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COMPARATIVE ANALYSIS OF WOODY PLANT SPECIES CARBON STOCK OF BUSKA DRY EVERGREEN AFROMONTANE FOREST AND ADJACENT GRASSLAND, SOUTHWESTERN ETHIOPIA

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ABSTRACT: Forest ecosystems significantly contribute to climate change mitigation; however, their estimated carbon stock variations across vegetation types are limited to prioritize vegetation conservation. This study explores the carbon stock in Buska natural forest and its variation among three vegetation types: Dry evergreen Afromontane forest and grassland complex (DAF), *Combretum-Terminalia* woodland and wooded grassland (CTW), and *Acacia-Commiphora* woodland and bushland (ACB). The data was collected from 92 plots placed at 50m altitudinal difference across eight transect lines laid at 2 km apart to each other. Accordingly, 30 plots for each DAF and CTW and 32 plots for ACB were used to collect vegetation data and biometric measurements. 113 woody species were recorded from all vegetation types and 1571.8 ton ha^{-1} carbon stock was estimated. Higher carbon stock was recorded for DAF (632.97 ton ha^{-1}) followed by CTW (554.05 ton ha^{-1}) and ACB (384.78 ton ha^{-1}). *Juniperus procera*, *Combretum molle* and *Tamarindus indica* were the first top woody species that contributed higher carbon stocks for DAF, CTW and ACB vegetation types respectively. The carbon stock variation within vegetation types was significant at $P < 0.03$. The carbon stock in DAF is significantly higher compared to ACB ($P = 0.02$). While the carbon stock variations between CTW and the remaining two vegetation types were not significant ($P < 0.05$). The Buska natural forest's carbon stock variation is influenced by species composition and basal areas. Though all three vegetation types contribute significantly, DAF vegetation type should be prioritized for conservation to mitigate climate change.

Keywords: *Acacia-Commiphora*; Buska; Carbon stock; *Combretum-Terminalia*; Dry evergreen

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INTRODUCTION

Global warming is a major threat to all biological resources (fauna, flora, microorganisms) in all levels of genetic, species and ecosystem diversity. Its consequent addresses all corners of the globe (IPCC, 2014: Climate Change, 2014). A macro and microclimate regulation are one of the major regulatory services of forest ecosystems through sequestering atmospheric carbon in above and below-ground biomass (Pradhan et al., 2019).˙ Forest ecosystems could take a large amount of carbon and are playing a crucial role in climate change mitigation (Zhu et al., 2010). Particularly, tropical forests are considered the largest above-ground carbon store and harbor 68% of the global forest carbon. Thus, protecting the forest ecosystems is one of the climate change mitigation strategies that can help to reduce the atmospheric carbon dioxide concentration as well as emission reduction from deforestation and forest degradation (Pan et al., 2011).

The carbon stock is largely affected by biotic and abiotic factors (Chave et al., 2014). Biotic factors such as species richness, composition, diversity, anthropogenic disturbance, invasive and expansive species (Haile et al., 2021); abiotic factors such as environmental gradients (*i.e.* altitude, slope, aspect), geographical features, soil, temperature, moisture, etc. are significantly affecting the carbon sequestration potential of certain forest (Mewded and Lemessa, 2020).

Although forest ecosystems are vital for climate regulation, the current challenges in Ethiopia particularly the fast-population growth and consequent demand and poverty, it remains impossible to address the county's forest ecosystem conservation. As a result, prioritizing the conservation of multi-functional forest ecosystems is a key strategy. The variation of woody carbon stock between disturbed and undisturbed sites, protected and unprotected areas, agroforestry and woodlots are explored (De Beenhouwer et al., 2016; Gebre et al., 2019; Toru and Kibret, 2019; Ibrahim et al., 2021; Kefalew et al., 2021). However, studies on woody carbon stock variation within the vegetation and ecosystem types are limited. Although

Ethiopia has about 12 vegetation types, including desert and semi-desert scrubland, *Acacia-Commiphora* woodland and bushland, wooded grassland of the western Gambella region, *Combretum-Terminalia* woodland and wooded grassland, dry evergreen Afromontane forest and grassland complex, moist evergreen Afromontane forest, transitional rainforest, Ericaceous belt, Afroalpine belt, riverine vegetation, fresh-water lakes, lake shores, marsh and floodplain vegetation and salt-water lakes, salt-lake shores, marsh and pan vegetation (Ib et al., 2010). However, there is a lack of studies examining the relationships between these vegetation types and carbon storage or sequestration potential. Identifying which vegetation contributes most significantly to carbon stock is crucial for prioritizing conservation efforts aimed at climate change mitigation.

Therefore, this study aims to analyze the variation in carbon stock within the Buska natural forest. Specifically, it compares carbon stocks across three vegetation types within the forest: the dry evergreen Afromontane forest and grassland complex (DAF), the *Combretum-Terminalia* woodland and wooded grassland (CTW), and the *Acacia-Commiphora* woodland and bushland (ACB). Additionally, the study investigates the factors that affect the carbon stock of Buska natural forest.

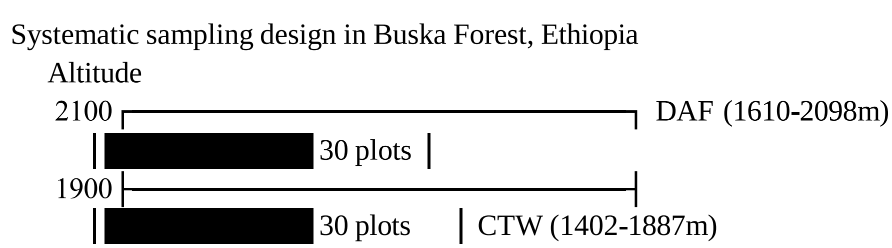
MATERIALS AND METHODS

Study area

The study was conducted in Buska natural forest located in Hamer District, South Omo Zone, Southern Nations, Nationalities, and Peoples' Region, Ethiopia. Buska natural forest mainly contains three types of vegetation adjacently. These are dry evergreen Afromontane forest and grassland complex (DAF), *Combretum-Terminalia* woodland and wooded grassland (CTW) and *Acacia-Commiphora* woodland and bushland (ACB) vegetation. The characteristics of key species, along with other environmental and geographical factors, were used to identify these vegetation types.

Sampling Design

A systematic stratified sampling approach was implemented to capture vegetation variation across the dominant altitudinal gradient (845–2098 m.a.s.l.), a key determinant of biomass and species distribution (Körner, 2007). Eight parallel transects were established at 2 km intervals spanning this elevation range. Along each transect, 20 × 20 m sample plots were systematically positioned at 50 m altitudinal intervals. This design resulted in a total of 92 plots, encompassing a sampled area of 3.68 hectares. The plots were distributed across three principal vegetation types identified in the Buska Natural Forest: Dry Evergreen Afromontane Forest (DAF), Combretum-Terminalia Woodland (CTW), and Acacia-Commiphora Bushland (ACB). This stratification ensured representative sampling of the forest's ecological continuum, with 30 plots sampled in both DAF and CTW types, and 32 plots in ACB. The systematic, elevation-based framework provided a robust spatial structure for comparative analysis of forest structure and carbon stocks across distinct ecological zones (Fig. 1).



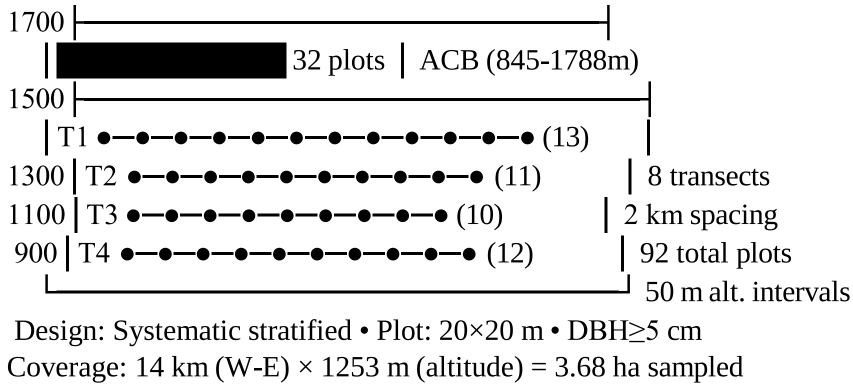


Figure 1. Systematic stratified sampling design employed in Buska Natural Forest

Data collection

Woody species data

All individuals of woody species (trees, shrubs and lianas) with diameter at breast height (DBH), diameter at stump height (DSH) ≥ 5 cm were measured and their growth habits were recorded as suggested (Awoke and Mewded, 2019; Mac Dicken, 1997) for carbon stock estimation method. DBH was measured at 1.3 m height and DSH at 0.3 m. Trees and shrubs with multiple stems were measured separately and converted later by square rooting the sum of all squared stem DBH. DBH, DSH, and height were measured using diameter tape and hypsometer (Forestry Pro), respectively. The geographical location and altitude of sample plots were recorded using GPS (Garmin 72). The plant specimens were collected, labeled, pressed, dried, and identified at Ethiopian Biodiversity Institute (EBI) and National Herbarium (ETH), Addis Ababa, Ethiopia.

Above-ground carbon stock estimation

Above-ground biomass was estimated from a diameter of woody species (Pearson et al., 2013) tropical county forests field carbon stock measurement guideline. Above-ground biomass was converted to carbon stock by multiplying by 0.5 which is the default carbon fraction (IPCC, 2006).

$$AGB = 34.4703 - 8.0671(DBH) + 0.6589\,(DBH^2)$$

$$AGC = AGB \times 0.5$$

Where AGB is the above-ground biomass (kg), DBH is the diameter of individuals (cm) and AGC is the above-ground carbon.

Below-ground carbon stock estimation

In addition to above-ground biomass, roots play an important role in the carbon sequestration and cycle (Darcha and Birhane, 2015). However, below-ground biomass estimation is difficult and time-consuming. Hence, different scholars (Houghton et al., 2001; Achard et al.,2002; Ramankutty, et al.,2007; Gibbs et al.,2007; Sharma and Chaudhry, 2015), are agreed on the root biomass is typically estimated to be 20% of the above-ground forest biomass. Accordingly, the amount of below-ground carbon was estimated as

$$BGC = BGB \times 0.5$$

Where BGC is below-ground carbon, BGB is below ground biomass and 0.5 is the conversion factor

Data analysis

The mean and total carbon stock of woody species was calculated using Microsoft Excel for the Buska natural forest and respective vegetation types. The carbon stock variation among vegetation types was statically tested using a one-way analysis of variance (ANOVA) with the R statistical program (version: 3.4. 6). The effects of altitude, species richness, abundance and basal area of species on woody carbon stock were determined by regression coefficient.

RESULTS

Overall, in Buska dry evergreen forest and adjacent vegetation types, 113 woody species belonging to 74 genera and 39 families were recorded. The Fabaceae family has the most species with 22, followed by the Euphorbiaceae and Rubiaceae families with 7 species each (Appendix 1). Five endemic species to Ethiopia were recorded (*i.e. Erythrina brucei*, *Maytenus arbutifolia*, *Millettia ferruginea*, *Vepris dainellii* and *Vernonia rueppellii*). *Prosopis juliflora* which is a highly invasive alien species was also recorded in two plots of *Acacia-Commiphora* woodland and bushland (ACB) vegetation type. In terms of growth habit, 58 species (51%) were trees, 48 species were shrubs and seven species were woody climbers. From these woody species, 5903.77 ton carbon stock was estimated in the studied sample which is 1571.78 ton ha^{-1} (average 17.08 ton ha^{-1}). *Combretum molle*, *Juniperus procera*, *Ficus vasta* and *Podocarpus falcatus* were the top four woody species that contributed higher carbon stock in the study area. Their carbon stocks were estimated to 149.93, 137.08, 108.21 and 107.07 ton ha^{-1}, respectively (Table 1). These woody species contributed 31% of above-ground and below-ground carbon stock in the studied forest.

Table 1. Overall top woody species contribute greater than 1% of total carbon stock

Species	AGC	BGC	TC	Percentage	Main habitat
Combretum molle	124.94	24.99	149.93	9.54	CTW
Juniperus procera	114.23	22.85	137.08	8.72	DAF
Ficus vasta	90.17	18.03	108.21	6.88	DAF
Podocarpus falcatus	89.22	17.84	107.07	6.81	DAF
Terminalia brownii	78.33	15.67	94.00	5.98	CTW
Olea europaea	59.54	11.91	71.44	4.55	DAF
Croton macrostachyus	51.17	10.23	61.41	3.91	DAF
Euclea racemosa	47.20	9.44	56.64	3.60	DAF
Tamarindus indica	40.35	8.07	48.42	3.08	CTW + ACB
Syzygium guineense	37.40	7.48	44.89	2.86	ACB
Acacia goetzei	33.45	6.69	40.14	2.55	ACB
Vitex doniana	26.82	5.36	32.18	2.05	DAF
Lannea fruticosa	25.55	5.11	30.66	1.95	ACB
Entada abyssinica	22.37	4.47	26.84	1.71	CTW
Ozoroa insignis	20.08	4.02	24.09	1.53	CTW

Adenium obesum	16.95	3.39	20.34	1.29	ACB
Acacia tortilis	16.85	3.37	20.23	1.29	ACB
Bridelia micrantha	16.51	3.30	19.81	1.26	DAF
Balanites rotundifolia	15.12	3.02	18.14	1.15	CTW
Acacia seyal	14.99	3.00	17.98	1.14	ACB
Cordia sinensis	13.77	2.75	16.53	1.05	CTW
Acacia hockii	13.30	2.66	15.96	1.02	ACB

Note: AGC = above ground carbon, BGC = below ground carbon, TC = total carbon (AGC + BGC)

Dry evergreen Afromontane forest

In Buska Dry evergreen Afromontane forest (DAF) vegetation type, 80 woody species (DBH/DSH ≥ 5cm) were identified in the elevation range of 1610 to 2098 m.a.s.l and 632.97 ton ha^{-1} carbon stock was estimated. *Juniperus procera*, *Podocarpus falcatus* and *Olea europaea*, were woody species that had the highest carbon stock (137.08, 107.07 and 68.18 ton ha^{-1}, respectively)(Table 2**)**.

Table 2. Top woody species in DAF vegetation with higher carbon stock (> 10 ton ha^{-1})

Species	AGC	BGC	TC
Juniperus procera	114.23	22.85	137.08
Podocarpus falcatus	89.22	17.84	107.07
Olea europaea	56.81	11.36	68.18
Ficus vasta	56.05	11.21	67.25
Croton macrostachyus	23.32	4.66	27.98
Euclea racemosa	21.62	4.32	25.94
Prunus africana	12.04	2.41	14.45
Maytenus senegalensis	11.34	2.27	13.61
Vitex doniana	10.72	2.14	12.87
Bridelia micrantha	10.10	2.02	12.12
Syzygium guineense	8.80	1.76	10.56

Note: AGC = above ground carbon, BGC = below ground carbon, TC = total carbon (AGC + BGC)

Combretum-Terminalia **woodland and wooded grassland**

Totally in this vegetation type 554.05 ton ha^{-1} of carbon stock was estimated from 71 woody species. The vegetation was identified in the elevation range of 1402 to 1887 m.a.s.l. Higher carbon stock was recorded for *Combretum molle* followed by *Terminalia brownii* (137.80 and 83.82, respectively). *Combretum molle* and *Terminalia brownii* are the main characteristics species in *Combretum-Terminalia* woodland and wooded grassland (CTW) vegetation and contributed 40% of carbon stock. 78% of carbon stock is produced from only 14 woody species (Table 3**)**.

Table 3.Woody species with higher carbon stock (> 10 ton ha^{-1}) in the CTW vegetation

Species	AGC	BGC	TC
Combretum molle	114.84	22.97	137.80
Terminalia brownie	69.85	13.97	83.82
Ficus vasta	27.14	5.43	32.57
Acacia goetzei	21.50	4.30	25.80
Tamarindus indica	20.70	4.14	24.84
Ozoroa insignis	18.06	3.61	21.67
Croton macrostachyus	13.67	2.73	16.40
Entada abyssinica	11.71	2.34	14.05
Combretum collinum	11.63	2.33	13.95
Euclea racemose	11.07	2.21	13.29
Balanites rotundifolia	10.83	2.17	13.00
Syzygium guineense	10.61	2.12	12.74
Vitex doniana	9.57	1.91	11.49
Lannea fruticosa	8.82	1.76	10.58

Note: AGC = above ground carbon, BGC = below ground carbon, TC = total carbon (AGC + BGC)

Acacia-Commiphora woodland and bushland

In this vegetation, 90 woody species were identified from 845 to 1788 m.a.s.l elevation range and 384.78 ton ha^{-1} carbon was estimated. Higher carbon stock was recorded for *Tamarindus indica, Syzygium guineense* and *Acacia seyal*, 22.17, 21.6 and 17.98 ton ha^{-1} respectively (Table 4**)**.

Table 4. Woody species with higher carbon stock (> 10 ton ha^{-1}) in the ACB vegetation

Species	AGC	BGC	TC
Tamarindus indica	18.48	3.70	22.17
Syzygium guineense	17.99	3.59	21.60
Acacia seyal	14.99	3.00	17.98
Euclea racemosa	14.50	2.90	17.41
Croton macrostachyus	14.18	2.84	17.02
Acacia tortilis	13.33	2.67	15.99
Acacia mellifera	12.57	2.51	15.09
Lannea fruticosa	12.39	2.48	14.87
Adenium obesum	12.07	2.41	14.48
Albizia anthelmintica	10.76	2.15	12.91
Stereospermum kunthianum	9.93	1.99	11.91
Acacia hockii	9.31	1.86	11.17
Acacia goetzei	8.41	1.68	10.10

Note: AGC = above ground carbon, BGC = below ground carbon, TC = total carbon (AGC + BGC)

Carbon stock variation across vegetation types

The mean total carbon stock in DAF, CTW and ACB vegetation types were 21.1 ± 15.5, 18.74 ± 15.8 and 12.02 ± 5.7 ton ha^{-1} respectively. The maximum woody carbon stock of DAF was 59.85 ton ha^{-1}, CTW 57.25 ton ha^{-1} and ACB 24.76 ton ha^{-1}. The minimum woody carbon stock estimated for DAF was 1.88, CTW 2.07 and ACB 3.96 ton ha^{-1}. The carbon stock variations of these vegetation types were significantly different at *P* < 0.03. The carbon stocks of DAF and ACB significantly varied (*P* = 0.02) whereas the carbon stock variations of CTW with DAF and ACB were not significant (*P* ≤ 0.05 (Fig. 2)).

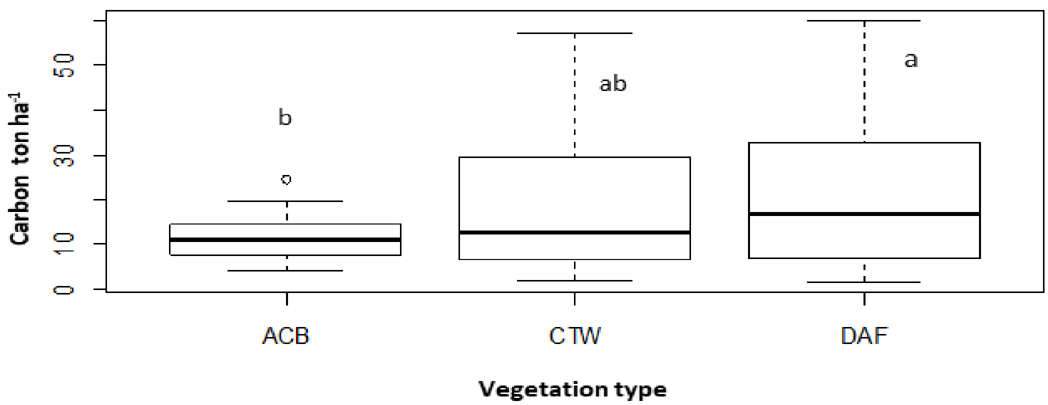


Figure 2. Carbon stock (AGC + BGC) variation across different vegetation types. Box plots with a different letter show significant carbon stock variation of vegetation types (P<0.05).

Effects of altitude, species richness, abundance and basal area on carbon stock

In Buska Dry evergreen Afromontane forest and adjacent vegetations, the estimated carbon stock of woody species was not significantly correlated with altitude, species richness and abundance. However, the carbon stock was specific to the species and basal area of individuals (R^2 = 0.87)(Fig.3).

