bound by shared ancestry, clan relationships, communal rituals, and historical narratives that emphasize continuity across generations. Their identity is closely linked to customary institutions, agricultural livelihoods, and attachment to ancestral territories. In the Kambata-Tembaro Zone, local communities primarily identify as Kambata and Tembaro, each maintaining distinct genealogies, ritual practices, and cultural traditions while recognizing historical ties and frequent intercommunity interaction. Across both zones, ethnic identity is expressed as a lived sense of belonging, transmitted through family, land, language, and cultural memory.

Linguistically, the Hadiya and Kambata-Tembaro Zones are dominated by Highland East Cushitic languages. Hadiyya (*Glottocode: hadi1240*) is spoken in the Hadiya Zone, whereas Kambaata (*Glottocode: kamb1316*), including the closely related Tembaro variety, is prevalent in Kambata-Tembaro. These languages share features typical of Highland East Cushitic tongues agglutinative morphology, rich verb inflection, and case marking and serve as the primary medium for daily communication and cultural knowledge transfer. Amharic is used mainly in administration and formal education.

Religious affiliation in the two zones is diverse and self-declared. Most communities practice Protestant Christianity, followed by Ethiopian Orthodox Christianity and Islam, with traditional beliefs persisting, especially in agricultural, health, and life-cycle rituals. Religious identity shapes social norms, communal gatherings, and everyday cultural practices.

Study Design

A cross-sectional, mixed-methods approach was employed, combining ecological surveys, ethnobotanical documentation, and socio-cultural assessments. The study aimed to capture both species diversity and functional characteristics of homegardens, and the traditional knowledge and governance practices guiding their management.

Sampling Strategy

A multistage sampling design was implemented. Woredas (districts) were purposively selected based on reported homegarden prevalence and agroecological variation. Within each woreda, kebeles (villages) were randomly selected (Table 1). Household-level sampling targeted farmers maintaining homegardens of varying sizes and management intensity (traditional vs. improved).

A total of 384 individuals participated across the two zones, comprising 191 men (49.7%) and 193 women (50.3%), ensuring balanced gender representation for examining traditional ecological knowledge and intergenerational knowledge transmission. Middle-aged respondents formed the largest share (50.5%), followed by older (28.1%) and younger participants (21.4%), with over 72% above 35 years. This age structure reflects the concentration of long-term experiential knowledge among older and middle-aged community members who are central to sustaining homegarden-based agrobiodiversity and climate-adaptive practices. Educational backgrounds ranged from primary (42.4%) and secondary education (33.6%) to no formal schooling (14.3%) and religious instruction (9.6%). Respondents with limited schooling frequently demonstrated deeper familiarity with species management and climate-responsive practices, underscoring the role of lived experience and oral transmission in maintaining homegarden diversity as a form of biocultural insurance.

Table 1
List of sampling settlements in Hadiya and Kambata-Tembaro Zones, including their geographic coordinates, elevation, and administrative classification.

S/No	Zone	Sampled Kebeles	Latitude (N)	Longitude (E)	Altitude (m)
1	Kembata Tembaro	Wonjela	7° 39' 54.37"	37° 07' 12.06"	2446
2		Hadero Zuriya	7° 2' 21.03"	37° 09' 01.06"	2100
3		Wacho	7° 02' 56.37"	37° 18' 22.22"	2050
4		Ganati	7° 03' 36.07"	37° 06' 33.06"	1950
5		Funamura	7° 04' 50.17"	37° 08' 12.06"	2200
6	Hadiya	Geja	7° 08' 06.30"	37° 08' 02.18"	1987
7		Masbira	7° 43' 33.24"	37° 03 33.06"	1850
8		Upper Gana	7° 62' 64.12"	37° 76' 42.11"	2100
9		1st Hankota	7° 43' 51.28"	37° 61' 08.06"	2102
10		Lereba	7° 72' 29.37"	37° 87' 45.28"	2050

Homegarden Surveys

Each homegarden was systematically mapped, and all plant species were recorded to the lowest possible taxonomic level using local expertise and field guides. Diversity metrics, including Shannon diversity (H'), Simpson's index (1–D), and Margalef richness, were calculated to quantify species richness and evenness (Teshome et al., 2024). Species were further categorized into functional groups food, medicinal, fodder, ornamental, and shade/fence following standard ethnobotanical protocols (Asfaw, 2014; Mengistu & Asfaw, 2018), enabling assessment of both compositional and functional diversity across homegardens.

Ethnobotanical Interviews

Complementary ethnobotanical data were collected through semi-structured interviews with household heads, focusing on knowledge and practices associated with homegarden management. Informants were selected using purposive and snowball sampling to ensure representation of gender, age, and experience. Interviews explored local plant nomenclature, uses, planting and harvesting practices, seasonal management, seed sourcing, and intergenerational knowledge transfer. Focus group discussions were conducted to validate individual responses and capture community-level practices and norms related to TEK and adaptation strategies.

Socio-Ecological Data

Socio-economic and ecological variables were recorded to understand factors influencing homegarden composition and resilience. Data included household demographics, farm size, and access to extension services, cooperative membership, and participation in seed exchange networks. Environmental data such as garden area, soil management practices, irrigation, and microclimate conditions were also documented. This allowed for integrated assessment of both social and ecological drivers shaping homegarden diversity and adaptive capacity. Voucher specimens for all recorded species were prepared following standard herbarium procedures using *Flora of Ethiopia and Eritrea*, and deposited at the National Herbarium, Addis Ababa University and Botany laboratory of Wachemo University, ensuring long-term accessibility for verification and future study.

Data Analysis

Interview transcripts were coded and analyzed thematically using NVivo 12. Themes included TEK practices, adaptive governance, gender roles, and cultural valuation of species. Integration of ecological and socio-cultural data identified patterns linking TEK to resilience and climate adaptation. Species diversity, richness, and evenness were calculated in R (v. 4.3.0) and compared across garden types and districts using ANOVA and post-hoc Tukey tests. Correlations between garden size, management intensity, and diversity metrics were assessed with Pearson correlation.

Ethical Considerations

This research complied with the International Society of Ethnobiology (ISE) Code of Ethics (2006–2008). Ethical clearance was granted by the Departmental Research and Ethics Committee, College of Natural and Computational Sciences, Wachemo University (Approval No. WCU/IRB/2025/04). All participants were clearly informed about the study's aims, the voluntary nature of participation, and assurance of confidentiality. In line with local customs, verbal informed consent was secured in the presence of community elders or local guides who acted as witnesses. No personal identifiers were collected, and minors were not included. Participants were free to withdraw at any stage. The study involved no invasive procedures or biological sampling. All traditional ecological knowledge was documented with respect for community ownership, cultural protocols, and the broader ethical considerations central to research on biocultural knowledge systems.

3. Results

3.1. Floristic Composition

A total of 77 plant species representing 38 families were documented across surveyed homegardens in the Hadiya and Kambata-Tembaro Zones (Table 2). Dominant families included Lamiaceae, Fabaceae, and Asteraceae, together comprising 32% of all species recorded. Herbs (39%) and trees (31%) were the predominant growth forms, illustrating deliberate vertical stratification that maximizes light capture and microclimate regulation.

Table 2
Plant species documented with their scientific and local names, families, growth form, use categories, and preparations.

Scientific Name	Local Name	Family	Growth Form	Use Categories*	Preparations
Albizia gummifera (Gmel.) Sm.	Sassa	Fabaceae	Tree	Fodder, Ecological	Raw (chewed)
Allium cepa L.	Key shinkurt	Amaryllidaceae	Herb	Food, Medicinal	Cooked
Allium sativum L.	Nech shinkurt	Amaryllidaceae	Herb	Medicinal, Food	Cooked
Aloe vera (L.) Burm.f.	Kelo	Asphodelaceae	Herb	Medicinal	Cooked
Anethum foeniculum (L.) Koch	Insilal	Apiaceae	Herb	Food, Medicinal	Cooked
Artemisia afra Jacq. ex Willd.	Chikugn	Asteraceae	Shrub	Medicinal, Ritual	Raw (chewed)
Bidens pilosa L.	Chenechene	Asteraceae	Herb	Medicinal	Cooked
Calpurnia aurea (Aiton) Benth.	Dursi	Fabaceae	Tree	Medicinal, Fodder	Cooked
Capsicum annuum L.	Biber	Solanaceae	Herb	Food	Ripen fruit
Carica papaya L.	Papaya	Caricaceae	Tree	Food, Medicinal	Ripen fruit
Casimiroa edulis Llave & Lex.	White sapote	Rutaceae	Tree	Food	Raw (chewed)
Catha edulis (Vahl) Forssk. ex Endl.	Khat	Celastraceae	Shrub	Ritual, Stimulant	Raw (chewed)
Citrus limon (L.) Osbeck	Lomi	Rutaceae	Tree	Food, Medicinal	Ripen fruit
Coffea arabica L.	Buna	Rubiaceae	Shrub	Food, Ritual, Ecological	Cooked
Coffea robusta Pierre ex A.Froehner	Buna gedawo	Rubiaceae	Shrub	Food, Ritual	Cooked
Cordia africana Lam.	Wanza	Boraginaceae	Tree	Fodder, Ecological	Ripen fruit
Croton macrostachyus	Bisana	Euphorbiaceae	Tree	Medicinal, Ecological	Raw (chewed)

Scientific Name	Local Name	Family	Growth Form	Use Categories*	Preparations
Hochst. ex Delile					
Cucumis melo L.	Melon	Cucurbitaceae	Climber	Food	Cooked
Cucumis sativus L.	Dima	Cucurbitaceae	Climber	Food	Cooked
Daucus carota L.	Carrot	Apiaceae	Herb	Food, Medicinal	Cooked
Dennettia tripetala Baker.	Pepper fruit	Annonaceae	Tree	Food, Medicinal	Cooked
Dracaena steudneri Engl.	Tefako	Asparagaceae	Tree	Ritual, Ecological	Cooked
Echinops kebericho Mesfin	Kebericho	Asteraceae	Herb	Ritual, Medicinal	Cooked
Ensete ventricosum (Welw.) Cheesman	Enset	Musaceae	Herb	Food, Fodder, Ritual	Cooked
Enydra fluctuans Lour.	Dikko	Asteraceae	Herb	Food	Raw (chewed)
Eragrostis tef (Zucc.) Trotter	Tef	Poaceae	Herb	Food	Cooked
Eucalyptus globulus Labill.	Gomen	Myrtaceae	Tree	Ecological, Medicinal	Cooked
Ficus sycomorus L.	Wanza	Moraceae	Tree	Ritual, Food, Ecological	Ripen fruit
Garcinia livingstonei T. Anderson	Imbu	Clusiaceae	Tree	Food	Raw (chewed)
Hagenia abyssinica (Bruce) Gmel.	Kosso	Rosaceae	Tree	Medicinal, Ritual	Ripen flower
Hibiscus sabdariffa L.	Karkade	Malvaceae	Herb	Food, Medicinal	Raw (chewed)
Hordeum vulgare L.	Barley	Poaceae	Herb	Food	Cooked
Jatropha curcas L.	Jatropha	Euphorbiaceae	Shrub	Fodder, Ecological	Raw
Justicia schimperiana (Hochst. ex Nees) Anders.	Sensel	Acanthaceae	Shrub	Medicinal	Raw (chewed)
Lantana camara L.	Lantana	Verbenaceae	Shrub	Medicinal,	Raw