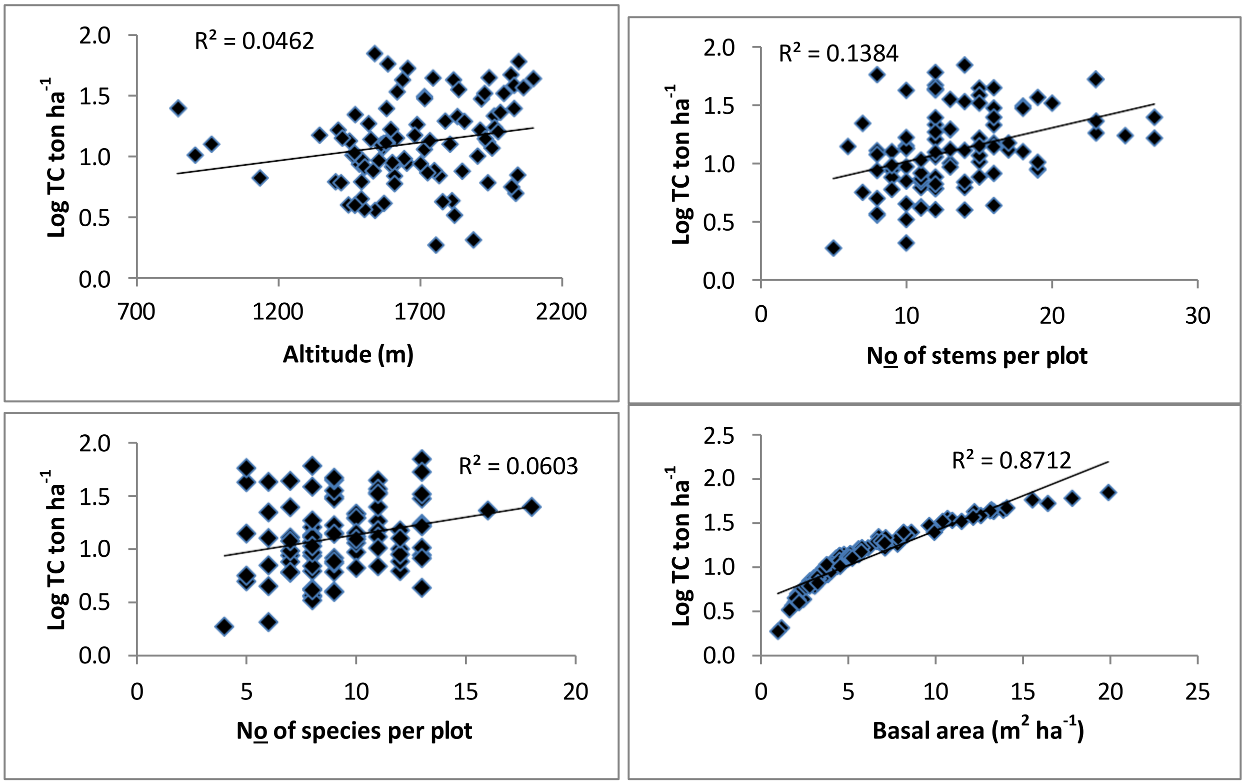


Figure 3. Correlation between carbon stock and altitude, species richness, abundance and basal area in the study area (TC = total carbon or AGC + BGC)

DISCUSSION

In the study area, Buska natural forest, higher woody species (≥ 5cm DBH/DSH) richness was recorded (113 species). Its wide-ranging altitude (845– 2098 m), comprising three vegetation types, diverse topography, lower disturbance and suitable environments (*i.e.* rainfall, temperature and moisture) could be reasons for the high species richness (Homeier et al., 2010 and Song et al., 2021). Altitudinal gradients are major factor for changing environmental conditions and subsequent species richness and turnovers. The mid altitude is known with higher species richness and diversity due to the environmental suitability for floral diversity (Acharya et al., 2011 and Xu et al., 2017). The study area covers from lower to typically mid altitudinal gradients with mountainous, plateau, plain, hilly, valley and riverine topography and bimodal rainfall pattern (mean annual precipitation 757 mm) and intermediate temperature (mean annual temperature 22.7°C). The higher species richness and different vegetation types in Buska natural forest highlight the potential of the forest for biodiversity conservation and provide multiple ecosystem services. The invasive alien species, *Prosopis juliflora* appearance in the study area indicated that the vegetation particularly in *Acacia-Commiphora* woodland and bushland (ACB) vegetation type needs urgent conservation priority. Hence the species is known for its fast growth, invasiveness, reproduction, and adaptive characteristics; it must be controlled before intensive expansion in ACB and other adjacent vegetation.

The estimated carbon stock of woody species in Buska natural forest (total 1571.8 ton ha^{-1} average 17.08 ton ha^{-1})), is higher than different natural forests in Ethiopia. For example, carbon stock estimated in Sirso moist evergreen Afromontane forest (Mewded and Lemessa, 2020), as well as that of temperate forest on Mt. Changbai, China and Miombo Woodland Landscape of Mozambique (Zhu et al., 2010 and Ryan et al., 2011). More than half of woody species recorded in Buska natural forest were trees in habit (58) and this might be the reason for the higher woody carbon stock estimated in the studied forest because tree-dominated forests are typical for higher carbon sequestration (Dimobe et al., 2019). The study indicated that Buska natural forest is one of the potential forests that contribute to climate change mitigation through sequestering atmospheric carbon. The top woody species that had higher carbon stock such as *Combretum molle*, *Juniperus procera*, *Ficus vasta* and *Podocarpus falcatus* are characterized by bigger in size and thereby contributing to higher carbon stock.

Our study revealed differences in carbon stock of three vegetation types of Buska natural forest. Carbon stock in studied vegetation types ranges from an average of 12.02 ton ha^{-1} in ACB to 21.1 ton ha^{-1} in Dry evergreen Afromontane forest and grassland complex (DAF). The estimated carbon stock in DAF vegetation is significantly higher than ACB (P = 0.02) but not *Combretum-Terminalia* woodland and wooded grassland (CTW) ($P \leq 0.05$). This result is attributed to the relative distribution of bigger size tree species among vegetation types. DAF vegetation is dominated by *Juniperus procera* and *Podocarpus* *falcatus* species, which are known for their bigger size individuals. However, the species richness in ACB is comparatively higher than in the other two vegetation types. This indicated the species richness is not a significant factor for the carbon stock variation between vegetation types rather carbon density is controlled by species composition. The insignificant correlation between carbon storage and species richness might be due to Buska natural forest/ecosystems may have reached climax species richness. Several studies reported that altitude, species richness and abundance are the major factors for the carbon stock variations within and/or among forests, vegetation types and land uses (Sintayehu et al., 2020; Salunkhe et al., 2018; Tetemke et al., 2021).

Contradictorily, in our study, these factors are not significant for the carbon stock variation between DAF, CTW and ACB vegetation types. However, the carbon stock is positively and highly correlates with basal areas of the individual species. The similar report was provided for higher carbon stock value independent to stand density and species richness of the forest rather than determined by the diameter of individuals of trees (Pradhan et al., 2019 and Zhu et al., 2010). The carbon stock dependent on the basal area of the species recorded in the study is that basal area is mainly dependent on the diameter of individuals (Gandhi and Sundarapandian, 2017). The insignificant relationship between species richness and woody carbon stock is revealed that the conservation of vegetation should be prioritized specific to the objectives of climate change mitigation as well as biodiversity conservation.

CONCLUSION

The findings from Buska Natural Forest offer critical, site-specific insights for Ethiopia's national forest monitoring and REDD+ implementation strategies. While confirming the forest's significant carbon storage potential overall, the study identifies key ecological drivers that must inform management priorities. The pronounced variation in carbon stocks among vegetation types—with Dry Evergreen Afromontane Forest (DAF) storing substantially more carbon than Combretum-Terminalia Woodland (CTW) or Acacia-Commiphora Bushland (ACB)—provides a actionable framework for prioritizing conservation and restoration interventions within national REDD+ action plans. Crucially, the finding that basal area, not altitude or species richness, is the primary determinant of carbon stock offers a vital operational metric for carbon stock modeling and monitoring at the project level. This enables more efficient, targeted forest inventories. To maximize climate mitigation benefits, national programs should prioritize the protection and sustainable management of high-carbon density vegetation types like DAF. This targeted approach aligns directly with REDD+ objectives by ensuring that conservation efforts deliver verifiable and additional carbon benefits, thereby strengthening Ethiopia's case for results-based climate finance.

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Appendix 1. Overall woody species carbon stock in Buska forest and adjacent vegetation types

Species	Family	AGC (ton ha^{-1})	BGC (ton ha^{-1})	TC	Percentage (%)
Combretum molle	Combretaceae	124.94	24.99	149.93	9.54
Juniperus procera	Cupressaceae	114.23	22.85	137.08	8.72
Ficus vasta	Moraceae	90.17	18.03	108.21	6.88
Podocarpus falcatus	Podocarpaceae	89.22	17.84	107.07	6.81
Terminalia brownie	Combretaceae	78.33	15.67	94.00	5.98
Olea europaea	Oleaceae	59.54	11.91	71.44	4.55
Croton macrostachyus	Euphorbiaceae	51.17	10.23	61.41	3.91
Euclea racemose	Ebenaceae	47.20	9.44	56.64	3.60
Tamarindus indica	Fabaceae	40.35	8.07	48.42	3.08
Syzygium guineense	Myrtaceae	37.40	7.48	44.89	2.86
Acacia goetzei	Fabaceae	33.45	6.69	40.14	2.55
Vitex doniana	Lamiaceae	26.82	5.36	32.18	2.05
Lannea fruticosa	Anacardiaceae	25.55	5.11	30.66	1.95
Entada abyssinica	Fabaceae	22.37	4.47	26.84	1.71
Ozoroa insignis	Anacardiaceae	20.08	4.02	24.09	1.53
Adenium obesum	Apocynaceae	16.95	3.39	20.34	1.29
Acacia tortilis	Fabaceae	16.85	3.37	20.23	1.29
Bridelia micrantha	Euphorbiaceae	16.51	3.30	19.81	1.26
Balanites rotundifolia	Balanitaceae	15.12	3.02	18.14	1.15
Acacia seyal	Fabaceae	14.99	3.00	17.98	1.14
Cordia sinensis	Boraginaceae	13.77	2.75	16.53	1.05
Acacia hockii	Fabaceae	13.30	2.66	15.96	1.02
Ehretia cymosa	Boraginaceae	13.09	2.62	15.71	1.00
Maytenus	Celastraceae	12.76	2.55	15.31	0.97
Acacia mellifera	Fabaceae	12.57	2.51	15.09	0.96
Sterculia africana	Sterculiaceae	12.30	2.42	14.53	0.92
Prunus africana	Rosaceae	12.04	2.41	14.45	0.92
Erythrina brucei	Fabaceae	11.67	2.33	14.01	0.89
Combretum collinum	Combretaceae	11.63	2.33	13.95	0.89
Albizia anthelmintica	Fabaceae	11.00	2.20	13.20	0.84
Balanites aegyptiaca	Balanitaceae	10.70	2.14	12.84	0.82
Stereospermum	Bignoniaceae	10.44	2.09	12.53	0.80
Dombeya torrida	Sterculiaceae	10.28	2.06	12.33	0.78
Acacia nilotica	Fabaceae	10.16	2.03	12.19	0.78
Maytenus undata	Celastraceae	9.29	1.86	11.15	0.71

Ximenia americana	Olacaceae	8.98	1.80	10.78	0.69
Phoenix reclinata	Arecaceae	8.59	1.72	10.31	0.66
Cordia africana	Boraginaceae	8.03	1.61	9.64	0.61
Acacia senegal	Fabaceae	7.38	1.48	8.86	0.56
Teclea nobilis	Rutaceae	7.10	1.42	8.52	0.54
Maytenus arbutifolia	Celastraceae	7.05	1.41	8.45	0.54
Dodonea angustifolia	Sapindaceae	6.77	1.35	8.13	0.52
Brucea	Simaroubaceae	6.66	1.33	8.00	0.51
Gardenia ternifolia	Rubiaceae	5.86	1.17	7.04	0.45
Carissa spinarum	Apocynaceae	5.72	1.14	6.87	0.44
Ziziphus mucronata	Rhamnaceae	5.61	1.12	6.73	0.43
Heteromorpha	Apiaceae	5.54	1.11	6.64	0.42
Acacia bussei	Fabaceae	5.46	1.09	6.55	0.42
Commiphora	Burseraceae	5.41	1.08	6.49	0.41
Piliostigma thonningii	Fabaceae	5.29	1.06	6.35	0.40
Maesa lanceolata	Myrsinaceae	5.14	1.03	6.17	0.39
Grewia velutina	Tiliaceae	5.11	1.02	6.13	0.39
Sterculia	Sterculiaceae	4.81	0.96	5.77	0.37
Dichrostachys cinerea	Fabaceae	4.77	0.95	5.73	0.36
Maerua angolensis	Capparidaceae	3.93	0.79	4.72	0.30
Millettia ferruginea	Fabaceae	3.83	0.77	4.60	0.29
Rhus vulgaris	Anacardiaceae	3.71	0.74	4.45	0.28
Ficus sycomorus	Moraceae	3.69	0.74	4.43	0.28
Calpurnia aurea	Fabaceae	3.68	0.74	4.42	0.28
Combretum	Combretaceae	3.50	0.70	4.20	0.27
Dalbergia lactea	Fabaceae	3.45	0.69	4.14	0.26
Euphorbia	Euphorbiaceae	3.18	0.64	3.81	0.24
Caesalpinia	Fabaceae	3.17	0.63	3.81	0.24
Celtis africana	Ulmaceae	3.04	0.61	3.65	0.23
Diospyros abyssinica	Ebenaceae	2.55	0.51	3.06	0.19
Celtis toka	Ulmaceae	2.51	0.50	3.01	0.19
Ricinus communis	Euphorbiaceae	2.27	0.45	2.73	0.17
Vepris dainellii	Rutaceae	2.06	0.41	2.47	0.16
Grewia trichocarpa	Tiliaceae	1.91	0.38	2.29	0.15
Combretum	Combretaceae	1.86	0.37	2.24	0.14
Galiniera saxifraga	Rubiaceae	1.86	0.37	2.23	0.14
Protea gaguedi	Proteaceae	1.83	0.37	2.19	0.14
Boswellia neglecta	Burseraceae	1.65	0.33	1.98	0.13
Euphorbia tirucalli	Euphorbiaceae	1.32	0.26	1.59	0.10

Commiphora tenuis	Burseraceae	1.28	0.26	1.54	0.10
Vernonia amygdalina	Asteraceae	1.22	0.24	1.46	0.09
Pterolobium stellatum	Fabaceae	1.19	0.24	1.43	0.09
Rhus natalensis	Anacardiaceae	1.12	0.22	1.34	0.09
Draceana steudneri	Dracaenaceae	1.06	0.21	1.28	0.08
Buddleja polystachya	Loganiaceae	1.06	0.21	1.27	0.08
Vangueria	Rubiaceae	0.91	0.18	1.09	0.07
Lannea schimperi	Anacardiaceae	0.87	0.17	1.05	0.07
Pavetta abyssinica	Rubiaceae	0.83	0.17	1.00	0.06
Albizia schimperiana	Fabaceae	0.81	0.16	0.97	0.06
Teclea borenensis	Rutaceae	0.80	0.16	0.96	0.06
Phytolacca	Phytolaccaceae	0.77	0.15	0.93	0.06
Capparis tomentosa	Capparidaceae	0.76	0.15	0.92	0.06
Myrsine africana	Myrsinaceae	0.60	0.12	0.72	0.05
Osyris quadripartita	Santalaceae	0.59	0.12	0.71	0.04
Ziziphus spina-christi	Rhamnaceae	0.52	0.10	0.62	0.04
Vepris glomerata	Rutaceae	0.49	0.10	0.58	0.04
Canthium setiflorum	Rubiaceae	0.47	0.09	0.57	0.04
Grewia ferruginea	Tiliaceae	0.45	0.09	0.54	0.03
Grewia villosa	Tiliaceae	0.44	0.09	0.52	0.03
Prosopis juliflora	Fabaceae	0.30	0.06	0.36	0.02
Diospyros scabra	Ebenaceae	0.27	0.05	0.33	0.02
Nuxia congesta	Loganiaceae	0.26	0.05	0.31	0.02
Clutia lanceolata	Euphorbiaceae	0.26	0.05	0.31	0.02
Nuxia oppositifolia	Loganiaceae	0.24	0.05	0.29	0.02
Pavetta gardeniifolia	Rubiaceae	0.19	0.04	0.23	0.01
Capparis fascicularis	Capparidaceae	0.15	0.03	0.18	0.01
Grewia bicolor	Tiliaceae	0.13	0.03	0.16	0.01
Salvadora persica	Salvadoraceae	0.13	0.03	0.16	0.01
Rosa abyssinica	Rosaceae	0.13	0.03	0.16	0.01
Vernonia rueppellii	Asteraceae	0.13	0.03	0.16	0.01
Premna schimperi	Lamiaceae	0.13	0.03	0.16	0.01
Zanthoxylum	Rutaceae	0.13	0.03	0.16	0.01
Senna didymobotrya	Fabaceae	0.13	0.03	0.16	0.01
Vernonia auriculifera	Asteraceae	0.13	0.03	0.16	0.01
Canthium	Rubiaceae	0.13	0.03	0.16	0.01
Securidaca	Polygalaceae	0.13	0.03	0.15	0.01
Rhus tenuinervis	Anacardiaceae	0.12	0.02	0.15	0.01
Clutia abyssinica	Euphorbiaceae	0.12	0.02	0.15	0.01

Grand Total	1310.01	261.96	1571.80	100.00

Note: *AGC = above ground carbon, BGC = below ground carbon, TC = total carbon or AGC + BGC*

Appendix 2: Woody species carbon stock in Buska Dry evergreen Afromontane forest

Species	AGC (ton ha^{-1})	BGC (ton ha^{-1})	TC
Juniperus procera	114.23	22.85	137.08
Podocarpus falcatus	89.22	17.84	107.07
Olea europaea	56.81	11.36	68.18
Ficus vasta	56.05	11.21	67.25
Croton macrostachyus	23.32	4.66	27.98
Euclea racemosa	21.62	4.32	25.94
Prunus africana	12.04	2.41	14.45
Maytenus senegalensis	11.34	2.27	13.61
Vitex doniana	10.72	2.14	12.87
Bridelia micrantha	10.10	2.02	12.12
Syzygium guineense	8.80	1.76	10.56
Entada abyssinica	7.10	1.42	8.52
Erythrina brucei	6.97	1.39	8.36
Sterculia africana	6.32	1.26	7.58
Cordia sinensis	5.88	1.18	7.06
Phoenix reclinata	5.29	1.06	6.35
Dombeya torrida	4.90	0.98	5.88
Brucea antidysenterica	4.43	0.89	5.31
Lannea fruticosa	4.35	0.87	5.22
Grewia velutina	3.69	0.74	4.43
Ficus sycomorus	3.69	0.74	4.43
Heteromorpha	3.65	0.73	4.39
Acacia goetzei	3.54	0.71	4.25
Acacia tortilis	3.53	0.71	4.23
Ziziphus mucronata	3.15	0.63	3.78
Euphorbia ampliphylla	2.99	0.60	3.59
Ehretia cymosa	2.56	0.51	3.07
Teclea nobilis	2.20	0.44	2.64
Combretum molle	2.14	0.43	2.57
Ricinus communis	2.14	0.43	2.57
Dodonea angustifolia	2.01	0.40	2.42
Cordia africana	1.95	0.39	2.33
Acacia nilotica	1.91	0.38	2.29
Diospyros abyssinica	1.78	0.36	2.13

Balanites rotundifolia	1.63	0.33	1.96
Calpurnia aurea	1.55	0.31	1.86
Millettia ferruginea	1.49	0.30	1.79
Acacia hockii	1.49	0.30	1.79
Terminalia brownii	1.25	0.25	1.50
Celtis toka	1.18	0.24	1.41
Tamarindus indica	1.17	0.23	1.41
Ozoroa insignis	1.10	0.22	1.32
Draceana steudneri	1.06	0.21	1.28
Maesa lanceolata	1.02	0.20	1.22
Maytenus undata	1.02	0.20	1.22
Vepris dainellii	0.88	0.18	1.05
Commiphora	0.86	0.17	1.03
Albizia schimperiana	0.81	0.16	0.97
Caesalpinia decapetala	0.76	0.15	0.91
Gardenia ternifolia	0.65	0.13	0.78
Carissa spinarum	0.64	0.13	0.76
Capparis tomentosa	0.63	0.13	0.76
Maytenus arbutifolia	0.59	0.12	0.71
Vangueria	0.53	0.11	0.64
Acacia bussei	0.51	0.10	0.61
Stereospermum	0.51	0.10	0.61
Phytolacca dodecandra	0.51	0.10	0.61
Myrsine africana	0.43	0.09	0.52
Vernonia amygdalina	0.41	0.08	0.49
Adenium obesum	0.41	0.08	0.49
Celtis africana	0.41	0.08	0.49
Teclea borenensis	0.39	0.08	0.47
Rhus vulgaris	0.30	0.06	0.36
Buddleja polystachya	0.29	0.06	0.35
Diospyros scabra	0.27	0.05	0.33
Clutia lanceolata	0.26	0.05	0.31
Albizia anthelmintica	0.25	0.05	0.30
Balanites aegyptiaca	0.19	0.04	0.23
Dalbergia lactea	0.18	0.04	0.21
Pterolobium stellatum	0.15	0.03	0.18
Rhus natalensis	0.13	0.03	0.16
Rosa abyssinica	0.13	0.03	0.16
Galiniera saxifraga	0.13	0.03	0.16

Pavetta abyssinica	0.13	0.03	0.16
Vernonia auriculifera	0.13	0.03	0.16
Vernonia rueppellii	0.13	0.03	0.16
Nuxia congesta	0.13	0.03	0.16
Premna schimperi	0.13	0.03	0.16
Maerua angolensis	0.13	0.03	0.15
Grewia trichocarpa	0.12	0.02	0.15
Grand Total	527.47	105.49	632.97

Note: *AGC = above ground carbon, BGC = below ground carbon, TC = total carbon or AGC + BGC*

Appendix 3: Carbon stock of woody species recorded in the CTW vegetation of study area