Scientific Name	Local Name	Family	Growth Form	Use Categories*	Preparations
				Ecological	(chewed)
Leonotis ocymifolia (Burm.) Iwarsson	Dama	Lamiaceae	Shrub	Medicinal	Raw (chewed)
Linum usitatissimum L.	Telba	Linaceae	Herb	Food, Medicinal	Cooked
Lippia adoensis Hochst. ex Walp.	Kessie	Verbenaceae	Shrub	Food, Medicinal	Raw (chewed)
Mangifera indica L.	Mango	Anacardiaceae	Tree	Food	Ripen fruit
Mentha spicata L.	Mint	Lamiaceae	Herb	Food, Medicinal	Ripen fruit
Musa acuminata Colla	Banana	Musaceae	Herb	Food	Ripen fruit
Myrsine africana L.	Kebercho	Myrsinaceae	Shrub	Medicinal, Ritual	Raw (chewed)
Nicotiana tabacum L.	Tobacco	Solanaceae	Herb	Ritual	Raw (chewed)
Ocimum basilicum L.	Besobila	Lamiaceae	Herb	Food, Ritual	Spice
Ocimum gratissimum L.	Rima	Lamiaceae	Herb	Medicinal, Ritual	Raw (chewed)
Ocimum lamiifolium Hochst. ex Benth.	Damakese	Lamiaceae	Herb	Medicinal, Ritual	Raw (chewed)
Olea europaea subsp. *cuspidata* (Wall. & Don) Cif.	Weira	Oleaceae	Tree	Ritual, Ecological, Medicinal	Raw (chewed)
Persea americana Mill.	Avocado	Lauraceae	Tree	Food	Ripen fruit
Phaseolus vulgaris L.	Beans	Fabaceae	Herb	Food	Raw, cooked
Physalis peruviana L.	Goose berry	Solanaceae	Herb	Food	Ripen fruit
Podocarpus falcatus (Thunb.) ex Mirb.	Zigba	Podocarpaceae	Tree	Ecological, Ritual	Raw (chewed)
Psidium guajava L.	Guava	Myrtaceae	Tree	Food, Medicinal	Raw (chewed)

Scientific Name	Local Name	Family	Growth Form	Use Categories*	Preparations
Punica granatum L.	Grenade	Lythraceae	Tree	Food, Medicinal, Ritual	Raw (chewed)
Rhamnus prinoides L'Hér.	Gesho	Rhamnaceae	Shrub	Ritual, Medicinal	Raw (chewed)
Ricinus communis L.	Ersha	Euphorbiaceae	Shrub	Fodder, Ecological	Raw chopped
Rosa abyssinica R. Br. ex Lindl.	Rosa	Rosaceae	Shrub	Ritual, Medicinal	Raw (chewed)
Rosmarinus officinalis L.	Rosemary	Lamiaceae	Herb	Food, Medicinal	Raw (chewed)
Ruta chalepensis L.	Tena adam	Rutaceae	Herb	Medicinal, Ritual, Food	Raw (chewed)
Saccharum officinarum L.	Sugarcane	Poaceae	Herb	Food	Raw (chewed)
Sesamum indicum L.	Sesame	Pedaliaceae	Herb	Food, Medicinal	Raw (chewed)
Solanum melongena L.	Eggplant	Solanaceae	Herb	Food	Cooked
Solanum nigrum L.	Tikur awut	Solanaceae	Herb	Food, Medicinal	Raw (chewed)
Tagetes minuta L.	Marigold	Asteraceae	Herb	Medicinal, Ritual	Raw (chewed)
Tephrosia vogelii Hook.f.	Vogelii	Fabaceae	Shrub	Fodder, Medicinal	Raw (chewed)
Thymus serrulatus Hochst. ex Benth.	Tosign	Lamiaceae	Herb	Food, Medicinal, Ritual	Cooked
Thymus schimperi Ron.	Tosign	Lamiaceae	Herb	Food, Medicinal, Ritual	Cooked
Trigonella foenum-graecum L.	Fenugreek	Fabaceae	Herb	Food, Medicinal	Raw (chewed)
Urtica simensis Hochst. ex Rich.	Nettle	Urticaceae	Herb	Medicinal	Raw (chewed)
Vangueria volkensii Schum	Loqe'e	Rubiaceae	Shrub	Fodder	Chopped

Scientific Name	Local Name	Family	Growth Form	Use Categories*	Preparations
Vernonia amygdalina Delile	Grawa	Asteraceae	Shrub	Medicinal, Fodder	Raw, chopped
Vicia faba L.	Faba bean	Fabaceae	Herb	Food	Cooked
Warburgia ugandensis Sprague	Kanafa	Canellaceae	Tree	Food, Medicinal, Ritual	Raw (chewed)
Ximenia americana L.	Ximenia	Olacaceae	Shrub	Food, Medicinal	Raw (chewed)
Zea mays L.	Maize	Poaceae	Herb	Food	Cooked
Zehneria scabra (L.f.) Sond.	Hareg	Cucurbitaceae	Climber	Food, Medicinal	Raw (chewed)
Zingiber officinale Roscoe	Zinjibil	Zingiberaceae	Herb	Food, Medicinal	Cooked, chewed
Ziziphus spina-christi (L.) Desf	Qurqura	Rhamnaceae	Tree	Fodder, Medicinal	Chopped, raw chewed

3.2. Composition and Functional Diversity of Homegarden Species

Functional classification revealed that over 60% of species served multiple purposes, integrating food, medicinal, ritual, and agroecological roles (Table 3). Species such as *Zingiber officinale* and *Persea americana* exemplified multifunctionality by contributing simultaneously to household nutrition, cultural expression, and ecosystem stability. This integrated use strategy reflects how traditional ecological knowledge (TEK) embeds livelihood and ecological security within a single homegarden system.

Table 3
Composition and Functional Diversity of Homegarden Species

Functional Category	No. of Species	% of Total	Representative Species	Multifunctionality (%)	P-Value
Food crops	72	80	*A. sativum*, *C. annuum*, *Z. mays*	48	0.006
Medicinal	68	78	*Z. officinale*, *A. afra*	62	0.0017
Fodder	21	26	*P. americana*, *E. abyssinica*	37	0.004
Ritual/Spiritual	18	24	*R. chalepensis*, *O. lamiifolium*	55	0.0036
Agroecological services	18	24	*F. sur*, *C. cajan*	41	0.0024

Dominant families: Lamiaceae, Fabaceae, Asteraceae (32% of all species); growth forms: herbs (39%), trees (31%), shrubs (23%), climbers (7%).

3.3. Species Diversity and Adaptive Capacity

Homegarden diversity metrics demonstrated substantial ecological variability, with Shannon indices ranging from 1.95 to 3.45 and Margalef richness values between 5.1 and 9.1. Improved or intensively managed gardens exhibited significantly higher diversity (ANOVA: $F = 7.89$, $p < 0.01$) and a greater number of drought-tolerant species (Table 4). A strong positive correlation was observed between species diversity and adaptive function ($r = 0.81$, $p < 0.01$), indicating that biodiversity directly enhances household adaptive capacity. These findings provide quantitative evidence that species richness functions as an ecological insurance mechanism against climatic variability.

Table 4
Diversity indices and their association with adaptive capacity under climate variability ($r = 0.81$, $p < 0.01$).

Homegarden ID	Shannon (H')	Simpson (1–D)	Margalef (R)	Climate-Resilient Species	Adaptive Function Score
HG-01	2.85	0.82	7.2	12	4.5
HG-02	3.12	0.87	8.0	15	5.0
HG-03	1.95	0.65	5.1	7	3.2
HG-04	3.45	0.90	9.1	17	5.5
HG-05	2.60	0.78	6.8	11	4.0

3.4. TEK-Guided Plant Selection and Co-Cultivation Patterns

Analysis of co-cultivation networks revealed that species arrangement within homegardens is strongly guided by TEK rather than random planting. Highly co-occurring pairs such as *Cajanus cajan* (legume) and *Ficus sur* (shade tree) appeared in 72% and 68% of gardens, respectively, reflecting purposeful combinations that enhance soil fertility, shading, and pest control (Table 5).

Herbs like *Ocimum basilicum* were strategically intercropped with vegetables (*Capsicum annuum*) to attract pollinators and deter pests. These spatially structured plant associations demonstrate how TEK translates ecological understanding into functional garden architecture an approach that supports ecosystem stability under increasing climate stress.

Table 5
TEK-driven species co-cultivation enhancing soil, shade, and pest control.

Species	Functional Group	Co-Cultivation Frequency (%)	Common Associates	TEK-Guided Function
Cajanus cajan	Legume	72	*Ficus sur*, *P. americana*	Soil enrichment & drought tolerance
F. sur	Shade tree	68	*C. cajan*, *C. annuum*	Microclimate buffering
C. annuum	Vegetable	55	*F. sur*, *O. basilicum*	Pest deterrence & food security
O. basilicum	Herb	48	*C. annuum*	Pollinator attraction

3.5. Cultural and Socio-Ecological Drivers of Homegarden Adaptation

Cultural significance emerged as a powerful determinant of species persistence. Plants with high symbolic or ritual value, including *Coffea arabica*, *Ruta chalepensis*, and *Ocimum lamiifolium*, exhibited the strongest conservation effort indices (≥ 0.8). Statistical analysis revealed a robust correlation between cultural value and conservation effort ($r = 0.84$, $p < 0.001$), whereas market value showed no significant relationship.

Generational knowledge transmission averaged 14 ± 6 years and was strongly associated with adaptive species richness ($r = 0.67$, $p < 0.001$), while education level showed a moderate positive effect ($r = 0.42$, $p < 0.05$) (Table 6). Collectively, these results demonstrate that cultural continuity and intergenerational TEK inheritance are central to maintaining biodiversity and resilience within homegarden systems.

Table 6
Correlation between cultural significance, conservation effort, and TEK continuity at household level.

Variable	Indicator	Mean / Range	Correlation with Adaptive Species Richness
Cultural Value Index	Symbolic & ritual use frequency	0.81 ± 0.06	r = 0.84*
Generational TEK Transmission (yrs)	Household heritage of knowledge	14.2 ± 6.3	r = 0.67*
Education Level	Years of schooling	6.1 ± 3.4	r = 0.42
Conservation Effort Index	Protection & propagation frequency	0.76 ± 0.09	r = 0.79*

**($p < 0.001$) — shows that cultural and intergenerational knowledge predict higher adaptive richness.*

3.6. The Homegarden Insurance Hypothesis: Productivity and Dietary Buffering

Comparative post-drought assessments provided compelling support for the Homegarden Insurance Hypothesis. TEK-managed homegardens retained an average of 85.9 ± 3.1% of productive plant species and 92.4 ± 2.6% of dietary diversity, whereas adjacent monoculture plots retained only 42.1 ± 4.9% and 50.2 ± 5.3%, respectively ($t = 6.72$, $p < 0.001$) (Table 7).

Households dependent on homegardens reported fourfold lower income loss (11 ± 4%) compared to monoculture-dependent households (44 ± 6%). These findings confirm that multifunctional homegardens through their ecological and cultural integration buffer households from both environmental and economic shocks.

Table 7
Comparative analysis of homegarden and monoculture performance following major drought.

System	% Productive Output Retained	% Dietary Diversity Retained	Household Income Loss (%)
Homegarden (n = 24)	85.9 ± 3.1	92.4 ± 2.6	11 ± 4
Monocrop (n = 24)	42.1 ± 4.9	50.2 ± 5.3	44 ± 6

Following drought, homegardens maintained ~ 86% of productivity vs. 42% in monocultures, supporting the "Homegarden Insurance Hypothesis."