Species	AGC (ton ha^{-1})	BGC (ton ha^{-1})	TC
Combretum molle	114.84	22.97	137.80
Terminalia brownii	69.85	13.97	83.82
Ficus vasta	27.14	5.43	32.57
Acacia goetzei	21.50	4.30	25.80
Tamarindus indica	20.70	4.14	24.84
Ozoroa insignis	18.06	3.61	21.67
Croton macrostachyus	13.67	2.73	16.40
Entada abyssinica	11.71	2.34	14.05
Combretum collinum	11.63	2.33	13.95
Euclea racemosa	11.07	2.21	13.29
Balanites rotundifolia	10.83	2.17	13.00
Syzygium guineense	10.61	2.12	12.74
Vitex doniana	9.57	1.91	11.49
Lannea fruticosa	8.82	1.76	10.58
Maytenus undata	7.87	1.57	9.44
Ehretia cymosa	7.33	1.47	8.80
Cordia sinensis	6.99	1.40	8.39
Cordia africana	4.48	0.90	5.38
Adenium obesum	4.47	0.89	5.37
Ximenia americana	3.61	0.72	4.33
Maesa lanceolata	3.54	0.71	4.25
Teclea nobilis	3.54	0.71	4.25
Maytenus arbutifolia	3.26	0.65	3.91
Combretum aculeatum	3.19	0.64	3.82
Rhus vulgaris	3.16	0.63	3.79
Dodonea angustifolia	2.91	0.58	3.50

Carissa spinarum	2.89	0.58	3.47
Maerua angolensis	2.65	0.53	3.18
Celtis africana	2.64	0.53	3.16
Balanites aegyptiaca	2.53	0.51	3.03
Acacia hockii	2.50	0.50	3.00
Acacia nilotica	2.37	0.47	2.84
Dombeya torrida	2.37	0.47	2.84
Phoenix reclinata	1.90	0.38	2.28
Combretum	1.86	0.37	2.24
Calpurnia aurea	1.86	0.37	2.23
Millettia ferruginea	1.83	0.37	2.20
Olea europaea	1.80	0.36	2.16
Bridelia micrantha	1.71	0.34	2.05
Piliostigma thonningii	1.70	0.34	2.04
Dalbergia lactea	1.45	0.29	1.74
Celtis toka	1.33	0.27	1.60
Commiphora	1.28	0.26	1.54
Vepris dainellii	1.18	0.24	1.41
Heteromorpha	1.10	0.22	1.32
Gardenia ternifolia	1.04	0.21	1.25
Protea gaguedi	0.95	0.19	1.14
Dichrostachys cinerea	0.77	0.15	0.93
Rhus natalensis	0.72	0.14	0.86
Ziziphus mucronata	0.66	0.13	0.80
Buddleja polystachya	0.63	0.13	0.76
Galiniera saxifraga	0.63	0.13	0.76
Lannea schimperi	0.63	0.13	0.76
Sterculia africana	0.51	0.10	0.61
Canthium setiflorum	0.47	0.09	0.57
Teclea borenensis	0.41	0.08	0.49
Pterolobium stellatum	0.38	0.08	0.45
Osyris quadripartita	0.34	0.07	0.40
Vernonia amygdalina	0.31	0.06	0.38
Grewia velutina	0.30	0.06	0.36
Vangueria	0.25	0.05	0.31
Vepris glomerata	0.24	0.05	0.29
Capparis fascicularis	0.15	0.03	0.18
Grewia villosa	0.13	0.03	0.16
Maytenus senegalensis	0.13	0.03	0.16

Phytolacca dodecandra	0.13	0.03	0.16
Brucea antidysenterica	0.13	0.03	0.15
Capparis tomentosa	0.13	0.03	0.15
Clutia abyssinica	0.12	0.02	0.15
Pavetta abyssinica	0.12	0.02	0.15
Rhus tenuinervis	0.12	0.02	0.15
Grand Total	461.71	92.34	554.05

Note: *AGC = above ground carbon, BGC = below ground carbon, TC = total carbon or AGC + BGC*

Appendix 4: Woody species carbon stock in the ACB vegetation of study area

Species	AGC (ton ha^{-1})	BGC (ton ha^{-1})	TC
Tamarindus indica	18.48	3.70	22.17
Syzygium guineense	17.99	3.59	21.60
Acacia seyal	14.99	3.00	17.98
Euclea racemosa	14.50	2.90	17.41
Croton macrostachyus	14.18	2.84	17.02
Acacia tortilis	13.33	2.67	15.99
Acacia mellifera	12.57	2.51	15.09
Lannea fruticosa	12.39	2.48	14.87
Adenium obesum	12.07	2.41	14.48
Albizia anthelmintica	10.76	2.15	12.91
Stereospermum kunthianum	9.93	1.99	11.91
Acacia hockii	9.31	1.86	11.17
Acacia goetzei	8.41	1.68	10.10
Balanites aegyptiaca	7.98	1.60	9.58
Combretum molle	7.97	1.59	9.56
Acacia senegal	7.38	1.48	8.86
Terminalia brownii	7.24	1.45	8.68
Ficus vasta	6.99	1.40	8.39
Vitex doniana	6.52	1.30	7.83
Acacia nilotica	5.89	1.18	7.06
Ximenia americana	5.37	1.07	6.44
Sterculia africana	5.29	1.05	6.34
Acacia bussei	4.95	0.99	5.94
Sterculia rhynchocarpa	4.81	0.96	5.77
Bridelia micrantha	4.70	0.94	5.64
Erythrina brucei	4.70	0.94	5.64
Gardenia ternifolia	4.17	0.83	5.01
Dichrostachys cinerea	4.00	0.80	4.80
Piliostigma thonningii	3.59	0.72	4.31
Entada abyssinica	3.57	0.71	4.28
Commiphora habessinica	3.27	0.65	3.92

Ehretia cymosa	3.20	0.64	3.84
Maytenus arbutifolia	3.20	0.64	3.84
Dombeya torrida	3.02	0.60	3.62
Balanites rotundifolia	2.66	0.53	3.19
Caesalpinia decapetala	2.42	0.48	2.90
Carissa spinarum	2.19	0.44	2.63
Brucea antidysenterica	2.11	0.42	2.53
Dodonea angustifolia	1.85	0.37	2.21
Dalbergia lactea	1.82	0.36	2.19
Ziziphus mucronata	1.80	0.36	2.15
Grewia trichocarpa	1.79	0.36	2.14
Boswellia neglecta	1.65	0.33	1.98
Cordia africana	1.61	0.32	1.93
Phoenix reclinata	1.40	0.28	1.69
Teclea nobilis	1.36	0.27	1.63
Euphorbia tirucalli	1.32	0.26	1.59
Commiphora tenuis	1.28	0.26	1.54
Maytenus senegalensis	1.28	0.26	1.54
Maerua angolensis	1.16	0.23	1.39
Grewia velutina	1.12	0.22	1.34
Galiniera saxifraga	1.09	0.22	1.31
Olea europaea	0.93	0.19	1.11
Ozoroa insignis	0.92	0.18	1.10
Cordia sinensis	0.90	0.18	1.08
Protea gaguedi	0.88	0.18	1.05
Heteromorpha arborescens	0.78	0.16	0.94
Diospyros abyssinica	0.77	0.15	0.93
Pterolobium stellatum	0.66	0.13	0.79
Maesa lanceolata	0.58	0.12	0.69
Pavetta abyssinica	0.58	0.12	0.69
Ziziphus spina-christi	0.52	0.10	0.62
Millettia ferruginea	0.51	0.10	0.61
Vernonia amygdalina	0.49	0.10	0.59
Grewia ferruginea	0.45	0.09	0.54
Maytenus undata	0.41	0.08	0.49
Combretum aculeatum	0.31	0.06	0.38
Grewia villosa	0.30	0.06	0.36
Prosopis juliflora	0.30	0.06	0.36
Calpurnia aurea	0.27	0.05	0.32
Rhus natalensis	0.27	0.05	0.32
Osyris quadripartita	0.25	0.05	0.30
Rhus vulgaris	0.25	0.05	0.30
Vepris glomerata	0.25	0.05	0.30
Lannea schimperi	0.24	0.05	0.29

Nuxia oppositifolia	0.24	0.05	0.29
Euphorbia ampliphylla	0.19	0.04	0.23
Pavetta gardeniifolia	0.19	0.04	0.23
Myrsine africana	0.17	0.03	0.20
Buddleja polystachya	0.13	0.03	0.16
Grewia bicolor	0.13	0.03	0.16
Phytolacca dodecandra	0.13	0.03	0.16
Ricinus communis	0.13	0.03	0.16
Salvadora persica	0.13	0.03	0.16
Canthium pseudosetiflorum	0.13	0.03	0.16
Nuxia congesta	0.13	0.03	0.16
Senna didymobotrya	0.13	0.03	0.16
Zanthoxylum chalybeum	0.13	0.03	0.16
Securidaca longepedunculata	0.13	0.03	0.15
Vangueria madagascariensis	0.12	0.02	0.15
Grand Total	320.64	64.11	384.79

Note: *AGC = above ground carbon, BGC = below ground carbon, TC = total carbon or AGC + BGC*

DIVERSITY AND CONSERVATION OF WILD EDIBLE MUSHROOMS IN MODO MISSA GAME RESERVE, DEMOCRATIC REPUBLIC OF CONGO

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ABSTRACT: This study explored the diversity and conservation of wild edible mushrooms in the Modo Missa Game Reserve, bordering Garamba National Park in the Democratic Republic of Congo. The reserve faces pressure from human activities, such as poaching, timber harvesting, mining, and agricultural expansion, all of which threaten biodiversity. Local communities depend on mushrooms as a seasonal food source, but cultivation remains limited due to climate constraints, lack of knowledge, and insufficient institutional support. Mushrooms are often overlooked in conservation planning despite their ecological and nutritional significance. Data were collected from 76 households across four localities using random sampling and field surveys. Diversity analysis revealed nine species, with a Shannon–Wiener index of 2.13 (moderate diversity), Simpson‟s index of 0.875 (high diversity and low dominance), and an evenness value of 0.915 (balanced distribution). *Schizophyllum commune* was the most prevalent species (13%), thriving in forest habitats, while *Termitomyces* spp. were more common in savanna areas. Fisher‟s Exact indicated no significant association between species occurrence and habitat type, implying that microhabitat and seasonal factors influence the distribution. Respondents highlighted key

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challenges, including pollution, climate change, habitat destruction, limited awareness, and insufficient cultivation skills. Recommended conservation strategies encompassed habitat protection, controlled harvesting, species documentation, and promotion of mushroom farming. The study emphasized that awareness campaigns, training, and further ecological research are vital, and that integrating community initiatives with formal conservation efforts is crucial to protect mushroom biodiversity, enhance food security, and bolster ecosystem resilience.

Keywords: Biodiversity, conservation, Shannon–Wiener index, Simpson"s index,

INTRODUCTION

Globally, an estimated 14,000–22,000 mushroom species are recognized, though only a fraction are cultivated or industrially utilized, mainly *Agaricus bisporus*, *Pleurotus* spp., and *Lentinula edodes* (Sileshi et al., 2023), with about 10,000 formally classified and described (Qwarse et al., 2024; Sitoe and Pinto, 2024). However, scientists believe the true number is much higher, as many species remain undocumented, particularly in tropical regions (Kała et al., 2024; Tarafder et al., 2024; Thunberg, 2024). The global mushroom market was valued at over USD 51 billion in 2024 and is projected to exceed USD 156 billion by 2033, with Asia, especially China, dominating production and consumption(Batubenga et al., 2021; Fernandes et al., 2021). In Africa, Nigeria, South Africa, and Zambia are among the African countries where mushroom cultivation and consumption are most widespread, with Nigeria leading in production and utilization for both food security and income generation(Angom et al., 2021; Fernandes et al., 2021; Gorenflo and Romaine, 2021).

The Democratic Republic of Congo (DRC) is renowned for its rich biodiversity, with vast forested areas supporting various plant and animal species, including these wild edible mushrooms (Boa, 2007). These mushrooms, lacking chlorophyll, cannot produce their own food through photosynthesis. However, they play a vital role in ecosystem functioning by recycling organic matter into the soil, promoting tree growth, and providing a substrate for mushroom cultivation through the reuse of farm waste(Kamalebo et al., 2018). Cultivating edible mushrooms for commercial purposes facilitates the recycling of agricultural waste into a unique and highly nutritious food source with a minimal ecological footprint (Wembodinga et al., 2024), offering significant benefits to smallholder farmers. Mushrooms have long been integral to traditional diets and cultural practices, with local communities passing down traditional knowledge and harvesting techniques through generations (Sileshi et al., 2023). Additionally, they hold cultural significance in ceremonies, rituals, and traditional medicine (Mjaika, 2022). Wild edible mushrooms play an important role not only in food security but also in traditional medicine across many cultures worldwide. Ethnomycological studies have documented their use in folk medicine to treat infections, enhance immune function, reduce inflammation, and support general health (Boa, 2004; Munyaneza, 2018). These medicinal properties are largely attributed to bioactive compounds such as polysaccharides, particularly β-glucans, phenolic compounds, terpenoids, and immunomodulatory proteins, which have been shown to stimulate immune responses, exhibit antimicrobial activity, and regulate oxidative stress (Sande et al., 2019; Qwarse et al., 2024).

Mushrooms contain moisture (85-95%), carbohydrates (35-70%), protein (15–34.7%), fat (10%), minerals (6–10.9%), and nucleic acids (3-8%). They also contain substantial amounts of vitamins such as thiamine 1.4–2.2 mg (%), riboflavin 6.7-9.0 mg (%), niacin 60.6-73.3 mg (%), biotin, ascorbic acid 92–144 mg (%), pantothenic acid 21.1–33.3 mg (%), and folic acid 1.2–1.4 mg/100 g in dry weight basis. Recent studies further highlight that edible and medicinal wild mushrooms contribute to the prevention and management of chronic diseases through their antioxidant, anti-inflammatory, and immunoregulatory effects, providing scientific support for their long-standing use in folk medicine (Nevins and Heale, 2018;Mjaika, 2021; Qwarse et al., 2021; Habineza Mpunga et al., 2025).

In African and tropical regions, traditional knowledge related to wild edible mushrooms represents an important part of cultural heritage and community health systems, reinforcing the need to conserve mushroom diversity alongside forest ecosystems (Singer, 1962; Smith, 2018; Shalimov et al., 2019; Sitoe and Pinto, 2024). Wild mushrooms contribute to local economic development by serving as a food source during times of scarcity, supporting hunger and poverty alleviation through well-developed farming strategies. However, their sustainability is threatened by conservation challenges (Sileshi et al., 2023). Factors such as climate change (Mjaika, 2022), habitat loss, pollution, and overexploitation of forests pose significant risks. Preserving the socioeconomic and ecological values of mushrooms requires raising awareness about responsible forest use and implementing sustainable conservation practices (Tarafder et al., 2024; Thunberg, 2024;Bhati, 2025). Moreover, limited attention has been given to promoting the uses and nutritional value of wild edible mushrooms, particularly in DRC (D‟haen et al., 2019). More efforts are needed to increase public awareness, disseminate knowledge, and establish systematic conservation and management strategies (Shalimov et al., 2019; Zhao et al., 2020).

Enhancing local capacity through training programmes and awareness campaigns is essential for promoting sustainable mushroom management and conservation. Areas surrounding Garamba National Park, such as the Modo Missa Game Reserve, have faced significant challenges from human activities such as poaching, wildlife resource collection, mining, and timber cutting

(Roncero-Ramos and Delgado-Andrade, 2017; Sevindik et al., 2023). Encouraging mushroom farming can help alleviate poverty, improve food security, create jobs, and reduce pressure on protected areas. Addressing these challenges and developing sustainable strategies for the diversity and conservation of wild edible mushrooms is crucial for safeguarding food security and unlocking socioeconomic opportunities through the use of edible mushrooms in the region (McKnight et al., 2021; Lu et al., 2025).

Garamba National Park, Democratic Republic of Congo (DRC), is recognized as one of the most diverse ecosystems in Africa. Previous studies in that region have largely concentrated on megafauna conservation, poaching pressures, and governance challenges, with limited attention to non-timber forest products such as wild edible mushrooms. For instance, UNESCO‟s State of Conservation reports emphasized threats from armed conflict and illegal hunting, while African Parks‟ monitoring programs highlighted elephants „recovery and species translocations but overlooked hidden biodiversity and ethnomycological resources (Bhati, 2025; Hyde et al., 2019).

Recent ethnomycological studies in Central Africa have documented traditional knowledge and dietary importance of wild mushrooms (Sileshi et al., 2023), yet these remain geographically restricted and do not extend to the Modo Missa Game Reserve. Moreover, existing studies often lack detailed ecological assessments of fungal diversity and conservation status, thereby limiting understanding of how mushroom resources contribute to local food security, cultural heritage, and ecosystem resilience (Desjardin, 2014; Dube et al., 2021; Kabacia and Muchane, 2023;Falk and Hagsten, 2025). This gap underscores the need for site-specific studies that integrate biodiversity surveys with conservation perspectives. Hence, the study addresses this limitation by assessing the diversity and conservation of wild edible mushrooms in the Modo Missa Game

Reserve, the area surrounding Garamba National Park (Smith, 2018). The study is significant to expand the basic knowledge of fungal resources in the DRC and to reinforce their role in both community health systems and forest ecosystem sustainability (Smith, 2018).

Documenting traditional knowledge and practices related to wild edible mushrooms collection, preparation, and utilization is crucial for engaging local communities and indigenous groups in the effort of hidden biodiversity conservation (Batubenga et al., 2021; Kabacia and Muchane, 2023). Furthermore, laboratory optimization and ex-situ conservation of mushrooms are increasingly recognized as essential strategies for safeguarding fungal biodiversity, as they enable the maintenance of viable cultures, genetic resources, and bioactive compounds outside natural habitats, thereby complementing in-situ conservation efforts.

MATERIAL AND METHODS

Description of the study site

Description of the study area Modo Missa Game Reserve is part of the Garamba Complex in northeastern Democratic Republic of the Congo (DRC), located east of Garamba National Park (Fig.1) and neighboring other hunting areas such as the Gangala na Bodio and Azande reserves (Linder et al., 2024). It is listed in the World Database on Protected Areas under ID 555781117. The reserve lies within the Garamba landscape, defined by latitudes 3.5°- 4.1° N and longitudes 29.1°- 29.5° E, with terrain ranging from 700 to 1,065 meters above sea level. Ecologically, Modo Missa shares the Garamba region‟s savanna grassland, characterized by tall grasses, scattered trees, and intermittent woodland. Gallery forests are found along rivers and depressions, while surrounding hunting areas include deciduous woodland and riparian forest components. The wider Garamba Complex features a forest- savanna mosaic (Sudano-Guinean savanna) where woodland, grassland, and gallery forest intersect, supporting both forest-edge species and savanna specialists (Smith, 2018;D‟haen et al., 2019).

The reserve lies within a tropical savanna climate, with a distinct wet season from May to October and a pronounced dry season from November to April. Annual rainfall across the Garamba Complex averages between 1,200 and 1,600 mm, supporting grassy savannas and forest patches, with high temperatures maintained year-round and cooler nights during the dry season. The Modo-Missa Reserve encompasses an area of approximately 1.83 km² (D‟haen et al., 2019). The local climate is characterized by average daytime temperatures ranging between 25 and 30 °C, with slight decreases during the night. Relative humidity remains moderately high, averaging around 50%(Mateso et al., 2024). The reserve was formally established in 1938 and later recognized as part of the UNESCO World Heritage network in 1980. Modo Missa, together with Azande and Gangala na Bodio, acts as a buffer zone for Garamba National Park, preserving habitat connectivity, seasonal wildlife movements, and ecological integrity across the broader landscape (Mateso et al., 2024).

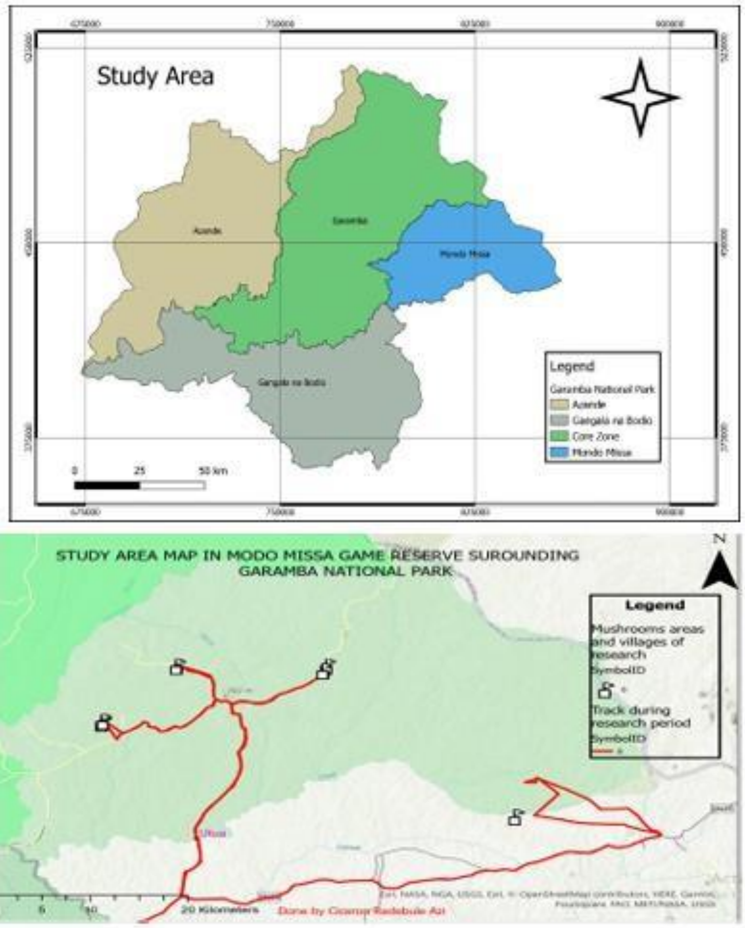

Figure 1. Location of the study site and location of sampling sites in Modo Missa Game Reserve, Democratic Republic of Congo.

Sampling technique and sample size determination

The total population across the four localities of Gbere, Tekadje, Leema, and Buru of Modo Missa is 1,448 people distributed in 324 households. Buru has the highest population of 760 people and the highest number of households, totaling 152. The second is Gbere with 304 people and 76 households, Tekadje presented 248 people in 62 households, while Leema presented the smallest population of 136 people in 34 households. The average household size is 4 people per household in Gbere, Tekadje, and Leema, while Buru has a slightly higher average of 5 people per household. Overall, the average household size across all four localities is approximately 4.47 people per household (Table 1).

Table 1: Distribution of population and sample size by locality (Author Field Survey, 2023)

Localities	Population	Households	Sample size
Gbere	304	76	17
Tekadje	248	62	15
Leema	136	34	8
Buru	760	152	36
Total	1448	324	76

The total population considered in this study is 324 households from four localities in Modo Missa. Factors such as age, gender, and location were considered to ensure that the whole population was represented. Yamane's formula: $n = N/(1+N(e)^2$ was used to determine the sample size of respondents from the total population, where n is the total sample size, N is the total population or households, and e is the margin of error (0.1). Therefore, the sample size in this study (n) $=324/ [1+324(0.1)^2] =76.42 \approx 76$ households (Boyd, 2022). To obtain individual respondents from the locality or the sample size within localities, the Neyman allocation formula: $n_i = (N_i * n)/N$. was used. Where ni: sample size from the stratum (locality), N_i: population size in the stratum, n: study's sample size, N: target population size as summarized in the table above (Table 1).

Data collection method and analysis

Wild edible mushrooms were sampled using a plot-based purposive sampling method in Modo Missa Game Reserve**.** Sampling plots were established in representative habitat types (forest, woodland, savanna, and forest edge) where mushroom occurrence was known or expected based on vegetation structure, substrate availability, and local ecological knowledge(Mjaika, 2022). Field surveys and direct observations were performed, and identification was based on morphological characteristics such as cap shape and color (Mateso et al., 2024). Taxonomic identification was conducted based on morphological characteristics cap morphology (cap color, cap surface, cap margin, cap diameter, cap size, structure), gill morphology and attachment (gills shape and color) , stipe (stalk) morphology (stipe length), volva morphology and rings (annulus) presence as described earlier (Wembodinga et al., 2024)**.** This helped to differentiate edible species from inedible or toxic ones by observing carefully those traits as well as smelling the odour (McKnight et al., 2021).

Additionally, habitat, substrate and vegetation types were also recorded for each wild edible mushroom collected to provide ecological context, facilitate interpretation of species distribution patterns, and assess the influence of environmental factors on mushroom diversity and occurrence(Sila and Koaze, 2025). Details such as morphological characteristics, sampling location, habitat type, and associated plant and substrate types were recorded with the assistance of residents and reference books (Irakiza et al., 2021). Information for each species was cross-checked with reference manuals (“*The Agaricales in Modern Taxonomy,* 4th Edition ““ and “ Identification of mushrooms - Getting started““), and local ecological knowledge to ensure accurate species identity (Degreef et al., 2016; Milenge Kamalebo et al., 2018).

Questionaries and interview for respondents were carried out where local leaders and community members were interviewed to gather information on edible mushroom conservation measures and strategies. Questionnaires were randomly distributed in households across villages to ensure representation of the entire population within Modo-Missa Game Reserve. Through the questionnaires, traditional knowledge regarding the harvesting and uses of edible mushrooms was collected, including the types harvested, seasonal availability, cultural practices, and their socio-economic significance, along with factors hindering conservation efforts (Boa, 2007; Cheng et al., 2019). Responses were expected to be concise, typically requiring a "yes" or "no". Insights were also sought on possible strategies and measures the local communities could propose to conserve this valuable resource, emphasizing the importance of understanding community perspectives and engaging them in conservation for sustainable mushroom management (Dejene et al., 2023). Data analysis was conducted using R software version 4.5.2 (available at *https://cran.r-project.org/bin/windows/base/*) and ArcGIS Pro (*pro.arcgis.com*).

RESULTS

Socio-demographic characteristics of respondents

Socio-demographic characteristics of respondents are summarized in Fig. 2. This part of the results analysis includes the general background information of respondents from Modo Missa Ame Reserve. It covers their sex, age, occupation, and educational level. A total of 76 questionnaires were distributed out of a population of 324. The complete set of 76 questionnaires was collected without incidence, ensuring no loss or damage. Accordingly, frequency and percentage values for each variable were used to present the socio-demographic data. The educational background of respondents revealed that the largest proportion had attained primary education (29.4%), followed by those categorized under “other” forms of education (26.3%). Vocational education (19.2%) and holders of A_2 diploma or secondary school graduates (18.2%) represented moderate shares, while university graduates accounted for the smallest group (6.8%). This distribution indicated that most respondents possess relatively low levels of formal education, with higher education being rare (Fig. 2a). In terms of occupation, farming was the dominant livelihood, reported by 53.7% of respondents. Traders constituted 23%, while public employees accounted for 20.3%. Handicraftsmen were the least represented, at only 3%. These findings highlight the central role of agriculture in the community, with trade and public employment serving as secondary sources of income (Fig. 2b).

Age distribution showed that respondents were predominantly in the 30–40-year category (25.3%), followed by those aged 18–29 years (17.2%) and 41–51 years (15.2%). Older age groups were less represented, with 6.8% in the 52–62-year range and 13.2% above 62 years. A notable proportion (22.3%) fell into the “other/unspecified” category. Overall, the sample was skewed toward younger and middle-aged adults, with relatively few elderly participants (Fig. 2c). Gender distribution was nearly balanced, with males comprising 51.7% and females 48.3%. This slight male majority suggests that both genders were fairly equally represented in the study population (Fig.2 d).

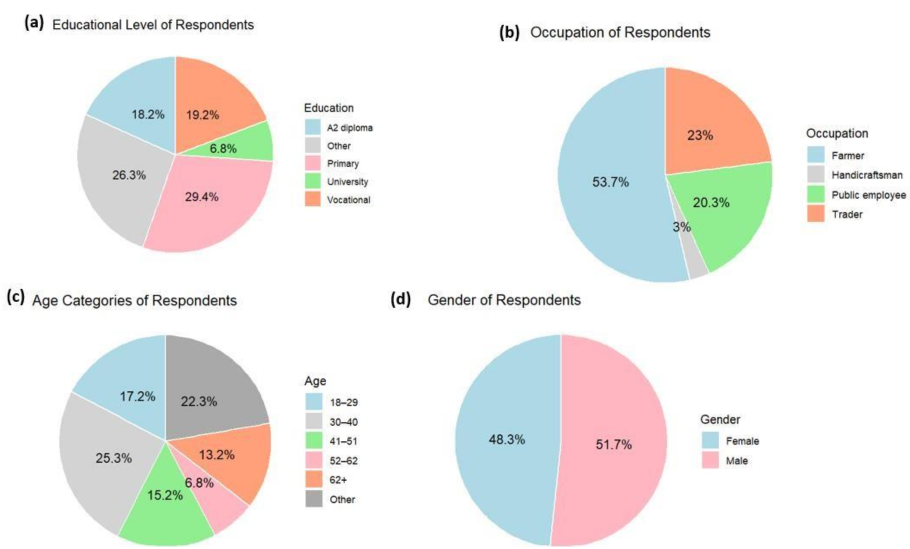

Figure 2. Demographic results of respondents on limiting factors of wild edible mushrooms utilization and conservation, management and conservation measures for wild edible mushrooms in Modo Missa Game Reserve, Democratic Republic of the Congo (DRC).

Diversity indices and distribution of wild edible mushrooms

The analysis of edible mushroom diversity in the Modo-Missa Game Reserve recorded a species richness (S) of 9. The Shannon–Wiener index (H′) was 2.13, indicating moderate diversity. Simpson‟s index (1- D) was 0.875, showing high diversity with low dominance. The evenness value (E) was 0.915, confirming that species were fairly evenly distributed across the reserve. The abundance of wild edible mushroom species varied across the surveyed habitat types (Fig.3). Forest/fallow and forest/woodland habitats supported species such as *Schizophyllum commune* and *Lentinus squarrosulus*, while termite-associated species such as *Termitomyces* spp. were more abundant in savanna woodland and savanna/forest edge habitats. Statistical analysis using Fisher‟s Exact Test indicated no significant association between mushroom species occurrence and habitat type (p =1), suggesting that the distribution of these species was largely independent of habitat in the study area.

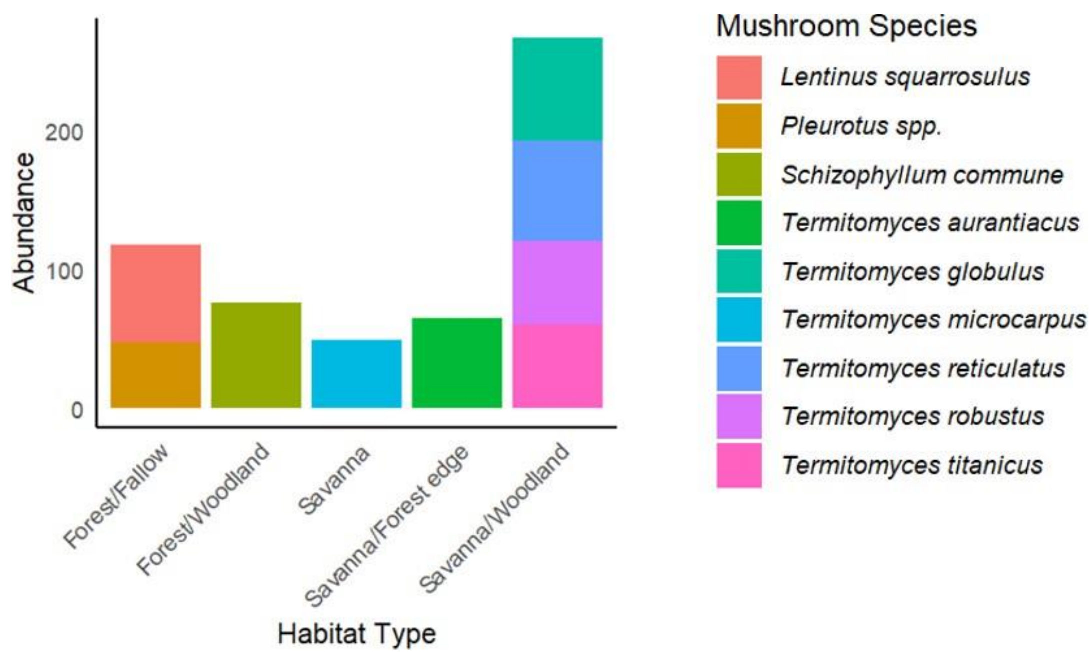

Figure 3. Abundance of wild edible mushroom species across different habitat types in Modo Missa Game Reserve. Species names are shown in the legend, and abundances represent the number of individuals collected per habitat.

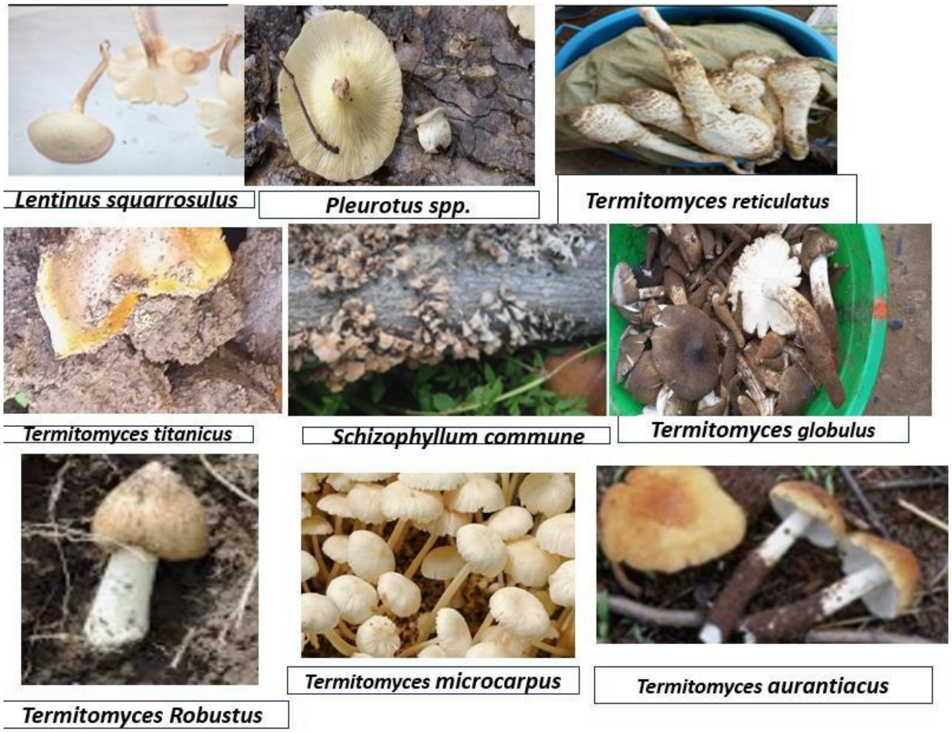

Figure 4. Pictures of wild edible mushroom species identified in Modo Misa Game Reserve, Democratic Republic of Congo (Image taken by Ciceron Redebule, 2023

Limiting factors of wild edible mushrooms utilization and conservation

From the Fig. 5, respondents identified a range of challenges affecting the sustainable use and conservation of wild edible mushrooms. The most frequently cited issues included the use of pesticides and fire in agriculture (7.3%), climate change (6.9%), air and soil pollution (6.5%), low public awareness (6.2%), and insufficient training (6.0%). Additional concerns were inadequate cultivation skills (5.8%), habitat destruction (5.6%), and deforestation (5.4%). Socioeconomic barriers such as poor primary infrastructure (5.1%), insufficient external support from government or private sector (4.9%), limited market access (4.7%), and limited capital (4.5%) were also noted. Less commonly mentioned were ignorance of mushroom importance (4.2%) and the availability of alternative protein sources such as meat and fish (4.0%).

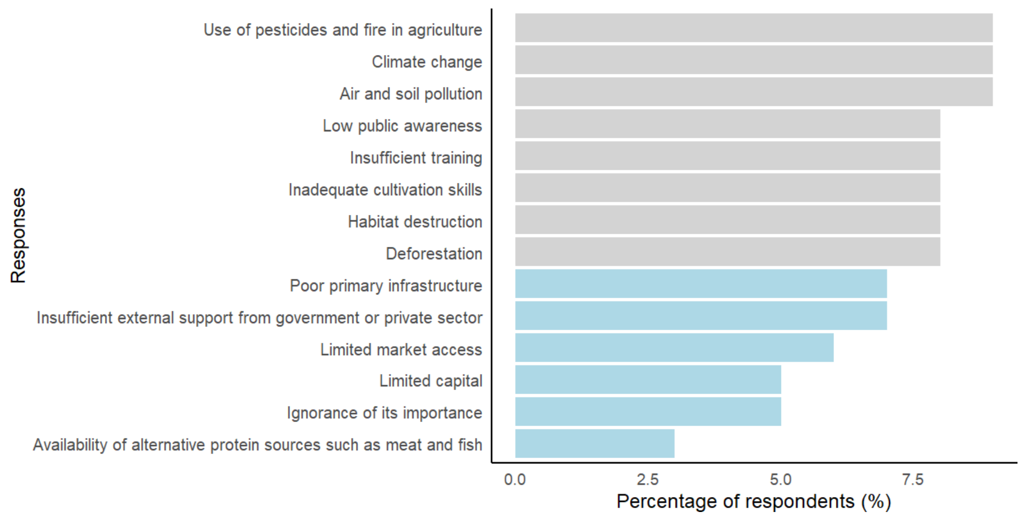

Figure 5. Socioeconomic and environmental constraints affecting the use and conservation of wild edible mushrooms in the Modo Missa Reserve, Democratic Republic of the Congo (DRC).

Relative importance of proposed management and conservation measures

The results on the relative importance of proposed management and conservation measures were summarized in Fig.6. Respondents proposed several measures to enhance the sustainable harvesting and conservation of wild edible mushrooms. The most frequently recommended actions included protection of natural habitats (9.8%), development of a comprehensive list of forest plant species producing edible mushrooms (9.4%), and documentation of animal species that consume mushrooms (9.0%). Other notable suggestions were implementation of controlled harvesting practices (8.7%), creation of an authorized list of edible mushroom species (8.3%), and compilation of poisonous and medicinal mushroom species (8.0%). Additional measures included signposting of illegal mushroom harvesting (7.6%) and bushfires (7.2%), regulation of mushroom spore culture methods (6.9%), formal recognition of mushroom collectors (6.5%), promotion of mushroom cultivation (6.2%), and publication of annual reports on harvested mushrooms (5.9%).

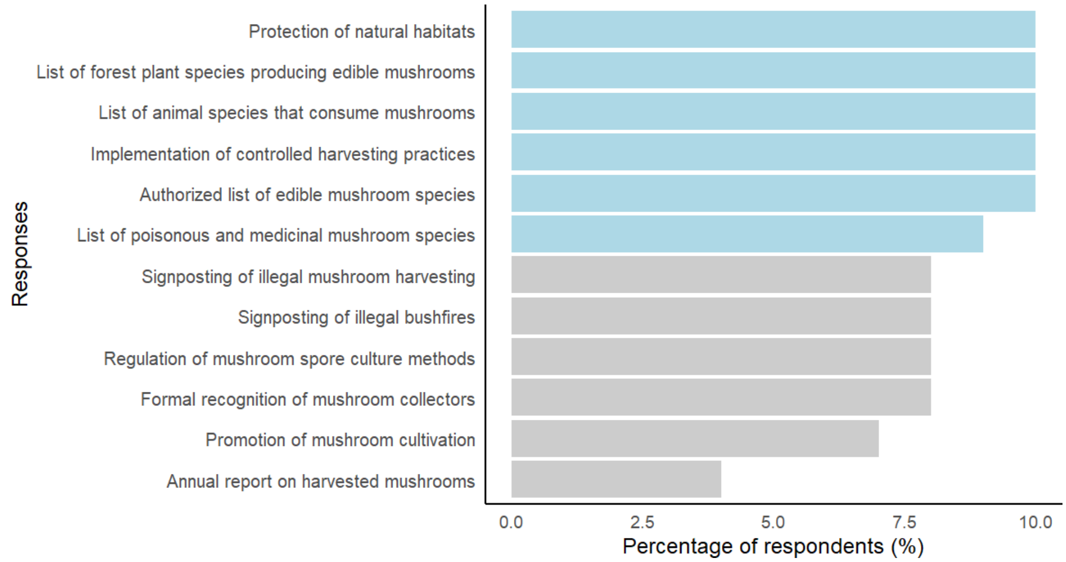

Figure 6. Proposed management and conservation measures for wild edible mushrooms, as perceived by respondents (%) in Modo Missa Game Reserve, Democratic Republic of the Congo (DRC)

DISCUSSION

Socio-demographic profile and its implications for resource engagement

The socio-demographic composition of respondents provides critical insight into the community‟s capacity and orientation toward utilization and conservation of wild edible mushroom in Modo Missa Game Reserve. Drawing parallels with recent findings by Fernandes et al. (2021), who emphasized the role of education and livelihood in shaping environmental attitudes and participation, the present study reveals a predominantly low-education population, with 29.4% having attained only primary education and just 6.8% holding university degrees (Fig. 2). This educational profile may limit access to formal conservation knowledge and restrict engagement with policy frameworks, echoing concerns raised in similar rural contexts (Fernandes et al., 2021).

Occupational data further underscored the community‟s dependence on agriculture, with 53.7% of respondents identifying as farmers. This aligns with the broader pattern observed in southern African community-based natural resources management initiatives, where farming communities are both key stakeholders and primary beneficiaries of sustainable forest resource use (Irakiza et al., 2021). The presence of traders (23%) and public employees (20.3%) suggests a modest diversification of livelihoods, though the marginal representation of handicraftsmen (3%) points to underutilized cultural and artisanal potential. Age distribution was skewed toward economically active groups, particularly those aged 30-40 years (25.3%), followed by younger adults (18-29 years, 17.2%). This demographic structure is favorable for participatory conservation, as younger and middle-aged individuals are more likely to engage in community-based initiatives and adaptive practices. However, the 22.3% classified as "other/unspecified" warrants further scrutiny, as it may obscure vulnerable or disengaged subgroups (Fig.2).

Gender representation was nearly balanced, with males at 51.7% and females at 48.3%, suggesting equitable participation potential (Fig.2). This is particularly relevant given the increasing recognition of gender-inclusive approaches in natural resource governance, as highlighted in recent participatory models(Sitoe and Pinto, 2024). Collectively, these findings suggest that while the community possesses a strong agricultural base and a relatively youthful population, targeted interventions, particularly in education and capacity-building, are essential to enhance effective engagement in sustainable resource management.

Edible wild mushroom diversity and distribution across Modo Missa Game Reserve

The diversity analysis conducted in the Modo Missa Game Reserve revealed a species richness (S) of 9, with a Shannon–Wiener index (H′) of 2.13, indicating moderate diversity. The Simpson‟s index (1-D) of 0.875 suggested high diversity with low dominance, while the evenness value (E = 0.915) confirmed that species were fairly evenly distributed across the reserve. These results are consistent with broader studies of wild edible fungi in Africa, which often report moderate to high diversity and relatively balanced species distributions in forested ecosystems (Sileshi et al., 2023).