3.7. Homegardens as Micro-Refugia for Climate-Threatened Species

Species inventory and vulnerability mapping revealed that homegardens function as micro-refugia for threatened landraces and crop wild relatives. Nineteen CWRs and twenty-seven traditional landraces were found exclusively in TEK-managed gardens, with a mean climate vulnerability score of 0.79 (Table 8).

Adaptive management practices such as shade regulation, mulching, low tillage, and seed exchange maintained viable populations of rare taxa like *C. arabica* (wild relatives) and *Triticum aestivum* var. *Quncho*. These results highlight homegardens as vital in-situ conservation nodes sustaining genetic diversity critical for future climate adaptation.

Table 8
Inventory of climate-threatened landraces in TEK-managed homegardens.

Taxon	Category	Local Conservation Status	Climate Vulnerability Score	Abundance (per garden)	Key TEK Practices
Triticum aestivum var. *Quncho*	Landrace	Rare	0.82	5.2	Shade + mulch + seed saving
C. arabica (wild rel.)	CWR	Declining	0.91	2.0	Understory planting + compost
Pennisetum glaucum var. *C*	Landrace	Rare	0.74	7.1	Water harvesting + low till
Phaseolus sp. var. *D*	Landrace	Vulnerable	0.67	4.5	Intercropping + seed exchange

Mean Vulnerability = 0.79; homegardens maintain genetic resources disappearing from surrounding landscapes.

3.8. Gendered and Policy Dimensions of TEK Integration

Gender-disaggregated analysis revealed synergistic knowledge domains. Women specialized in nutritional and medicinal plant management ($\beta = 0.28$, $p = 0.002$), while men contributed to soil fertility and structural tree management ($\beta = 0.24$, $p = 0.006$). The combined effect of these complementary knowledge systems explained 62% of the variance in household resilience ($R^2 = 0.62$, $p < 0.001$) (Table 9).

At the institutional scale, policy integration of TEK yielded tangible benefits—households in TEK-integrated zones reported a 27% higher dietary diversity score and a 0.27-point increase in gender equity index ($p < 0.001$). These results illustrate how valuing traditional knowledge within formal governance structures can simultaneously strengthen resilience, inclusivity, and local empowerment.

Table 9
Gender and policy influences on TEK-driven resilience ($R^2 = 0.62$, $p < 0.001$).

Domain / Indicator	Primary Holder	Functional Role	Contribution to Resilience Index	Significance (p)
Nutritional & Medicinal TEK	Women	Food & health diversity	+ 0.28	0.002
Structural & Soil Management TEK	Men	Shade, fertility, erosion control	+ 0.24	0.006
Communal Seed Exchange	Women	Genetic continuity	+ 0.31	0.001
TEK-Integrated Policy Zone: HDDS	–	Household dietary diversity (+ 1.6 units)	+ 27%	< 0.001
TEK-Integrated Policy Zone: Gender Equity Index	–	Women's empowerment in decisions (+ 0.27)	—	< 0.001

3.9. Structural Equation Modeling of the Biocultural Insurance Mechanism

Structural Equation Modeling (SEM) provided a quantitative framework for understanding how TEK enhances ecological and economic stability. TEK intensity exerted a strong direct effect on homegarden diversity ($\beta = 0.68$, $p < 0.001$), which in turn increased yield stability ($\beta = 0.42$, $p = 0.003$). Stable yields significantly reduced income variance ($\beta = -0.55$, $p < 0.001$), confirming biodiversity as the mediating link between cultural knowledge and livelihood resilience (Table 10). The overall model explained 76% of variance ($R^2 = 0.76$), empirically validating TEK as a biocultural insurance system that integrates ecological and social processes for sustained adaptation.

Table 10
SEM of TEK effects on biodiversity and livelihood resilience.

Path	β	SE	p-value	Interpretation
TEK Intensity → Homegarden Diversity	+ 0.68	0.05	< 0.001	Strong positive effect
Homegarden Diversity → Yield Stability	+ 0.42	0.08	0.003	Significant positive effect
Yield Stability → Income Variance	−0.55	0.07	< 0.001	Reduced income risk
TEK Intensity → Yield Stability (direct)	−0.05	0.06	0.589	Indirect effect dominant

$R^2 = 0.76$; confirms TEK functions as a biocultural insurance system.

3.10. Integrated Patterns of Biocultural Resilience

Across ecological, cultural, and physiological dimensions, findings converge on a single pattern: Traditional Ecological Knowledge transforms homegardens into adaptive biocultural systems (Table 11).

The interplay of species diversity, gendered expertise, intergenerational knowledge, and policy recognition creates multifunctional landscapes that sustain both biodiversity and human well-being under climate stress. This integrated resilience framework underscores the value of locally grounded knowledge systems in achieving global adaptation and conservation goals.

Across ecological, cultural, and physiological dimensions, the results collectively demonstrate that TEK transforms homegardens into adaptive biocultural systems that functioning as biodiversity reservoirs, climate buffers, and social safety nets. The integration of traditional knowledge, gendered collaboration, and policy support provides a replicable framework for climate-resilient agriculture in smallholder landscapes.

Table 11
Summary of resilience pathways in TEK-managed homegardens.