Species abundance varied across habitat types. Forest/fallow and forest/woodland habitats supported species such as *Schizophyllum commune* and *Lentinus squarrosulus,* while termite-associated *Termitomyces* spp. were more abundant in savanna woodland and savanna/forest edge habitats (Fig.3 and 4). This ecological partitioning reflects the well-documented association of *Termitomyces* with termite mounds, a relationship observed across Eastern and Central Africa (Mjaika et al., 2023). However, statistical analysis using Fisher‟s Exact Test indicated no significant association between mushroom species occurrence and habitat type (p = 1), suggesting that distribution patterns in Modo Missa may be influenced more by microhabitat conditions and seasonal variability than by broad habitat categories(Sitoe and Pinto, 2024). Across the reviewed studies, there is a strong consensus that the democratic DRC is a global hotspot for indigenous food, particularly wild edible mushrooms, owing to its vast forest ecosystems and high biodiversity. The SADC study by Kazige et al. (2022) highlights that indigenous plant and animal foods, especially edible fungi, play a critical role in food security,

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nutritional security and household income for rural and urban households, yet remain underutilized and weakly integrated into formal food systems in the country.

The survey further highlighted community recognition of mushrooms as naturally occurring resources, with uses ranging from food to medicine. The dominance of *Schizophyllum commune* (13% of identified species) is notable, as this species thrives in humid forest environments on decaying wood (Fig.3). Its prevalence in Modo Missa aligns with findings from Mjaika et al. (2023), who reported widespread occurrence of *Schizophyllum commune* and other edible fungi across the Democratic Republic of Congo. Similarly, Kazige et al. (2022) emphasized the importance of continuous exploration and identification of fungal species across both dry and rainy seasons, underscoring the dynamic nature of mushroom diversity in African landscapes. These results demonstrated that wild edible mushrooms in Modo Missa exhibited moderate diversity, balanced distribution, and habitat-specific abundance patterns. They also strengthened the broader literature that highlights the ecological importance of fungi in forest and savanna systems, while also pointing to the need for sustained monitoring and documentation. Such efforts are critical not only for biodiversity conservation but also for safeguarding the nutritional and medicinal values of these underutilized resources (Sileshi et al., 2023).

The systematic review by Mjaika (2022) provides quantitative evidence of this richness, documents over 377 edible mushroom species in DRC, far exceeding neighbouring countries in Southern and Central Africa. This underscores the DRC"s central role in regional mycological biodiversity. However, the study also reveals fragmented documentation, uneven geographic coverage, and growing threats from habitat loss and overharvesting. A study by Mpunge et al. (2025) focused on the value chain research from the Virunga landscape from demonstrates that

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wild and cultivated mushrooms are important non-timber forest products (NTFPS) supporting livelihoods, particularly for rural communities living adjacent to protected areas. Despite their economic potential, value chains remain informal and poorly coordinated and constrained by limited processing, storage, and market access. Kamalebo et al. (2018) ethnobiological evidence from Tshopo province demonstrated that traditional knowledge strongly governs mushroom identification, harvesting and consumption, with fungi valued for nutrition, medicine and cultural identity. However, this knowledge is rapidly eroding due to generational shifts and a lack of formal documentation. A complementary ecological study in Lake Kivu by Munyaneza (2018) reinforces the importance of riparian and forest ecosystems in sustainable mushroom diversity, emphasizing transboundary conservation relevance between DRC and Rwanda.

Challenges to edible wild mushroom utilization and conservation

The study identified a range of challenges constraining the sustainable utilization and conservation of wild edible mushrooms in Modo Missa. Respondents most frequently cited the use of pesticides and fire in agriculture (7.3%), climate change (6.9%), and air and soil pollution (6.5%) as major threats (Fig.5). These findings are consistent with broader evidence that anthropogenic pressures, particularly unsustainable farming practices and climate variability, are key drivers of biodiversity loss in fungal communities (Sileshi et al., 2023). Low public awareness (6.2%) and insufficient training (6.0%) further limit community capacity to engage in sustainable harvesting, while inadequate cultivation skills (5.8%), habitat destruction (5.6%), and deforestation (5.4%) highlight ecological vulnerabilities. Socioeconomic barriers, including poor infrastructure (5.1%), limited external support (4.9%), restricted market access (4.7%), and lack of capital (4.5%), mirror structural constraints observed in other rural contexts where wild foods remain undervalued despite their nutritional and economic potential. Less frequently mentioned

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factors, such as ignorance of mushroom importance (4.2%) and reliance on alternative protein sources (4.0%), underscore cultural and dietary dynamics that may reduce mushroom utilization (Foyet, 2024).

Proposed conservation strategies for edible wild mushrooms

In response to these limitations, respondents proposed a suite of conservation measures. The most frequently recommended actions included protection of natural habitats (9.8%), development of comprehensive lists of forest plant species producing edible mushrooms (9.4%), and documentation of animal species that consume mushrooms (9.0%) (Fig.6). These strategies align with findings by Gorenflo and Romaine (2021) and, Sitoe and Pinto (2024), who emphasized the broader health benefits of forests and the importance of mitigating human–wildlife conflicts to safeguard natural resources. Other notable measures such as controlled harvesting (8.7%), authorized lists of edible species (8.3%), and compilation of poisonous and medicinal mushrooms (8.0%), reflect community awareness of both ecological and health dimensions. Additional proposals, including signposting illegal harvesting and bushfires, regulating spore culture methods, and formally recognizing mushroom collectors, highlight the need for institutional support and governance frameworks (Mjaika, 2022; Sitoe and Pinto, 2024; Bhati, 2025).

An apparent lack of knowledge about mushroom cultivation necessitates prioritizing in-situ conservation while gradually introducing ex-situ techniques. This gap underscores the importance of community engagement and education initiatives, particularly in regions where research remains limited. Similar calls have been made in India and Central Africa, where participatory approaches have proven effective in enhancing conservation outcomes (Mjaika,

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2022). Legal frameworks, such as Law No. 14 of the DRC National Constitution, reinforce the need for structured governance to restrict unauthorized access to protected areas and ensure biodiversity documentation. Expanding on these findings, comprehensive conservation strategies must encompass environmental protection, community engagement, and education initiatives. Efforts to mitigate pollution, address climate change impacts, and promote sustainable agricultural practices are crucial for conserving mushroom habitats (Hickisch et al., 2019; MJAIKA, 2021; Gorenflo and Romaine, 2021). Moreover, raising awareness among local communities about the ecological significance of mushrooms and their role in biodiversity conservation is essential for fostering long-term stewardship of natural resources (Crosier et al., 2025).

CONCLUSION AND RECOMMENDATIONS

This study in the Modo Missa Reserve, the area surrounding Garamba National Park, highlighted the complexity of conserving wild edible mushrooms and the intricate links between environmental factors, human activities, and biodiversity. The findings demonstrate that air and soil pollution, climate change impacts, deforestation, and insufficient institutional support are major threats to mushroom habitats.

Limited community knowledge of mushroom cultivation, rooted in historical neglect of research and awareness initiatives, has reinforced the perception that mushrooms naturally thrive without human intervention. Despite these challenges, local communities recognize the importance of protecting wild habitats and have expressed interest in mushroom farming as a strategy to conserve wild species while enhancing food security.

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The socio-demographic profile of respondents offers further insight into the community‟s capacity for resource engagement. With most respondents having only primary education and a heavy reliance on agriculture, the community‟s knowledge base and livelihood focus influence both opportunities and challenges for mushroom conservation. The youthful age structure and nearly balanced gender ratio suggest potential for inclusive participation in conservation initiatives, while limited higher education highlights the need for targeted capacity development. These demographic realities emphasize that effective conservation strategies must be adapted to local contexts, incorporating education, livelihood diversification, and gender-sensitive approaches to boost engagement. Moderate species richness, high diversity, and a balanced distribution of wild edible mushrooms across Modo Missa were observed. Habitat-specific abundance patterns, such as the prevalence of *Schizophyllum commune* in forest environments and *Termitomyces* spp. in savannah habitats, reflect ecological partitioning consistent with broader African studies. These findings underline the ecological significance of fungi in forest and savannah systems and highlight the necessity for ongoing monitoring to protect their nutritional and medicinal values.

Drawing from these insights, several targeted actions are recommended. First, awareness campaigns should be launched to educate communities about the nutritional and economic benefits of mushroom cultivation, emphasizing its potential to provide year-round food and create employment opportunities. Second, training programs are needed to equip local communities with practical skills in cultivation techniques and sustainable harvesting practices. Third, comprehensive studies should be conducted to document mushroom biodiversity, inform conservation policies, and guide both in-situ and ex-situ conservation strategies. Such studies

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should account for seasonal fluctuations in mushroom availability, requiring extended study durations to capture reliable ecological data.

Finally, collaborative efforts among policymakers, conservation managers, NGOs, enterprises, and scientists are essential to integrate community-driven initiatives with formal conservation frameworks. By combining education, livelihood diversification, and scientific research, stakeholders can foster sustainable mushroom utilization, strengthen local resilience, and contribute to biodiversity conservation. This holistic approach aligns with broader goals of environmental stewardship and socio-economic development, ensuring that edible mushrooms remain available for future generations while supporting the well-being of communities dependent on natural resources in and around Garamba National Park.

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INTRODUCED ORNAMENTAL PLANTS: DIVERSITY AND INVASION RISK IN ADDIS ABABA AND BISHOFTU, ETHIOPIA

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ABSTRACT: Invasive Alien Plant Species (IAPSs) pose serious threats to biodiversity and economies. Ornamental horticulture has been a major pathway for the of IAPSs introduction in Ethiopia. Despite this, limited attention has been given to the diversity and invasiveness potential of introduced ornamental plants in urban areas. Hence, this research aimed to study the diversity and potential invasiveness of introduced ornamental plant species in selected nursery sites of Addis Ababa and Bishoftu. An inventory survey was conducted across seven nursery sites, documenting 149 plant species representing 127 genera and 52 families. Of the total recorded species, 38 (25.5%) were identified as naturalized and Invasive Alien plant species. In addition, 26.77% of the documented genera and 36.54% of the recorded families contained invasive alien representatives. A one-way ANOVA, followed by Tukey's Honestly Significant Difference (HSD) test, was used to analyze the effects of introduced ornamental plant species (measured by percentage area coverage) on the richness of Invasive Alien Plant Species (IAPS). The analysis revealed a significant positive relationship, indicating that many introduced ornamentals possess considerable invasiveness potential within the study area. These findings highlight ornamental horticulture as a critical pathway for the introduction and spread of alien plant species. Consequently, raising public awareness about the origins and purposes of ornamental plant introductions, together with the implementation of effective biosecurity measures and management strategies, is essential to mitigate future threats to regional biodiversity.

Key words/phrases: Horticulture, Introductions, Invasive Alien Plant Species, Nursery Sites

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INTRODUCTION

The introduction of non-native plant species has become a major global concern, as many of these species have the potential to become invasive and disrupt native ecosystems (Allendorf and Lundquist, 2003). Ornamental plants, in particular, hold a significant share of introduced species, as they are often traded and planted for their aesthetic appeal (Virtue *et al*., 2008). The ornamental horticulture industry, which encompasses cultivation, production, and trade of flowers, ornamental plants, and landscaping products, is responsible for the introduction, propagation, and transport of thousands of nonnative plant species worldwide. While a majority of these introduced plant species remain confined to their intended locations or spread without causing significant environmental damage, some have proven to be remarkably invasive and pose a serious threat to native ecosystems (Pheloung *et al*., 1999; Niemiera and Holle, 2009).

The introduction of ornamental plants from distant lands has undoubtedly enriched our horticultural landscape. Species like tulips from Turkey, roses from China, and dahlias from Mexico have become integral parts of our gardens, adding a touch of exotic beauty to our surroundings (Gessert, 2010). However, the introduction of ornamental plants has also introduced a hidden threat: the potential for becoming invasive alien species (IAS). IASs are non-native species that have been introduced into a new environment and have the ability to spread aggressively, causing harm to native ecosystems and human livelihoods (Mooney *et al*., 2005). In other words, IAS are among today's most daunting environmental threats, costing billions of dollars in economic damages and wreaking havoc on ecosystems around the world.

Lantana camara L.is a prime example of an invasive alien species that was originally introduced for ornamental purposes worldwide but has since spread aggressively into natural ecosystems, causing significant ecological damage (Boy and Witt, 2013). Its ability to thrive in a variety of habitats, coupled with its prolific seed production and tolerance to various environmental conditions, has made it a challenging invader in many parts of the world. The species is a significant weed of which there are some 650 varieties in over 60 countries (GISD, 2023a). Similarly, *Eichhornia crassipes* (Mart.) Solms (water hyacinth), introduced as an aquatic ornamental plant, has become a formidable invader of waterways, choking rivers and lakes, and disrupting aquatic ecosystems in Ethiopia and elsewhere in the world (Rezene, 2005). Originally from South America, *E. crassipes* is one of the worst aquatic weeds in the world. It's beautiful, large purple and violet flowers make it a popular ornamental plant for ponds. It is now found in more than 50 countries on five continents (GISD, 2023b). Another example is the *Parthenium hysterophorus L.*(congress grass), native to tropical America. Introduced as an ornamental plant elsewhere, it has since become a notorious IAS, infesting vast tracts of land and causing significant economic losses in agriculture and livestock production. The species has been introduced into Ethiopia with contaminated cereal grain in the 1970's (Taye, 2002; Taye *et al*., 2004; GISD, 2023c ;).

Invasive alien species (IAS) rank among the primary direct drivers of biodiversity loss. The detrimental effects of IAS on biodiversity stem from their competition with native species for resources, and introduction of pathogens. Additionally, they alter the composition and structure of ecosystems, diminishing the services these ecosystems provide. Beyond their environmental impact, IAS poses a threat to food security, human health, and economic activities.

The global trade in ornamental plants has inadvertently facilitated the introduction and spread of IAS into new environments. These non-native plants, often introduced for their aesthetic appeal, pose a significant threat to native biodiversity, ecosystem function, and economic productivity. Understanding the pathways, drivers and invasiveness of plants introduced through the ornamental plant trade is crucial for developing effective prevention and control strategies. Various studies have been conducted in Ethiopia on the distribution, impact and controlling and management methods of IAS (e.g.Shiferaw *et al*., 2004; Berhanu and Tesfaye, 2006; Shiferaw *et al*., 2021).

However, existing research on IAS in Ethiopia has focused on well-established and problematic species that already pose significant threats to the environment, biodiversity, and livelihoods. Accordingly, there is a lack of research on the potential invasiveness of newly introduced ornamental plants, which may eventually become serious invaders in the future. Therefore, the objective of this study was to identify potential invasive species among the introduced ornamental plant species in Addis Ababa, Bishoftu and surrounding areas. Consequently, we tested the hypothesis that a significant number of introduced ornamental plants have invasiveness potential in Ethiopia.

Materials and methods

Study Area

The study was conducted in Addis Ababa, the capital city of Ethiopia, and Bishoftu where the majority of ornamental plants are introduced, reproduced and distributed to users. Bishoftu Town, which is about 45kms south of Addis Ababa, is a major supplier of introduced and reproduced ornamental plants. Generally, seven study sites (five in Addis Ababa and two in Bishoftu) were purposely selected and investigated (Fig.1).

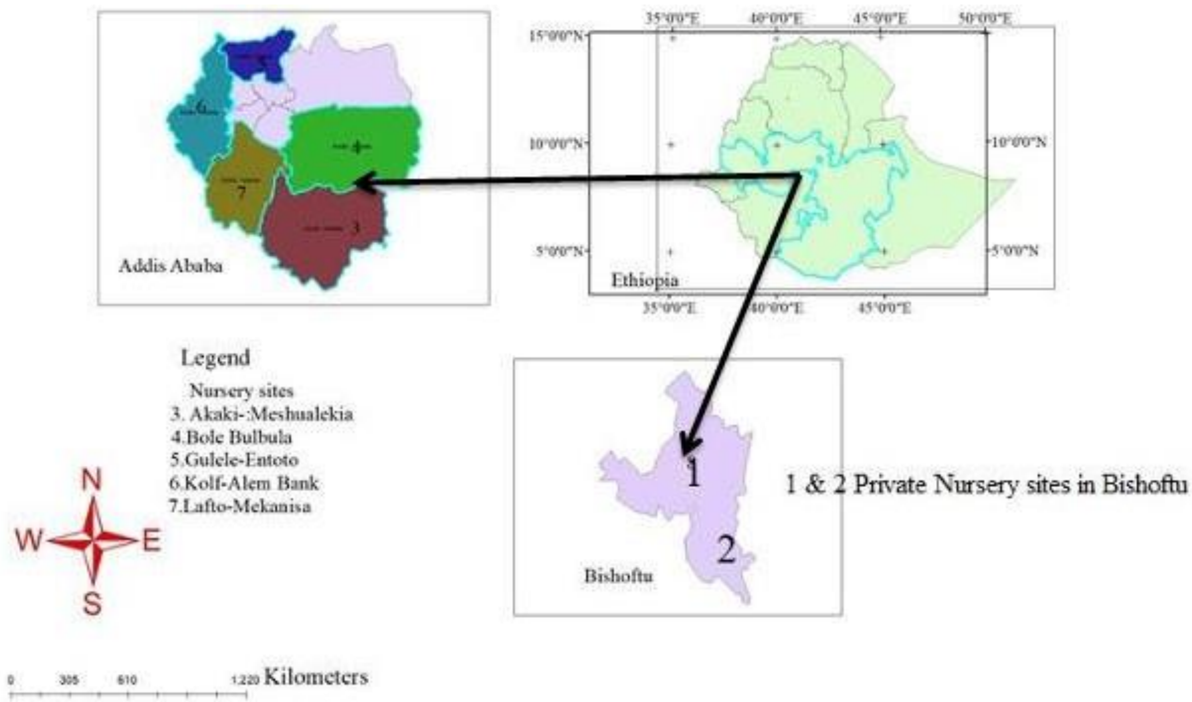

Figure 1. Map of Ethiopia showing the study sites (Addis Ababa and Bishoftu)

Data Collection

A detailed review of bibliography and online botanical databases was conducted prior to an extensive fieldwork and botanical identification. Direct field observations were combined with data obtained from the questionnaire survey with the local residents to identify introduction pathways and invasion history. Surveys in national databases and queries to global databases were conducted to determine the invasive alien ornamental plants.

An inventory of ornamental plant species was conducted in five and two nursery sites of Addis Ababa and Bishoftu, respectively. Systematic field surveys were conducted in the specified study sites to detect the presence of invasive alien ornamental plant species. Data on species name, genus, family, habit, use and impacts were collected. Photographs of each species in its current state were taken and archived.

A thorough review of scientific literature and comparative searches of online IAS databases such as Global Invasive Species Database (http://www.iucngisd.org/gisd) and CABI Compendium (https://www.cabidigitallibrary.org/journal/cabicompendium) was also conducted to gather information on introduced ornamental plant species in the study area and elsewhere.

Data on top five species of their weed history in other countries such as countries of origin and countries of introduction, impacts and pathways for the spread of propagules (dispersal mechanisms) were investigated based on established IAS databases and literature surveys.

Data Analysis

Established Weed Risk Assessment tools elsewhere such as the Weed Risk Assessment Protocol (WRAP) (Pheloung *et al*., 1999; Virtue *et al*., 2008; Conser *et al*., 2015) was used to evaluate the invasiveness potential of each introduced ornamental plant species. Data was analyzed using spreadsheet programs to prioritize potentially invasive alien species and identify patterns and relationships between ornamental plant introduction, invasion success, and potential ecological impacts.

For the constraints, specifically, the percentages (area coverage) of introduced ornamental plant species, the collected data were analyzed via a one-way Analysis of Variance (ANOVA) to test for statistically significant differences in the mean richness of Invasive Alien Plant Species (IAPS). Where the ANOVA indicated significant effects, post-hoc pairwise comparisons of treatment means were conducted using Tukey’s Honestly Significant Difference (HSD) test at a 5% significance level ($\alpha = 0.05$). This analysis identified which specific introduced ornamental plant species coverage/ percentage groups (0–25%, 26–50%, 51–75%, and 76–100%) differed significantly from one another.

Plant identification

Plants were identified onsite using plant identification tools, namely Pl@ntNet (Goëau *et al.*, 2014) using Northeast Tropical Africa and World Flora databases and at the National Herbarium (ETH). Plant specimens were collected, pressed and deposited at the Ethiopian Biodiversity Institute Herbarium. Accuracy of 70% and above of the Pl@ntNet identification tool were regarded as correct scientific names of the species (https://powo.science.kew.org/)

RESULTS

Richness of Introduced Ornamental Plant Species

A total of 149 plant species were identified in the study areas (Appendix 1). From the total identified plant species, 38 of them were naturalized and Invasive Alien Plant Species (IAPS) according to the Global Invasive Species Database (GISD); whereas 111 were non-invasive plant species. Regarding the reason for introduction of the identified IAPS, from the total identified IAPS, 31 (81.58%) of them were introduced primarily for ornamental purposes.

Other uses include medicine, timber, hedge, bee forage, fodder, nitrogen fixation, soil conservation, etc.; whereas seven species (18.42%) were introduced accidentally as a contaminant/weeds (*Alternanthera pungens* Kunt, *Argemone ochroleuca* Sweet, *Bidens pilosa* L, *Cuscuta campestris* Yunck and *Galinsoga parviflora* Flora Cav.) and two species (5.27%) were introduced for restoration and erosion control (*Acacia saligna* (Labill.) H.L.Wendl) and as edible fruit *(Psidium guajava* L.) (Table 1). *Lantana camara* is the most dominant and notorious IAS in the nursery sites and in most parts of the country.

Table 1. Lists of identified naturalized and IAPS during the investigation including reasons for their introduction and origin based on GISD and other sources (mentioned in the table below)

	Scientific name	Families	Reason for introduction	Origin/native to	Source
1.	*Acacia saligna* (Labill.) Wendl	Fabaceae	For restoration and erosion	Southwestern and Western Australia	(Witt and Luke, 2017).
2.	*Agave americana* L.	Agavaceae	For its fiber and ornamental	Mexico and southern USA	(Witt and Luke,2017)
3.	*Ageratum conyzoides* L.	Asteraceae	Accidentally as a contaminant/weed and ornament	Central and South America and West Indies.	(Witt and Luke,2017)
4.	*Ageratum houstonianum* Mill.	Asteraceae	Accidentally as a contaminant/weed and ornament	Central and South America and West Indies	(Witt and Luke,2017)
5.	*Alternanthera pungens* Kunth.	Amaranthaceae	Accidentally as a contaminant/weed	Tropical America	(Kuma *et al.*,2021)
6.	*Argemone ochroleuca* Sweet	Papaveraceae	Accidentally as a contaminant	Mexico and West Indies	(Witt and Luke ,2017)
7.	*Azadirachta indica* A.Juss.	Meliaceae	For restoration and ornament.	Bangladesh, India, Malaysia and Myanmar	(Witt and Luke, 2017).
8.	*Bidens pilosa* L.	Asteraceae	Accidentally as a contaminant/weed	Tropical America, specifically Mexico, central America, the Caribbean and parts of south America	(Mekonnen *et al*.,2018)
9.	*Caesalpinia decapetala*(Roth) Alston	Fabaceae	For bee forage and ornament.	Tropical and subtropical Asia.	(Witt and Luke, 2017).
10.	*Casuarina cunninghamiana* Miq.	Casuarinaceae	For timber and ornament	Australia.	(Witt and Luke,2017)
11.	*Casuarina equisetifolia* L.	Casuarinaceae	For timber and ornament.	Australia	(Witt and Luke, 2017).
12.	*Catharanthus roseus (L.) G. Don*	Apocynaceae	For medicine and ornament	Madagascar	(Witt and Luke, 2017).
13.	*Cuscuta campestris* Yunck.	Convolvulacee	Accidentally as a contaminant /weed	Bahamas, Canada, Cuba, Guadeloupe, Jamaica, Martinique, Mexico and USA.	(Witt and Luke, 2017).
14.	*Datura stramonium* L.	Solanaceae	Ornament and accidentally as a contaminant	Tropical North America	(Witt and Luke, 2017).
15.	*Delonix regia* (Hook.) Raf.	Fabaceae	Ornamental	Madagascar.	(Witt and Luke, 2017).
16.	*Dovyalis caffra* (Hook.f. & Harv.) Sim	Salicaceae	Hedge and ornament.	Mozambique, South Africa, Swaziland and Zimbabwe	(Witt and Luke, 2017).
17.	*Duranta erecta* L.	Verbenaceae	Hedge/barrier and ornament.	Tropical America, Mexico, the Caribbean, enteral and south America	(Witt and Luke, 2017).

18.	*Galinsoga parviflora Cav.*	Asteraceae	as a contaminant /weed	South America	(Mekonnen *et al.*,2018)
19.	*Grevillea robusta* A. Cunn. ex R. Br.	Proteaceae	Timber, bee forage, and ornament	Australia	(Witt and Luke, 2017).
20.	*Helianthus annuus* L.	Asteraceae	Accidentally as a contaminant.	Mexico and USA.	(Witt and Luke,2017)
21.	*Ipomoea purpurea* (L.) Roth	Convolvulaceae	Ornament	South America and Mexico	(Witt and Luke,2017)
22.	*Jacaranda mimosifolia* D. Don	Bignoniaceae	Timber, shade and ornament	Argentina and Bolivia	(Witt and Luke,2017)
23.	*Lantana camara* L.	Verbenaceae	Hedging/barrier and ornament	Colombia, Costa Rica, Cuba,Jamaica, Mexico and Venezuela	(Witt and Luke, 2017).
24.	*Leucaena leucocephala* (Lam.) de Wit	Fabaceae	Fodder, nitrogen fixation, soil conservation, and ornament	Belize, Guatemala and Mexico	(Witt and Luke, 2017).
25.	*Melia azedarach* L.	Meliacea	Timber, medicine, shade and Ornament.	Australia, China, India, Indonesia, Japan, and Sri Lanka.	(Witt and Luke, 2017).
26.	*Mimosa pigra* L.	Fabaceae	Nitrogen fixation, medicine, hedge and ornament.	Tropical America ,Mexico, northern Argentina and central America	(Witt and Luke,2017)
27	*Mirabilis jalapa* L.	Nyctaginaceae	Ornament	Peru	(Witt and Luke,2017)
28.	*Nicotiana glauca* Graham	Solanaceae	Medicine, insecticide and ornament	Argentina, Brazil, Bolivia, Chile, Ecuador, Paraguay, Peru and Uruguay	(Witt and Luke, 2017).
29.	*Parkinsonia aculeata* L.	Fabaceae	Hedge. shade and ornament	Argentina, Bolivia, Galápagos Islands, Paraguay, Peru and Uruguay.	(Witt and Luke, 2017).
30.	*Parthenium hysterophorus* L.	Asteraceae	Medicine, ornament and accidentally as a contaminant/weed	Argentina, Bolivia, Cuba, Guatemala, Haiti, Jamaica, Mexico, Paraguay, Uruguay, Venezuela and Virgin Islands.	(Witt and Luke, 2017).
31.	*Pinus patula Schiede* ex Schltdl. & Cham.	Pinaceae	Timber, paper, pulp production and ornament	Mexico	(Witt and Luke,2017)
32.	*Psidium guajava* L.	Myrtaceae	Edible fruit.	Argentina, Bolivia, Brazil, Colombia, Ecuador, Mexico, Paraguay, Peru, Venezuela and the Caribbean.	(Witt and Luke,2017)
33.	*Ricinus communis* L.	Euphorbiaceae	Castor oil and ornament	Uncertain; from multiple Sources of introduction.	(Witt and Luke,2017
34.	*Salvia coccinea* Buc'hoz ex Etl.	Lamiaceae	Ornament.	Brazil, Colombia, El Salvador, Guatemala, Mexico,	(Witt and Luke, 2017).

				Peru, southeastern USA ,and Caribbean	
35.	*Salvia leucantha* Cav.	Lamiaceae	Ornament.	Mexico and possibly elsewhere in Central America	(Witt and Luke, 2017).
36.	*Salvia tiliifolia* Vahl.	Lamiaceae	Accidentally as a contaminant and as ornamental plant	Mesoamerica (Mexico, central America and northern south America)	(Friis,2006)
37.	*Senna didymobotrya (Fresen.)* H.S. Irwin & Barneby	Fabaceae	introduced elsewhere for medicine and Ornament	Tropical Africa	(Witt and Luke,2017)
38.	*Verbesina encelioides*(Cav.) Benth. & Hook. f.	Asteraceae	Ornament and accidentally as a contaminant/weed	Mexico and USA.	(Witt and Luke, 2017).

The highest plant species richness was recorded in Entoto and Denbi nursery sites (richness = 37), followed by Bole Bulbula (richness = 35) and Akaki-Meshualekia nursery sites (Richness = 30). Conversely, the smallest plant species richness was documented in Mekanisa (Richness = 22) followed by Alem Bank nursery sites (richness = 24). The outcomes of this study also revealed significant variations in the richness of IAPS across different nursery sites. The highest IAPS richness was recorded in Entoto nursery site (richness = 19), followed by Denbi (richness = 16). Conversely, the smallest IAPS richness was documented in Mekanisa nursery site (Richness = 7) followed by Gadiku areas (richness = 8) (Fig 2).

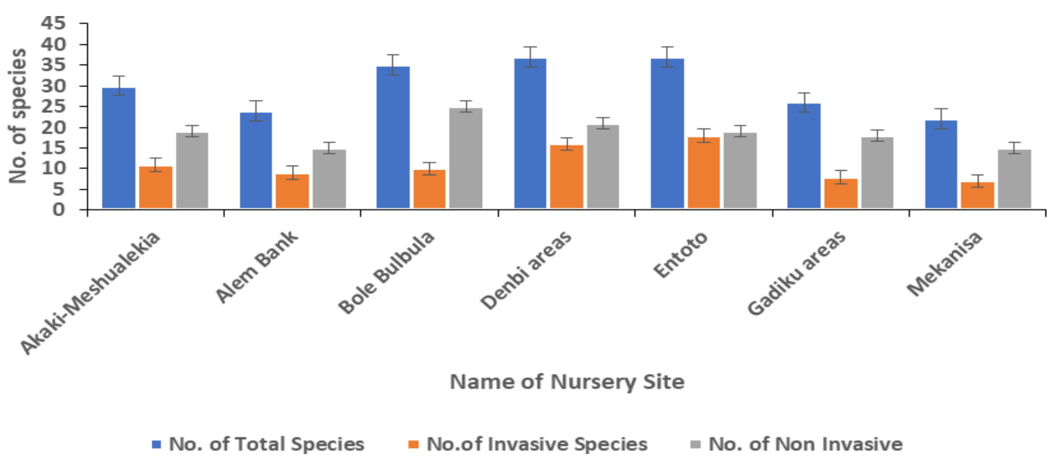

Figure 2. Number of invasive alien and non-invasive plant species in each nursery site

Plant species composition

A total of 149 plant species belonging to 127 genera and 52 families were documented from the study areas (Fig.3). From the total identified plant species, 38 (25.5%) of them were IAPS. Besides, from the total identified genera, 26.77% of them were IAPS. Regarding the families identified during the study, 36.54% of them were IAPS (Table 2).

Table 2. Proportion of IAOPS and invasive alien weeds species, genus and families to all identified plant species during the study

	Taxonomic unit	Proportion of IAS to all (%)
1.	Species	25.5
2.	Genus	26.77
3.	Family	36.54

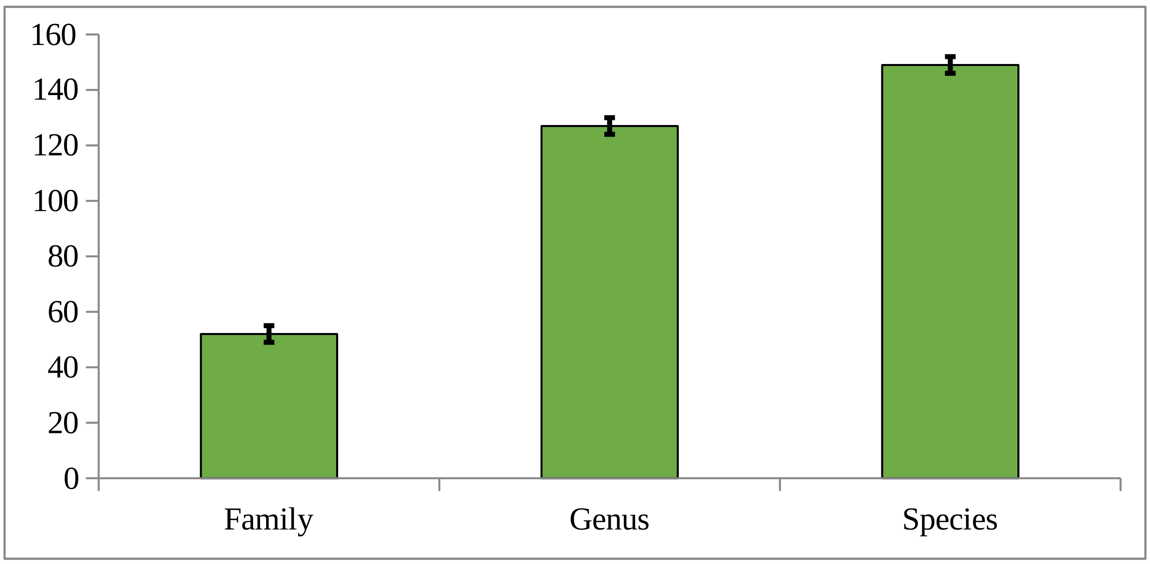

Figure 3. Total number of family, genus and species of the identified plant species

Moreover, a total of 38 IAPS belonging to 34 genera and 19 families (Fig. 4) and 111 non-invasive plant species belonging to 43 families were identified (Appendix 1)

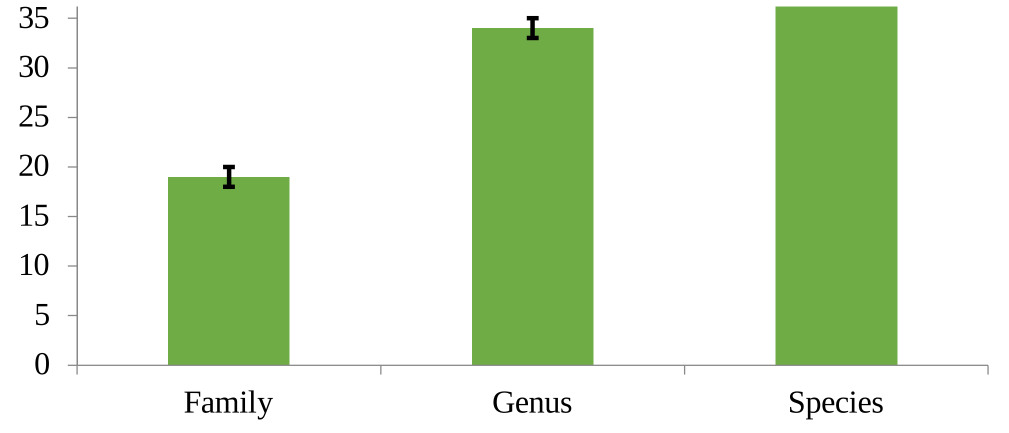

Figure 4. Total number of family, genus and species of the identified IAPS

The most dominant IAPS belong to the families Asteraceae and Fabaceae, where each family contributed seven species (18.42%); followed by Lamiaceae, which contributed three species (7.89%) (Fig. 5).

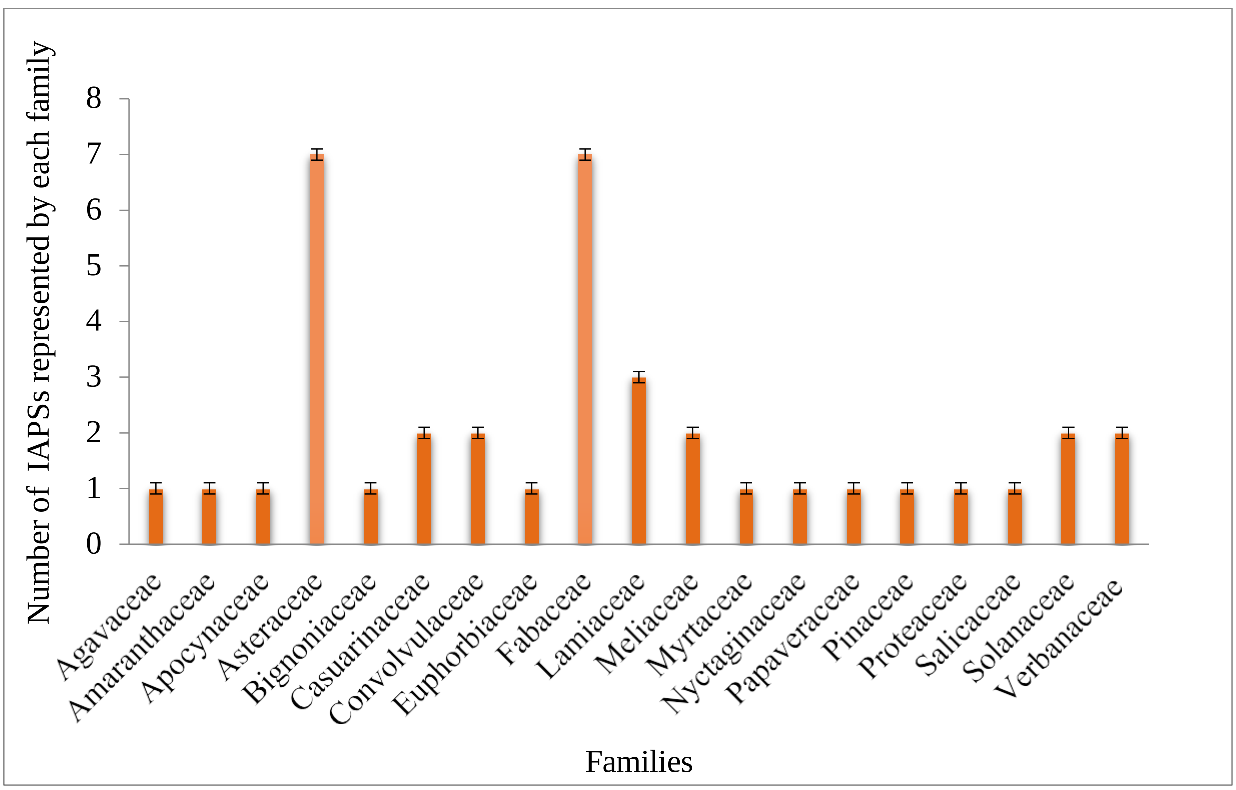

Figure 5. Number of Invasive Alien Plant Species in each Family

Habit Distribution of Invasive Alien Plant species (IAPS)

The composition in habit of IAPS showed that the identified species were herbs, shrubs, trees and liana. The majority of the species were herbs followed by shrubs in most of the nursery sites (Fig. 6).

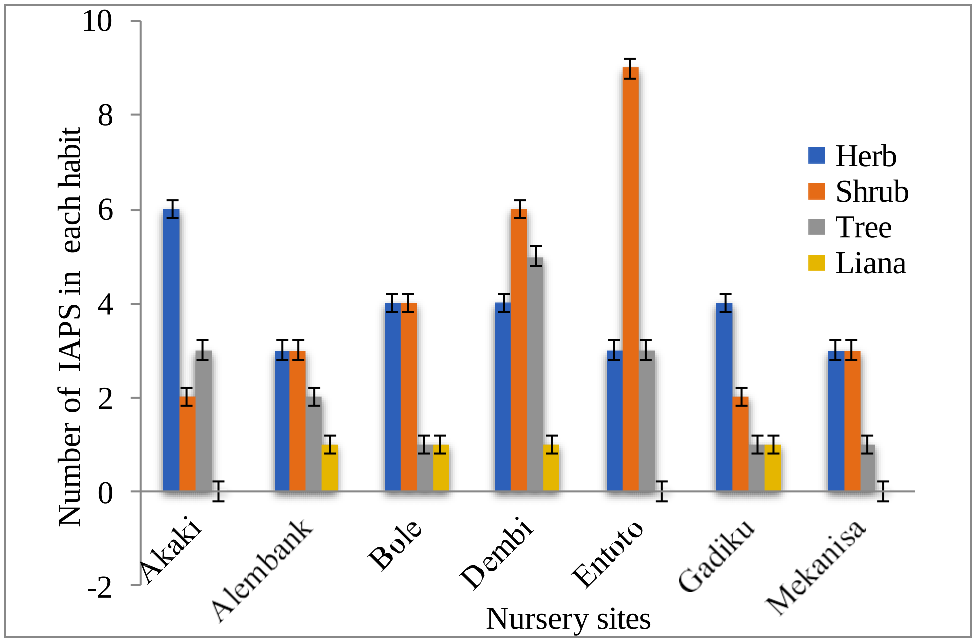

Figure 6. The composition in habit of IAPS in the study areas

Moreover, the composition in habit of all plant species, the majority of the species were herbs followed by shrubs in the study areas (Fig. 7).

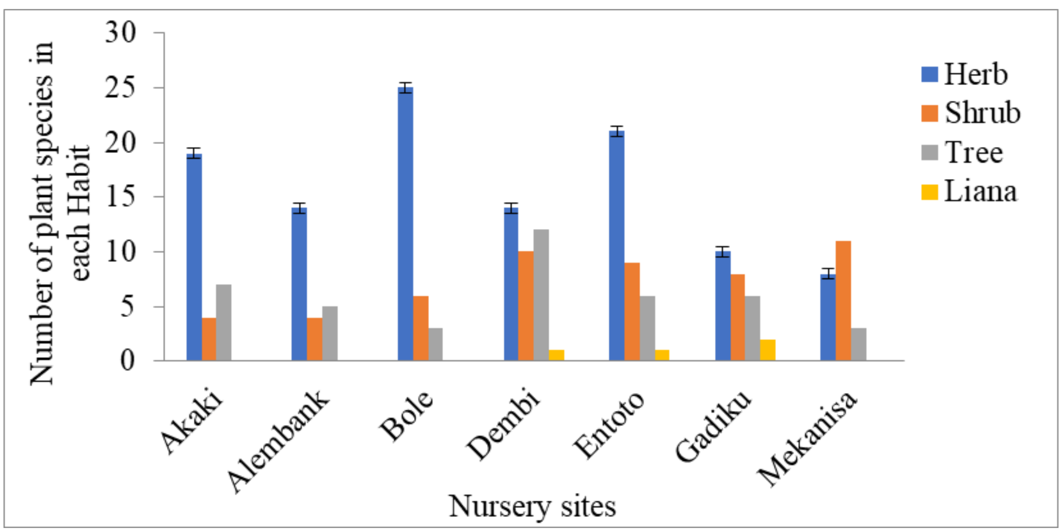

Figure 7. The composition in habit of all plant species in the study areas

Potential and actual uses of Invasive Alien Plant Species (IAPS)

The majority (81.58%) of the identified Invasive Alien Plant Species (IAPS) were used as ornamental plants and other multipurpose uses such as construction, soil conservation, fencing, shade, firewood, afforestation, oil production, etc. On the other hand, 13.15% of them were invasive alien weeds with no other known uses and 5.27% were used as soil conservation and afforestation purposes (e.g. *Acacia saligna)* and edible fruit (e.g. *Psidium guajava*).