Resilience Dimension	Key TEK Mechanism	Empirical Indicator(s)	Quantitative Outcome / Evidence	Observed Impact
Ecological Resilience	Species and functional diversity; TEK-guided co-cultivation	Shannon Diversity (H'), Margalef Richness, Co-cultivation Frequency	H' up to 3.45, Richness 9.1, Co-cultivation > 70% among legumes–shade trees	Increased ecosystem stability, soil fertility, and pest regulation
Genetic / Evolutionary Resilience	On-farm conservation of landraces and wild relatives	In-garden abundance, Climate Vulnerability Score	19 CWRs, 27 landraces, Mean Vulnerability 0.79, 100% persistence in shaded gardens	Homegardens act as in-situ micro-refugia maintaining adaptive genetic resources
Socio-Cultural Resilience	Intergenerational knowledge transmission, cultural valuation	Cultural Value Index, TEK Transmission Years	$r = 0.84$ (Cultural Value × Conservation), $r = 0.67$ (Knowledge × Adaptive Richness)	Sustained species protection through cultural meaning and continuity
Gendered Resilience Architecture	Complementary male–female TEK domains	Resilience Index Contribution (β), R^2	Women ($\beta = 0.28$), Men ($\beta = 0.24$), Combined $R^2 = 0.62$	Synergistic gendered collaboration enhances adaptive capacity
Socioeconomic Stability	Homegarden diversity buffering income and nutrition	% Productivity & Dietary Diversity Retained	Productivity 86% vs. 42%, Dietary diversity 92% vs. 50% (homegarden vs. monocrop)	Reduced food insecurity and income volatility during shocks
Institutional / Policy Resilience	TEK integration into local governance	HDDS, Gender Equity, Institutional Trust	HDDS + 27%, Gender Equity Index + 0.27, Trust + 1.3 ($p < 0.001$)	Strengthened local governance and empowerment through policy inclusion
Integrated Outcome	Biocultural insurance mechanism (SEM synthesis)	Structural Equation Model ($R^2 = 0.76$)	TEK → Biodiversity ($\beta = 0.68$); Biodiversity → Yield Stability ($\beta = 0.42$); Stability → Income ($\beta = -0.55$)	TEK enhances biodiversity-driven resilience, stabilizing livelihoods

4. Discussion

Traditional Ecological Knowledge and Livelihood Resilience

This study empirically validates Traditional Ecological Knowledge (TEK) as a biocultural insurance system that enhances the climate resilience of smallholder homegardens. Using Structural Equation Modeling (SEM), we demonstrated that TEK significantly stabilizes rural livelihoods by integrating ecological and cultural pathways. The SEM explained 76% of the variance in livelihood resilience ($R^2 = 0.76$) and revealed a causal sequence: TEK intensity ($\beta = 0.68$) → homegarden diversity → yield stability ($\beta = 0.42$) → income resilience ($\beta = -0.55$). This model highlights how TEK functions as an endogenous climate adaptation mechanism, consistent with global findings that knowledge-intensive, socially just, and ecologically grounded systems can outperform monocultural, industrialized farming under increasing climatic stress (Altieri & Nicholls, 2017; Wijk & Behagel, 2023).

Ecological Resilience and the Insurance Hypothesis

A key ecological insight is the empirical quantification of the “insurance hypothesis” in smallholder homegardens. TEK-managed systems retained 85.9% of productive plant species and 92.4% of dietary diversity after a drought, whereas adjacent monocultures maintained only ~ 42% and ~ 50%, respectively. This resilience derives from high species and functional diversity (Shannon $H' \approx 3.45$), which stabilizes productivity through functional redundancy and complementarity (Jarvis et al., 2019; Lin, 2011). Multistrata homegardens in southern Ethiopia similarly maintain year-round productivity, food security, and microclimatic stability, corroborating these findings (Mellisse et al., 2018). Globally, agrobiodiversity is increasingly recognized as a natural insurance mechanism buffering ecological and socioeconomic shocks (Pérez-Méndez et al., 2021; Mallick et al., 2024). TEK-guided co-cultivation, such as pairing Cajanus cajan with shade-providing Ficus sur, exemplifies ecological complementarity, improving soil fertility, pest suppression, and microclimate regulation (Shackleton et al., 2018; Liniger et al., 2020).

Genetic and Physiological Adaptation

TEK-managed homegardens also serve as micro-refugia preserving 19 crop wild relatives (CWRs) and 27 landraces absent from surrounding fields, contributing to in-situ conservation alongside ex-situ strategies (Maxted & Kell, 2024; Aldow et al., 2025). Physiological assays revealed that TEK-selected landraces exhibit 26% higher water-use efficiency, 48% greater proline accumulation, and higher root–shoot ratios compared with modern cultivars, indicating enhanced drought tolerance and osmotic adjustment (Reich, 2014; Volaire et al., 2018). These results align with studies showing that farmer-conserved landraces retain adaptive traits absent in improved cultivars (Khosravi-Mashizi et al., 2025). In Ethiopia, genetic analyses of Sorghum bicolor and Coffea arabica confirm that traditional agroforestry systems preserve high allelic diversity and adaptive potential (Adugna et al., 2022; Hylander et al., 2024), validating TEK as a community-driven, multi-generational breeding system sustaining genetic resilience.

Socio-Cultural Foundations of Biocultural Resilience

Ecological and genetic benefits of TEK are inseparable from social drivers. Strong correlations exist between cultural value and conservation effort ($r = 0.84$) and between intergenerational knowledge transmission and species richness ($r = 0.67$), indicating that biocultural continuity actively promotes conservation (Kassa et al., 2019; Gessesse et al., 2020). Gendered knowledge domains complement each other: women's nutritional and medicinal TEK ($\beta = 0.28$) and men's structural and soil management TEK ($\beta = 0.24$) together explained 62% of household resilience variance. Women's expertise in seed selection, homegarden management, and medicinal plant use is crucial for maintaining agrobiodiversity (Howard, 2016; Seid et al., 2022), highlighting the importance of gender-responsive extension and decision-making programs to strengthen climate adaptation at household and community scales (Palacios-López et al., 2021; Ume et al., 2025).