One-Way Analysis of Variance on Percentage of Introduced Ornamental Plant Species versus Richness of Invasive Alien Plant Species (IAPS)

The findings of the study demonstrated a positive correlation between the percentage of introduced ornamental plant species and the richness of Invasive Alien Plant Species (IAPSs) (Fig.8). In general, IAPS richness increased concomitantly with greater land area coverage by introduced ornamental plants. Consequently, the highest mean IAPS richness was recorded in the maximum coverage category (76–100%), with a value of 22 ± 2.47. This was followed by the 51–75% coverage category, which exhibited a mean richness of 16.29 ≈ 16. In contrast, the lowest mean IAPS richness was observed in the lowest coverage category (0–25%), with a value of 6.67 ≈ 7 ± 1.59.Thus, compared to the high-coverage areas (76–100%), the mean IAPS richness in low-coverage areas (0–25%) was reduced by 68.18% (Table 3). These results indicated that introduced ornamental plant species possess a high potential for facilitating invasiveness.

Table 3. Invasiveness Potential of Introduced Ornamental Plant Species

Percentage(coverage) of introduced ornamental plant Species	N	Mean number of IAPSs	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
0-25%	21	6.67	1.592	0.347	5.94	7.39
26-50%	21	11.81	1.990	0.434	10.90	12.72

51-75%		21	16.29	1.793	0.391	15.47	17.10
76-100%		21	22.00	2.470	0.539	20.88	23.12
Total		84	14.19	6.009	0.656	12.89	15.49
Model	Fixed Effects			1.988	0.217	13.76	14.62
	Random Effects				3.262	3.81	24.57

The analysis demonstrated statistically significant differences in the mean richness of Invasive Alien Plant Species (IAPS) across the gradient of area coverage by introduced ornamental plants. The highest mean IAPS richness was associated with the greatest coverage level (76–100%). A one-way Analysis of Variance (ANOVA) confirmed that IAPS richness varied significantly among the different percentage coverage categories (Table 4).

Table 4. One-way ANOVA on the number of IAPSs across the given Percentage (coverage) of Ornamental Plant Species

	df	Mean Square	F	Sig.
Between Groups	3	893.587	226.088	0.000
Within Groups	80	3.952		
Total	83			

Based on a one-way Analysis of Variance (ANOVA), significant variation was observed in Invasive Alien Plant Species (IAPS) richness across the gradient of introduced ornamental plant species coverage. Subsequent post-hoc analysis using Tukey’s Honestly Significant Difference (HSD) Test confirmed that the percentage of area coverage (0–25%, 26–50%, 51–75%, and 76–100%) exerted a statistically significant impact on IAPS richness. Consequently, pairwise comparisons revealed that IAPS richness differed significantly ($p \leq 0.0001$) between all four coverage categories. These results demonstrate that IAPS richness is highly dependent upon the extent of introduced ornamental plant coverage, with a pronounced increase in IAPS diversity corresponding to progression from low to high percentage coverage (Table 5).

Table 5. Tukey's Honestly Significant Difference (HSD) Test to compare the variation in the Richness of IAPS among the various percentage (coverage) of introduced ornamental plant species

(I)Percentage of introduced ornamental plant species	(J)Percentage of introduced ornamental plant species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
0-25%	26-50%	-5.143*	0.614	0.000	-6.75	-3.53
	51-75%	-9.619*	0.614	0.000	-11.23	-8.01
	76-100%	-15.333*	0.614	0.000	-16.94	-13.72
26-50%	0-25%	5.143*	0.614	0.000	3.53	6.75
	51-75%	-4.476*	0.614	0.000	-6.09	-2.87
	76-100%	-10.190*	0.614	0.000	-11.80	-8.58
51-75%	0-25%	9.619*	0.614	0.000	8.01	11.23
	26-50%	4.476*	0.614	0.000	2.87	6.09
	76-100%	-5.714*	0.614	0.000	-7.32	-4.10
76-100%	0-25%	15.333*	0.614	0.000	13.72	16.94
	26-50%	10.190*	0.614	0.000	8.58	11.80
	51-75%	5.714*	0.614	0.000	4.10	7.32

*. The mean difference is significant at the 0.05 level.

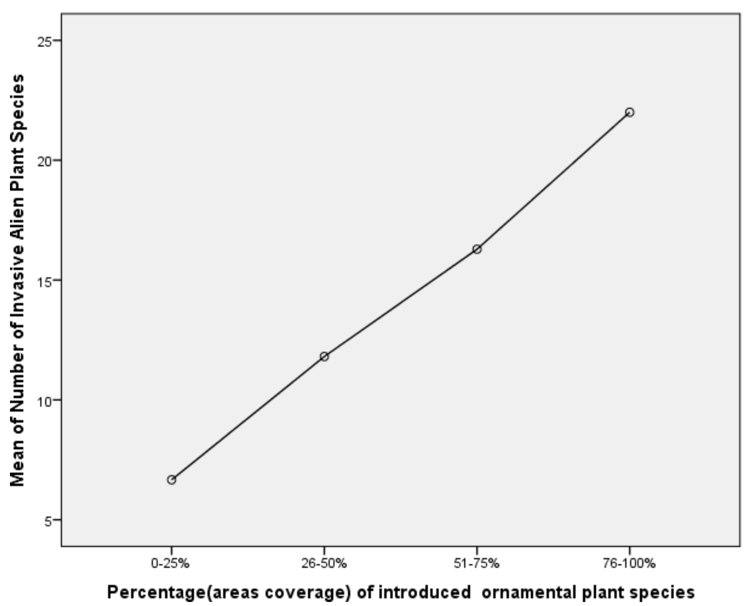

Figure 8. The relationship between percentages (area coverage’s) of introduced ornamental plant species and richness of Invasive Alien Plant Species (IAPSs)

Potential Impacts of Invasive Alien Plant Species (IAPS) in the study areas

Based on the outcomes of this study, IAPS have been identified as one of the causes for the loss of biological diversity, ecosystem services degradation and economic damage in the study areas. From the identified IAPS, 36.84% of them had high and very high impacts on biodiversity of the nursery sites and the surrounding areas; whereas the remaining (63.16%) had medium impacts (Table 6).

Table 6. Impacts and levels of the impacts of naturalized and IAPS

	Scientific name	Impacts	Impacts Levels
1	*Acacia saligna* (Labill.) Wendl	Biodiversity	Medium
2	*Agave americana* L.	Biodiversity	Medium
3	*Ageratum conyzoides* L.	Farm, weed	Very high
4	*Ageratum houstonianum* Mill.	Biodiversity	High
5	*Alternanthera pungens* Kunth.	Farm, biodiversity	High
6	*Argemone ochroleuca* Sweet	Farm, biodiversity	Very high
7	*Azadirachta indica* A.Juss.	Biodiversity	Medium
8	*Bidens pilosa* L.	Farm	High
9	*Caesalpinia decapetala*(Roth) Alston	Road, biodiversity	High
10	*Casuarina cunninghamiana* Miq.	Biodiversity	Medium
11	*Casuarina equisetifolia* L.	Biodiversity	Medium
12	*Catharanthus roseus* (L.) G. Don	Biodiversity	Medium
13	*Cuscuta campestris* Yunck.	Farm, biodiversity	Very high
14	*Datura stramonium* L.	Biodiversity	Medium
15	*Delonix regia* (Hook.) Raf.	Biodiversity	Medium
16	*Dovyalis caffra* (Hook.f. & Harv.) *Sim*	Biodiversity	High
17	*Duranta erecta* L.	Biodiversity	High
18	*Galinsoga parviflora* Cav.	Biodiversity	High
19	*Grevillea robusta* A. Cunn. ex R. Br.	Biodiversity	Medium
20	*Helianthus annuus* L.	Biodiversity	Medium
21	*Ipomoea purpurea* (L.) Roth	Farm, biodiversity	Medium
22	*Jacaranda mimosifolia* D. Don	Biodiversity	Medium
23	*Lantana camara* L.	Farm, road, biodiversity	Very high

24	*Leucaena leucocephala* (Lam.) de Wit	Biodiversity	Medium
25	*Melia azedarach* L.	Biodiversity	Medium
26	*Mimosa pigra* L.	Biodiversity;	Medium
27	*Mirabilis jalapa* L.	Farm;road; biodiversity	Medium
28	*Nicotiana glauca* Graham	Biodiversity;	High
29	*Parkinsonia aculeata* L.	biodiversity	Medium
30	*Parthenium hysterophorus* L.	Farm, biodiversity	Very high
31	*Pinus patula Schiede* ex Schltdl. & Cham.	Biodiversity	Medium
32	*Psidium guajava* L.	Biodiversity	Medium
33	*Ricinus communis* L.	Biodiversity	Medium
34	*Salvia coccinea* Buc'hoz ex Etl.	Biodiversity	Medium
35	*Salvia leucantha* Cav.	Biodiversity	Medium
36	*Salvia tiliifolia* Vahl.	Farm, road, biodiversity	High
37	*Senna didymobotrya* *(*Fresen.) H.S. Irwin & Barneby	Farm; road; biodiversity	Medium
38	*Verbesina encelioides*(Cav.) Benth. & Hook. f.	Biodiversity, farm	High

DISCUSSION

The results of the study indicated that from the total identified IAPS, the majority were Invasive alien ornamental plant species (IAOPS) based on the Global Invasive Species Database (Witt and Luke, 2017). This indicated that ornamental horticulture is the major pathway for the introduction of IAPS. In agreement with our finding, the results of the study by Mayer *et al*. (2017) indicated that, from the identified 1268 ornamental garden plant species, 75% of them were alien to Germany. The study by Sirbu *et al*. (2022) also indicated that 25% of the recorded species were introduced intentionally for ornamental purposes. The findings of the investigation by Oduor *et al.* (2023) also confirmed that ornamental horticulture constitutes a major pathway of alien plant species introductions into different biogeographic regions. In addition, in line with our findings, the study by Raicu *et al*. (2024) showed that ornamental horticulture has significantly contributed to the proliferation of plant invasions on a worldwide scale.

In agreement with the finding of our study, the investigation by Drew *et al*. (2010) also confirmed that the horticulture industry, particularly ornamental horticulture, is deliberated as an essential pathway for introducing and spreading IAPS. The findings of the study by Silva *et al*. (2024) indicated that ornamental horticulture is known as an essential passageway for introducing IAPS into new habitats. Therefore, Ornamental plants have been escaping from cultivated environments for centuries, and human activities are considered serious factors in the invasion process, as they facilitate the spread of species outside their native habitats.

The most dominant IAPS families were Asteraceae and Fabaceae. In agreement with the findings of our investigation, the results of a study by Zhang *et al*. (2021) showed that species in the Asteraceae and Fabaceae families had a high dominance among alien, naturalized, and invasive species.

Regarding the habit of all plant species (IAPS and non-invasive plant species), the majority of the species were herbs, followed by shrubs in most of the nursery sites. This might be because herbs produce a large number of seeds and possess greater genetic flexibility and evolutionary rates. In addition, herbs are characterized by high growth rates due to their short life cycle and fast pollen grain and seed dispersal rates. They also occur in places where the weather conditions are not good for most plants (Belbase and Ghimire, 2021). In terms of growth form, herbaceous species played a greater role in promoting homogenization, followed by shrubs and trees (Dar and Resh, 2015).

As to the potential uses of the identified IAPS in our study, they were used for ornamental purposes, construction, soil conservation, afforestation, furniture production, etc. In agreement with our finding, the study by Witt *et al*. (2018) indicated that most plant species were intentionally introduced and are now cultivated and utilized for various purposes. Their study indicated that the majority of IAPS (46%) were grown as ornamentals or used as barriers/hedges (15%), for soil conservation, and as agricultural crops. In line with our finding, the study by Onozuka and Osawa (2022) indicated that *Agave americana L.*, an IAPS, had high ornamental value. The finding of the study by Bayón and Vilà (2019) confirmed that as the number of invasive ornamentals is very high, resources are limited to manage them all in the same way and it is necessary to create prioritization lists of plant species. Therefore, there is a need to identify those that are invasive and regulate their use for commercial and other purposes to reduce the risk of causing numerous impacts on the environment and biodiversity (Dehnen-Schmutz, 2011).

Rojas-Sandoval and Ackerman (2021) found that considerably more IAPS (54%) were intentionally introduced for ornamental purposes than for any other reasons in the Caribbean. Their results showed that hosted ornamental plants are effectively invading most important habitats across the Caribbean, deteriorating ecosystem services and threatening native biodiversity. The ornamental horticulture industry has the potential to foster the invasion process. The introduction of large numbers of non-indigenous species is one of the most important factors that contribute to an area being invaded (Von-Holle and Simberloff, 2005).

Moreover, several other studies carried out in this field of research, including Meyerson *et al*. (2005); Roberts *et al*. (2015); CABI (2016); Paini *et al*. (2016); Lone *et al*. (2019); Rai and Singh (2020); Syliver *et al*. (2020); Waghmode (2022); Najberek *et al*. (2024) support our findings. From the identified 38 IAPSs, the top five were selected, and their families, countries of origin, their impacts, and means of spread were discussed below based on established IAS databases and literature surveys. These are *Parthenium hysterophorus, Lantana camara, Argemone ochroleuca, Ageratum conyzoides,* and *Nicotiana glauca.*

Parthenium hysterophorus is a herbaceous IAPS of the Asteraceae family with common names like carrot weed, famine weed, or Congress grass. *P. hysterophorus* is native to Central and South America. It has been introduced to Ethiopia and East Africa for different reasons, such as medicine, ornament, and accidentally as a contaminant. In Ethiopia, it was regarded to be introduced accidentally through aid shipments or from Somalia during the Ethio-Somali War in 1976/77. It has now spread to almost every part of the country (Witt and Luke, 2017). *P. hysterophorus* is the most dangerous to natural biodiversity, flora, fauna and human health. It disrupts the ecology of grasslands, invades woodlands, and generally disturbs native vegetation through aggressive competition (Rwomushana *et al*., 2019). Being allelopathic, it inhibits the germination and growth of other plants, reducing crop yields and displacing palatable species in natural and improved pastures. It is one of the fastest spreading invasive plants, via different mechanisms 'such as water, animals, wind, agricultural materials, and transportation, occupying millions of hectares in Ethiopia (Evans, 1997).

Lantana camara is one of the worst IAOPS worldwide. It is an evergreen perennial shrub in the family Verbenaceae (Gooden et al., 2009). It is native to tropical and subtropical America. *L. camara* has usually been deliberately introduced into various localities in Ethiopia as an ornamental shrub. The distribution of *L. camara* in Ethiopia is very wide, and many ecosystems are affected by this species, including most nursery sites (Witt and Luke, 2017). About half of its flowers produce seeds. Mature plants can produce up to 12,000 seeds per plant every year. Seeds are believed to remain viable for several years under natural conditions (Nel, 2015). Its spread is stimulated by animal activities and human disturbances, such as cultivation and road construction (Sharma *et al*., 2005). *L. camara* has been categorized as the uppermost impacting IAOPS. It is a major threat to biodiversity and ecosystem services. Its impact is noticeable because of the species' invasive characteristics, such as fire tolerance, high seed production, allelopathy, high percentage fruit set, rapid vegetative growth, aggressive competitive ability, and proliferation throughout the year in ideal environmental conditions (Nel, 2015; Kumar *et al*., 2016).

Argemone ochroleuca is the other worst IAPS, which is native to Mexico and the West Indies. Common names: Devil's figs, Mexican prickle poppy, Mexican thistle, and white thistle (English) belongs to the family Papaveraceae (Patel, 2013; Witt and Luke, 2017). It reproduces by producing a large number of seeds, which may fall naturally to the ground. The majority of seed is dispersed by flood (Malik and Grover, 1973). *A. ochroleuca* has commonly been introduced into numerous localities in Ethiopia and East Africa accidentally as a contaminant (Witt and Luke, 2017). It is capable of adapting and even displacing the native flora. *A. ochroleuca* has been often confused with *A. mexicana* by their close biological link because they share similar phenotypic characteristics (Haisova and Slavik, 1975).

Ageratum conyzoides is one of the most widely adaptive weeds in Ethiopia in the family Asteraceae. *A. conyzoides* is native to tropical America. It has spread worldwide in the tropical and subtropical areas. It is an annual aromatic herbaceous plant (Dogra *et al*. 2009). *A. conyzoides* produces more than 40,000 seeds from a single plant. These seeds are easily dispersed into wide areas by wind and water, which will help in their establishment in a wide range of climatic conditions (Kohli *et al*., 2006). *A. conyzoides* has generally been introduced into different areas in Ethiopia and East Africa accidentally as a contaminant and ornamental plant. It has invaded predominantly in the grasslands, agricultural fields, forests, wastelands, plantations, natural pastures, riparian areas, lowlands, nursery sites, coastal dunes, and horticultural fields. It is a main threat to biodiversity, agriculture and ecosystem services (Witt and Luke, 2017).

Nicotiana glauca L, in the family Solanaceae, is the other IAOPS worldwide. It is native to South America. *N. glauca* has largely been introduced into different areas in Ethiopia and East Africa as medicine, insecticide, and an ornamental plant. It is invasive in Ethiopia and East Africa (Henderson, 2002). In Ethiopia, *N. glauca* grows in a wide variety of open and disturbed habitats, including roadsides, abandoned and disturbed land, nursery sites, and lakeshores. It is mainly a problem in relatively dry areas. Its overall negative impacts are ecosystem alteration, agricultural damage, and economic burden (Witt and Luke, 2017). *N. glauca* poses a threat to biodiversity by competing with native species for resources. All parts of the plant are poisonous (Brandes, 2000).Therefore, these and others introduced ornamental plant species had substantial invasiveness potential in Ethiopia.

CONCLUSION AND RECOMMENDATION

The results of this study indicated that a significant proportion of the introduced ornamental plant species possess a high potential for invasiveness within the study area. Statistical analysis via one-way ANOVA, followed by Tukey's Honestly Significant Difference (HSD) test, revealed a significant positive relationship between the proportional coverage of introduced ornamental plants and Invasive Alien Plant Species (IAPS) richness. This correlation confirms that numerous introduced ornamentals exhibit considerable invasive potential. Consequently, the ornamental horticulture industry is implicated as a primary vector for the introduction, propagation, and dissemination of numerous non-native species. These introduced ornamental plant species have demonstrated pronounced invasiveness and are environmentally detrimental. A comprehensive understanding of introduced ornamental plant species diversity and composition is therefore essential for interpreting current invasion trends, assessing and forecasting impacts on biodiversity and economy, and informing effective biosecurity policy. While the role of ornamental plants in biological invasions is substantial, it is acknowledged that they provide significant economic and aesthetic value. Thus, reconciling the trade in ornamental species with conservation imperatives is critical for sustainable biodiversity management. It is recommended that integrated management and prevention strategies be implemented, including: pre-introduction risk assessment and screening; public awareness campaigns; support for the identification of problematic Invasive Alien Ornamental Plant Species(IAOPS); regulatory measures, such as restrictions on the sale and transport of invasive alien species and the promotion of native or non-invasive alternatives to replace invasive ornamentals plant species.