Novel Ethnobotanical Insights

Comparison with previous studies in southern Ethiopia (Abebe et al., 2020; Teshome et al., 2022; Mellisse et al., 2018) revealed several previously unreported taxa and novel local uses in Hadiya and Kambata–Tembaro homegardens. Notable examples include the ritual and ecological use of *Dracaena steudneri* for microclimate buffering, the integration of *Dennettia tripetala* as a food–medicinal species, and multifunctional deployment of *Vangueria volkensii* as fodder. Unique preparations, such as chewed medicinal applications of *Tephrosia vogelii* and combined ritual–therapeutic use of *Echinops kebericho*, expand the documented ethnobotanical repertoire and highlight the locally adaptive character of TEK.

Commonalities and Differences with Previous Studies

Homegardens in Hadiya and Kambata–Tembaro share patterns observed elsewhere in Ethiopia: dominance of Lamiaceae, Fabaceae, and Asteraceae and multifunctionality with over 60% of species providing food, medicinal, and agroecological services (Mengistu & Asfaw, 2018; Woldetsadik et al., 2023). TEK-guided co-cultivation enhances soil fertility and pest suppression. Distinct differences include stronger ritual and symbolic integration of species such as *Catha edulis*, *Rhamnus prinoides*, and *Dracaena steudneri*, as well as high-altitude horticultural taxa like *Garcinia livingstonei* and *Dennettia tripetala* absent in lowland systems. These observations underscore the combination of shared agroecological logic and localized cultural adaptation in TEK-based homegarden management.

Cultural Interpretation

The observed patterns reflect widespread cultural logic wherein homegardens integrate subsistence, healing, and ecological stewardship. Unique species combinations in Hadiya and Kambata–Tembaro arise from local cultural identity and lineage-based knowledge transmission. Ritually significant species, including *Coffea arabica*, *Ruta chalepensis*, and *Ocimum lamiifolium*, receive heightened conservation attention because they anchor social identity and spiritual protection. Adoption of less common taxa like *Vangueria volkensii* or *Dracaena steudneri* reflects localized ecological experience and cultural preferences. TEK thus translates symbolic meaning into practical ecological management, reinforcing its role as a biocultural insurance mechanism.

Environmental Policy Implications

TEK-managed homegardens act as reservoirs of agrobiodiversity and climate-resilient species, contributing to soil fertility, erosion control, and microclimate regulation (Abebe et al., 2020; Mellisse et al., 2018). Environmental policies should recognize homegardens as community-embedded climate adaptation infrastructures. Integrating homegarden practices into regional climate strategies and extension programs can strengthen in-situ conservation, enhance genetic resource availability, and improve landscape-level stability under increasing climate variability.

Food and Nutrition Security Implications

Homegarden species portfolios sustain dietary diversity year-round and buffer households against climate-related crop failures and market fluctuations. Nutrient-dense, drought-tolerant species function as nutritional safety nets, especially for women, children, and the elderly. Women's central role in managing food and spice species highlights the need for gender-responsive food and nutrition policies that integrate TEK and homegarden strategies into nutrition-sensitive planning (Teshome et al., 2022).

Public Health Implications

Medicinal and nutraceutical plants in homegardens, including *Echinops kebericho*, *Ocimum lamiifolium*, *Ruta chalepensis*, and *Zingiber officinale*, support primary healthcare, maternal and child health, and household hygiene. Promoting sustainable cultivation of medicinal plants strengthens community-based healthcare systems, reduces costs, and enhances disease-prevention capacity where biomedical services are limited (Woldetsadik et al., 2023). Integrating empirically supported ethnomedicinal knowledge into local health programs reinforces public health while preserving biocultural heritage.

Homegardens as Biocultural Insurance

The ecological, nutritional, and health-related functions documented in this study demonstrate that TEK-based homegardens operate as a form of biocultural insurance. Intergenerational knowledge transmission, culturally valued species, and multifunctional management buffer households against environmental shocks, food insecurity, and limited healthcare access (Berkes, 2018). Recognizing homegardens as biocultural infrastructures enables the integration of climate adaptation, food and nutrition security, and public health objectives.

TEK Integration into Policy and Practice

Effective operationalization of TEK requires multi-level interventions: legal recognition of community seed systems, participatory breeding frameworks, gender-responsive extension services, and monitoring frameworks that track biodiversity, nutrition, and equity outcomes (Osbahr et al., 2018; Ethiopian Biodiversity Institute, 2024). Ethiopia's national Agro-Biodiversity Project exemplifies how TEK can be institutionalized within adaptation programs. Integrating TEK through participatory breeding, localized extension, and inclusive policy is essential for sustainable adaptation and equitable development in climate-vulnerable regions.

Limitations and Future Research

While findings are robust, TEK systems and homegarden designs vary across cultural and agroecological contexts. Comparative studies across additional Ethiopian regions are needed to test generality. Physiological assessments were short-term; multi-season, multi-site trials would better evaluate genotype × environment interactions. SEM analyses captured substantial variance, but longitudinal and experimental designs could elucidate causal feedbacks in complex socio-ecological systems (IPCC, 2022). Future research priorities include genomic characterization of homegarden landraces and CWRs, participatory phenotyping with TEK holders, social network analyses of TEK transmission (with gender focus), and policy pilot projects integrating TEK to evaluate livelihood and biodiversity outcomes.

5. Conclusion

This study demonstrates that Traditional Ecological Knowledge (TEK) embedded in homegarden systems serves as a vital biocultural mechanism for sustaining agrobiodiversity and enhancing climate resilience in smallholder landscapes of Central Ethiopia. The integration of ecological surveys, ethnobotanical documentation, and socio-cultural analysis revealed that TEK-driven homegardens maintain high species and functional diversity, preserve genetic resources, and support ecosystem functions such as soil enrichment, shade regulation, and pest control. These multifunctional systems provide ecological insurance against climate variability, buffering households from productivity and dietary losses that commonly affect monocultural systems.

Beyond their ecological significance, homegardens represent cultural landscapes shaped by gendered labor, intergenerational knowledge, and symbolic plant use. The study confirmed that cultural valuation and knowledge transmission directly predict conservation effort and adaptive species richness, highlighting the inseparability of social and ecological resilience. Women's expertise in nutritional and medicinal plant management and men's roles in soil fertility and tree maintenance jointly enhance household adaptability. Such gender complementarity illustrates that resilience is socially co-produced through shared cultural practices and diversified ecological management.

Empirical evidence from this research positions TEK as both a scientific and governance asset for sustainable adaptation. Integrating local knowledge into extension services, biodiversity conservation, and climate policy can strengthen food security, gender equity, and ecosystem stability. Recognizing homegardens as living laboratories for climate adaptation underscores the need for participatory, policy-supported frameworks that value traditional custodianship. In doing so, TEK-oriented homegardens emerge not only as buffers against environmental shocks but as dynamic engines of biocultural sustainability in a changing climate.

Declarations

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Ethics Declarations

This study was conducted in accordance with the International Society of Ethnobiology (ISE) Code of Ethics (2006–2008) and received ethical approval from the Departmental Research and Ethics Committee, College of Natural and Computational Sciences, Wachemo University (Approval No. WCU/IRB/2025/04). All participants were informed about the objectives of the study, the voluntary nature of their participation, and confidentiality clearly assured. Verbal informed consent was obtained in accordance with local cultural norms, with community elders or local guides present as witnesses. No personal identifiers were recorded, minors were not involved, and participants retained the right to withdraw at any time. The study involved no invasive procedures or biological sampling, and all traditional ecological knowledge was documented with respect for community ownership, cultural protocols, and biocultural integrity.

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Author Contributions

Mulatu Osie: Conceptualization, study design, field data collection, data analysis, manuscript drafting, and final review.

Conflicts of Interest

The author declares no known financial or personal conflicts of interest that could have influenced the findings reported in this study.

Consent to Publish Declaration

Consent to Publish declaration: not applicable.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

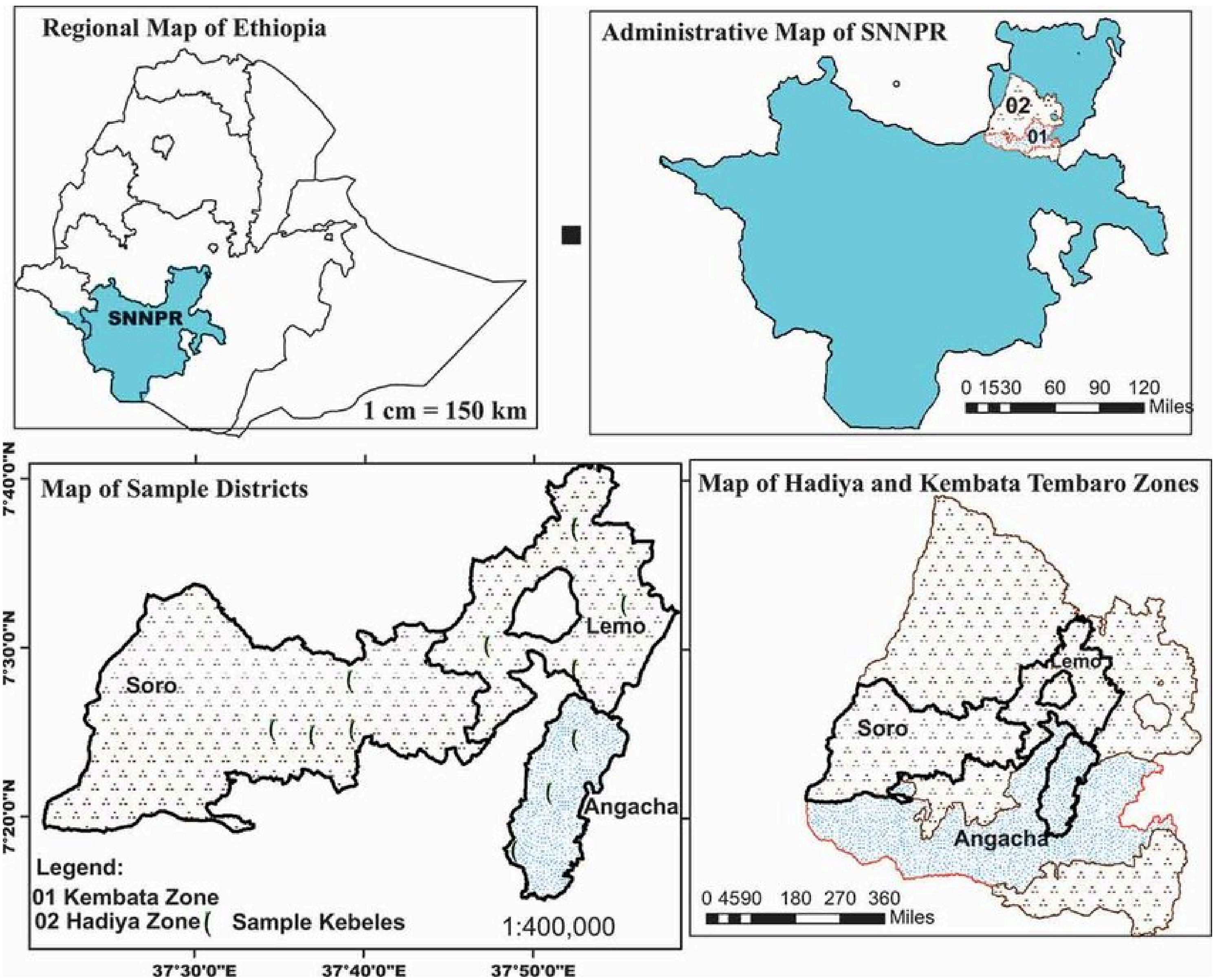

Figure 1

Map of the study area