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Appendix 1

List of plant species identified during the study including their families

No.	Scientific name	Family
1	*Acacia abyssinica* Hochst.	Fabaceae
2	*Acacia mearnsii* De Wild.	Fabaceae
3	*Acacia melanoxylon* R. Br.	Fabaceae
4	*Acacia saligna* (Labill.) Wendl.	Fabaceae
5	*Aeonium leucoblepharum* A. Rich.	Crassulaceae
6	*Agave americana* L.	Agavaceae
7	*Ageratum conyzoides* L.	Asteraceae
8	*Ageratum houstonianum* Mill.	Asteraceae
9	*Allophylus abyssinicus* (Hochst.)	Sapindaceae
10	*Alternanthera pungens* Kunth.	Amaranthaceae
11	*Amaranthus palmeri S. Wats.*	Amaranthaceae
12	*Amaranthus sparganiocephalus* Thell.	Amaranthaceae
13	*Amaranthus spinosus* L.	Amaranthaceae
14	*Amaranthus thunbergii* Moq.	Amaranthaceae
15	*Argemone ochroleuca* Sweet.	Papaveraceae
16	*Artemisia annua* L.	Asteraceae
17	*Artemisia rehan* Chiov.	Asteraceae
18	*Azadirachta indica* A. Juss.	Meliaceae
19	*Begonia cucullata* Willd.	Begoniaceae
20	*Bidens pilosa* L.	Asteraceae
21	*Caesalpinia decapetala*(Roth) Alston	Fabaceae
22	*Melaleuca citrina*(Curtis)Dum.Cours	Myrtaceae
23	*Callistemon rigidus* R.Br.	Myrtaceae
24	*Callistephus chinensis*(L.)Less.	Asteraceae
25	*Carica papaya* L.	Caricaceae
26	*Carpobrotus edulis* (L.) L. Bolus	Mesembryanthemaceae

27	*Casuarina cunninghamiana* Miq.	Casuarinaceae
28	*Casuarina equisetifolia* L.	Casuarinaceae
29	*Catharanthus roseus* L.	Apocynaceae
30	*Cenchrus setaceus*(Forssk)	Poaceae
31	*Chlorophytum comosum* (Thunb.) Jacques	Asparagaceae
32	*Citrus limon* L.	Rutaceae
33	*Codiaeum variegatum*	Euphorbiaceae
34	*Coffea arabica* L.	Rubiaceae
35	*Coleus scutellarioides* (L.)	Lamiaceae
36	*Colocasia esculenta* (L.)	Araceae
37	*Cordia africana* Lam.	Boraginaceae
38	*Cordyline fruticosa*(L.)	Asparagaceae
39	*Coreopsis grandiflora* Hogg ex Sweet	Asteraceae
40	*Coreopsis lanceolta* L.	Asteraceae
41	*Crinum asiaticum* L.	Amaryllidaceae
42	*Crocosmia crocosmiiflora* (Montbretia) - FSUS	Iridaceae
43	*Cuphea hyssopifolia* Kunth	Lythraceae
44	*Cuphea ignea* A. DC.	Lythraceae
45	*Cupressus lusitanica* Mill.	Cupressaceae
46	*Cupressus macrocarpa* Hartw.	Cupressaceae
47	*Cuscuta campestris* Yunck.	Convolvulaceae
48	*Cymbopogon martini* (Roxb.) Wats.	Poaceae
49	*Dahlia pinnata* Cav.	Asteraceae
50	*Datura stramonium* L.	Solanaceae
51	*Delonix regia* (Boj.ex Hook.) Raf.	Fabaceae
52	*Dianthus chinensis* L.	Caryophyllaceae
53	*Dodonaea angustifolia* L. f.	Sapindaceae
54	*Dovyalis caffra* Hook.f. & Harv.	Salicaceae
55	*Duranta erecta* L.	Verbanaceae

56	*Echeveria secunda* Booth ex Lindl. .	Crassulaceae
57	*Erythrina abyssinica* Lam. ex DC.	Fabaceae
58	*Euphorbia milii* Des Moul. *;*	Euphorbiaceae
59	*Euphorbia tithymaloides* L.	Euphorbiaceae
60	*Falcataria moluccana* (L.) Greuter & R.Rankin	Fabaceae
61	*Ficus benjamina* L.	Moraceae
62	*Ficus elastic* Roxb. ex Hornem.	Moraceae
63	*Ficus microcarpa* L.F.	Moraceae
64	*Fuchsia magellanica* Lam.	Onagraceae
65	*Galinsoga parviflora* Cav.	Asteraceae
66	*Garcinia subelliptica* Merr.	Guttiferae
67	*Gazania rigens* (L.) Gaertn.	Asteraceae
68	*Gladiolus gandavensis* Van Houtte	Iridaceae
69	*Glandularia tenera (*Spreng.) Cabrera	Verbenaceae
70	*Glandularia x hybrida* (Groenland & Rümpler) G.L.Nesom & Pruski	Verbenaceae
71	*Grevillea robusta* R. Br	Proteaceae
72	*Hagenia abyssinica* (Bruce) J.F.Gmelin	Rosaceae
73	*Helianthus annuus* L.	Asteraceae
74	*Hibiscus rosa-sinensis* L.	Malvaceae
75	*Hippeastrum striatum*(Lam.)	amaryllidaceae
76	*Hydrangngea macrophylla* (H)|hortensia	Hydrangeaceae
77	*Impatiens hawkeri* (W. Bull)	Balsaminaceae
78	*Ipomoea purpurea* (L.) Roth	Convolvulaceae
79	*Iresine diffusefa*.f..herbstii	amaranthaceae
80	*Iris germanica* L.	Iridaceae
81	*Jacaranda mimosifolia* D. Don	Bignoniaceae
82	*Juniperus procera* Hochst.	Cupressaceae
83	*Lantana camara* L.	Verbenaceae
84	*Lavandula dentatata* L.	Lamiaceae

85	*Leucaena leucocephala* Lam.	Fabaceae
86	*Ligustrum ovalifolium* Hassk.	Oleaceae
87	*Lippia adoensis* Hochst. ex Walp.	Verbenaceae
88	*Malus sylvestris* Miller.	Rosaceae
89	*Mandevilla sanderi* Hemsl.	Apocynaceae
90	*Mangifera indica* L.	Anacardiaceae
91	*Melia azedarach* L.	Meliacea
92	*Mentha spicata* L.	Lamiaceae
93	*Millettia ferruginea* (Hochst.) Bak.	Fabaceae
94	*Mimosa pigra* L	Fabaceae
95	*Mirabilis jalapa* L.	Nyctaginaceae
96	*Nerium oleander* L	Apocynaceae
97	*Nicotiana glauca* Graham	Solanaceae
98	*Ocimum americanum* L.	Lamiaceae
99	*Ocimum lamiifolium* Hochst. ex. Benth.	Lamiaceae
100	*Olea europaea* L. subsp. cuspidata	Oleaceae
101	*Osteospermum ecklonis* (DC.) Norl.	Asteraceae
102	*Oxytenanthera abyssinica* (A. Rich.) Munro.	Poaceae
103	*Parkinsonia aculeata* L.	Fabaceae
104	*Parthenium hysterophorus* L.	Asteraceae
105	*Pelargonium hortorum* LH Bailey-	Geraniaceae
106	*Persea americana* Mill.	Lauraceae
107	*Phoenix canariensis* H.Wildpret	Arecaceae
108	*Phyllanthus urinaria* L.	phyllanthaceae
109	*Pilea pepermioides* Diels.	Urticaeceae
110	*Pinus patula* Schiede ex Schltdl. & Cham.	Pinaceae
111	*Plumeria rubra* L.	Apocynaceae
112	*Podocarpus falcatus* (Thunb.) Mirb.	Podocarpaceae
113	*Poikilospermum suaveolens* (Blume) Merr.	Urticaeceae

114	*Prunus africana* (Hook.f.) Kalkm.	Rosaceae
115	*Psidium guajava* L.	Myrtaceae
116	*Pterolobium stellatum* (Forssk.) Brenan	Fabaceae
117	*Pyrostegia venusta* (Ker Gawl.) Miers	Bignoniaceae
118	*Rhodiola pachyclados* (Aitch. & Hemsl.) H.Ohba	Crassulaceae
119	*Ricinus communis* L.	Euphorbiaceae
120	*Rosa x-richardii* Rehder.	Rosaceae
121	*Rosmarinus officinalis* L.	Lamiaceae
122	*Ruta chalepensis* L.	Rutaceae
123	*Saccharum officinarum* L.	Poaceae
124	*Salix purpurea* L.	Salicaceae
125	*Salvia coccinea Buc'hoz ex Etl.*	Lamiaceae
126	*Salvia farinacea* Benth.	Lamiaceae
127	*Salvia leucantha* Cav.	Lamiaceae
128	*Salvia officinalis* L.	Lamiaceae
129	*Salvia splendens* Sellow ex Nees	Lamiaceae
130	*Salvia tiliifolia* Vahl.	Lamiaceae
131	*Sanguisorba officinalis* L.	Rosaceae
132	*Sansevieria trifasciata* hort. ex Prain	Asparagaceae
133	*Sedum dendroideum* Moc. & Sessé ex DC.	Crassulaceae
134	*Senna didymobotrya (*Fresen.) Irwin & Barneby	Fabaceae
135	*Sesbania sesban*(L.)	Fabaceae
136	*Spathodea campanulata* P. Beauv.	Bignoniaceae
137	*Stephania abyssinica* (Dillon & A. Rich.) Walp.	Menispermaceae
138	*Symphyotrichum* novi-belgii	Asteraceae
139	*Syngonium podophyllum* Schott	Araceae
140	*Terminalia catappa* L.	Combretaceae
141	*Thymus schimperi* L.	Lamiaceae
142	*Thymus vularis* L.	Lamiaceae

143	*Tulbaghia violacea* Harv.	amaryllidaceae
144	*Verbesina encelioides* (Cav.) Benth. & Hook. f.	Asteraceae
145	*Vernonia amygdalina* Del.	Asteraceae
146	*Vigna radiate* (L.) R. Wilczek)	Fabaceae
147	*Vinca major* L.	Apocynaceae
148	*Yucca gigantean* Lem.	Asparagaceae
149	*Zantedeschia aethiopica*(L.)	Araceae

ETHIOPIA'S ACCESS AND BENEFIT-SHARING FRAMEWORK: LEGAL FOUNDATIONS, BIO-TRADE OPPORTUNITIES, AND GOVERNANCE CHALLENGES

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ABSTRACT: Ethiopia's Access and Benefit-Sharing (ABS) framework, grounded in Proclamation No. 482/2006 and Regulation No. 169/2009, represents a national effort to assert sovereignty over genetic resources while promoting community rights, equitable development, and biodiversity conservation. This article provides a comprehensive analysis of Ethiopia's ABS regime, examining its legal provisions, institutional implementation, enforcement mechanisms, and potential to drive sustainable bio-trade. Drawing on international benchmarks including the Nagoya Protocol and experiences from Brazil, India, and South Africa; it identifies key gaps in clarity, enforcement, community participation, and inter-agency coordination. Case examples highlight how Ethiopia's rich biodiversity could serve as a foundation for climate-resilient development and inclusive growth if ABS is effectively operationalized. The article concludes with strategic recommendations to enhance legal clarity, decentralize ABS governance, strengthen community involvement, improve transparency and compliance monitoring, and integrate ABS into national development and climate agendas.

Keywords: Access and Benefit-Sharing, Bio-piracy, Bio-trade, Nagoya Protocol, Traditional Knowledge

INTRODUCTION

Ethiopia's biodiversity is both a national heritage and a global asset. From endemic medicinal plants to indigenous food crops like *teff* and *enset*, the country's biological resources are deeply intertwined with the livelihoods, identities, and traditional knowledge of its people. As a party to the Convention on Biological Diversity (CBD, 1992) and its Nagoya Protocol, Ethiopia has

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sought to codify access and benefit-sharing (ABS) principles in national law; notably through Proclamation No. 482/2006 and Regulation No. 169/2009. In general, ABS refers to legal mechanisms by which benefits derived from the use of genetic resources and associated traditional knowledge are shared equitably with the provider country and local communities (CBD, 1992; Nijar, 2011). For biodiversity-rich countries like Ethiopia, an ABS framework has a dual purpose: conserving biological diversity while creating economic opportunities through sustainable use (i.e. bio-trade).

Ethiopia's ABS framework is often praised as progressive on paper but faces significant operational challenges. Key issues include centralized implementation, legal ambiguities, low community participation, and limited capacity for monitoring and enforcement. This paper critically examines the strengths and weaknesses of Ethiopia's ABS system and explores how it can better support sustainable biotrade, biodiversity conservation, and equitable development. The analysis draws on Ethiopia's laws and policy documents, empirical studies, and lessons from other countries. It argues that Ethiopia needs to move toward a more decentralized, transparent, and community-inclusive ABS governance model to realize its objectives.

The finding and analysis section assess the doctrinal architecture of Ethiopia's ABS laws, identifies operational gaps, and links those gaps to unrealized bio-trade opportunities and governance constraints, with particular focus on transparency, monitoring, and enforcement. It also distills comparative lessons and feasible implementation options. Besides, in the given section presents prioritized legal and institutional recommendations.

Guiding questions are: (1) why has Ethiopia's ABS framework underperformed despite comparatively progressive legal provisions? (2) Which legal and institutional reforms are most feasible in the short and medium term to convert Ethiopia's biodiversity endowment into compliant biotrade and measurable community benefits? The central thesis is that underperformance is primarily structurally rooted in centralized administration, weak inter-agency interfaces (customs, intellectual property, research governance), and limited transparency rather than a lack of substantive legal principles.

MATERIALS AND METHODS

This article uses qualitative doctrinal and policy analysis. Primary sources include Proclamation No. 482/2006, Regulation No. 169/2009, and relevant policy and institutional documents. Secondary sources include peer-reviewed literature, technical reports, and comparative guidance under the CBD and the Nagoya Protocol.

The analysis combines (i) doctrinal assessment of rights, obligations, and legal definitions (PIC, MAT, benefit-sharing, derivatives, and IPR-related provisions) with (ii) governance assessment of operational capacity, transparency, and enforcement interfaces, including customs controls, patent examination processes, and post-access monitoring.

As part a comparative approach Brazil, India, and South Africa were selected as comparators because they are biodiversity-rich, have established ABS implementation experience, and illustrate distinct institutional models: Brazil's digital registration and compliance system (SISGEN), India's multi-tier governance with local biodiversity committees and patent-related clearance, and South Africa's mature benefit-sharing practice in commercial biotrade cases (e.g., Rooibos and Hoodia).

The study is based on document analysis and does not include primary fieldwork, interviews, or permit-file audits. Accordingly, the article prioritizes legal and institutional design issues and triangulates implementation claims through published studies and official reports, while acknowledging that some compliance dynamics may vary across regions and sectors.

FINDINGS AND ANALYSES

Legal Foundations and Gaps

This subsection distinguishes Ethiopia's ABS regime's normative commitments; sovereign rights over genetic resources, community entitlements, and benefit-sharing obligations from the operational compliance chain required making those commitments enforceable in practice. In ABS governance, legal rights are not self-executing: they depend on workable permit conditions, verifiable PIC and MAT, monitoring and reporting systems (including functional registers), checkpoint/customs and IP linkages, and accessible remedies for breach. Using this lens, the following section maps the core legal architecture of Proclamation No. 482/2006 and Regulation No. 169/2009 and identifies areas where ambiguity, centralization, and inter-agency fragmentation predictably weaken compliance and benefit capture.

Proclamation No. 482/2006 (Access to Genetic Resources and Community Knowledge, and Community Rights)

Ethiopia's ABS law is one of the most detailed in Africa. It affirms national sovereignty over genetic resources and explicitly recognizes the rights of local communities to their traditional knowledge. The proclamation attempts to balance biodiversity conservation, commercial utilization, and community benefits; an ambitious triad that has proven difficult in practice.

Drawing on principles of the CBD and the African Union's model law, the proclamation establishes key definitions and procedures shaping ABS in Ethiopia.

Notably, the law defines *"genetic resource"* broadly to include both the material itself and its *"derivatives,"* such as extracts, oils, resins, and proteins (Proclamation 482/2006, Art. 2(3)–(6); FDRE, 2006). By explicitly covering derivatives, Ethiopia's law goes further than some ABS frameworks that focus only on raw biological materials. In principle, this means that downstream products and innovations (for example, a pharmaceutical compound derived from an endemic plant) should also be subject to benefit-sharing obligations. The proclamation also defines *community knowledge* as the collective knowledge, practices, and innovations of local communities developed over generations (Art. 2(14)), thereby establishing a legal basis for communities' rights over their traditional knowledge. However, the law does not create a specific intellectual property mechanism for protecting this collective knowledge, which limits the enforceability of those community rights outside Ethiopia's jurisdiction (Birhanu, 2010).

The proclamation requires Prior Informed Consent (PIC) of the concerned local community and Mutually Agreed Terms (MAT) as prerequisites for access to any genetic resource or associated community knowledge. Any bio-prospector or entity (domestic or foreign) seeking access in Ethiopia must obtain PIC from the local community and an access permit from the state (Art. 6, 12). The law mandates that at least 50% of monetary benefits from an ABS agreement go to the community that provided the resource or knowledge (Art. 9(2); Art. 18(1)), underscoring the equity goal. It also provides for non-monetary benefits (technology transfer, training, etc.) through MAT. Significantly, the law prohibits the granting of intellectual property rights (e.g. patents or plant breeders' rights) on genetic resources or community knowledge without the prior consent of the state and the relevant community (Art. 17). In theory, if an invention is developed from Ethiopian genetic resources, the inventor must renegotiate benefit-sharing before seeking a patent. However, this provision lacks detailed implementation mechanisms and has not been effectively enforced in practice, as discussed later (Mirete, 2010; Ejara, 2022).

Despite its strong provisions, the proclamation adopts a highly centralized approach. It designates a federal institution; originally the Institute of Biodiversity Conservation, now the Ethiopian Biodiversity Institute (EBI) as the *competent authority* to administer ABS permits and agreements (Art. 4, 13, 27). Local/regional authorities are given only limited advisory or facilitating roles. Thus, a law intended to empower communities is implemented via top-down structures, contributing to gaps between principle and practice. The proclamation does include criminal penalties for violations (e.g. up to 12 years imprisonment and fines for accessing genetic resources without a permit or failing to share benefits) (Art. 35), signaling the legislature's intent to treat bio-piracy as a serious offense.

The Proclamation provides an advanced normative platform particularly on derivatives, community entitlements, and benefit-sharing but its enforceability depends on operational rules and inter-agency checkpoints that were not fully embedded in the legal and institutional ecosystem.

Regulation No. 169/2009 (Council of Ministers Regulation for ABS)

To operationalize the proclamation, Ethiopia enacted Regulation 169/2009, which provides detailed procedures for ABS access applications, permit issuance, and benefit-sharing contracts (FDRE, 2009). The regulation prescribes how an access application is submitted to EBI, evaluated, and approved. It introduces standardized forms (e.g. a permit application form in an

Annex) and defines roles of various actors in more detail. For instance, once EBI receives a complete application, it should publish a public notice of the intended access, allowing any objections or claimants to come forward (Art 3–5). The regulation also outlines how *community consent* is obtained: rather than each community negotiating directly, local government bodies (woreda or zonal councils) are to act on behalf of communities in PIC deliberations (Art. 12, 21–23). This was meant to streamline the process, but effectively bureaucratizes community consent by inserting government intermediaries, potentially diluting direct community agency.

Importantly, the regulation mandates the creation of an *Access Register;* a public registry of all access permits and agreements (Art 6, 24) to promote transparency. It also obliges EBI to coordinate with customs authorities to control exports of genetic resources and with other relevant institutions (e.g. sectoral agencies) to ensure compliance (Art 25–30). In principle, this envisions a cross-sector monitoring system. In practice, however, these coordination mechanisms have remained largely on paper. The access register has not been effectively implemented, and inter-agency cooperation has been weak (Jalleta, 2021; Mihretu, 2018).

The regulation attempts to differentiate access for purely academic research versus commercial purposes, but in reality both follow similar permitting processes, and benefit-sharing clauses are included regardless of intent. Crucially, the regulation does *not* delegate substantive decision-making authority to regional states or local institutions, despite Ethiopia's federal system.

While the proclamation (under Art. 29) assigns regional/local conservation bodies and kebele administrations concrete compliance tasks; i.e preventing access without permits, checking permits, seizing unlawfully accessed resources, the core legal gap is that, despite assigning regional/local bodies compliance duties the regulation is silent to establish a mandatory, institutionalized EBI–regional bureau coordination framework (mandates, reporting, data-sharing, accountability), leaving cooperation largely discretionary and ad hoc.

Gaps and Ambiguities in the Legal Framework

Ethiopia's ABS laws cover key concepts with admirable breadth: sovereign ownership of genetic resources, community rights and consent, derivatives, benefit-sharing (monetary and non-monetary), and penalties for violations. The objectives of conservation, sustainable use, and equity are clearly stated (Proclamation Art. 3). However, several gaps in detail undermine effective implementation. For example, while "derivative" is defined and theoretically covered, there is no clear procedure for tracking or valuing derivatives once genetic material leaves Ethiopia. Users might obtain a permit for a raw plant sample, then develop a derivative product (like an extract or drug) and argue it falls outside the original agreement; a loophole Ethiopia aimed to close on paper, but without a monitoring mechanism or patent disclosure requirement, it remains difficult to enforce (Mulesa and Westengen, 2020; Ejara, 2022).

Similarly, although the law forbids IPRs without consent, Ethiopia's Intellectual Property Office currently has no routine process to check ABS compliance when reviewing patent applications. Patent examiners do not ask for evidence of PIC or an ABS permit, and there is no legal requirement in Ethiopia's patent law for disclosure of genetic resource origin (Gebru, 2018). This lack of linkage means a company could potentially patent an invention based on Ethiopian genetic material without Ethiopian authorities or communities being aware (Mirete, 2010; Phillips, 2016).

Another ambiguity lies in community representation and benefit distribution. The law says communities "own" their traditional knowledge and must consent and share benefits, but it provides few details on how communities should organize for negotiations or how benefits should be managed at the local level. In practice, PIC has often been treated as a one-time formality rather than a continuous dialogue, and benefits (if any) are usually paid into local government accounts or trust funds with limited transparency (Ameha et al., 2014). If benefits don't reach the intended grassroots beneficiaries, the spirit of ABS is defeated.

In summary, Ethiopia's ABS legislation is comprehensive in scope and strong in intent, but gaps in operational detail; especially regarding derivatives, IP coordination, community representation, and inter-agency enforcement have left it under-implemented. The next sections explore how these legal gaps manifest in practice and affect bio-trade potential and compliance.

Table 1. Key legal and governance gaps and their practical consequences

Legal / governance gap	Why it matters	Practical consequences	Targeted fix (legal or administrative)
a. Derivatives tracing and valuation	Benefit-sharing is triggered by utilization, including downstream products; without traceability, derivatives become legally "invisible".	Users can commercialize extracts/compounds without renegotiation; Ethiopia cannot verify benefit obligations or challenge misuse.	Define downstream notification triggers in MAT; require periodic utilization reports; integrate IRCC identifiers into export and research documentation.
b. Patent and IPR linkage (disclosure/clearance)	Article 17 restrictions are ineffective without a screening checkpoint at the patent office and plant variety protection procedures.	Patents or plant breeders' rights may be granted without PIC/MAT verification; disputes arise late, after commercialization.	Introduce disclosure of origin and evidence of ABS compliance in IP procedures; create a domestic checkpoint between EBI and the IP authority.

c.	Community representation and benefit management	Community rights require legitimate representatives and auditable benefit flows to prevent elite capture.	PIC becomes a one-off formality; benefits may not reach customary holders; mistrust undermines cooperation.	Establish community ABS committees or trusts; require community signatures/receipts; publish benefit delivery summaries (non-confidential).
d.	Transparency and access register	A functioning register is the backbone of verification for customs, research governance, and public accountability.	Limited oversight; weak deterrence; duplication and inconsistent decisions; communities lack information.	Deploy a national ABS portal and register; publish permit summaries; integrate with the ABS Clearing-House and issue IRCCs routinely.
e.	Centralization and weak field monitoring	Centralized permit issuance is mismatched with field realities in a federal system; monitoring must be proximate to collection sites.	Delayed processes; low detection of unauthorized access; limited follow-up on reporting obligations.	Designate regional focal units; empower trained inspectors; standardize escalation and reporting to EBI.
f.	Emerging issues (DSI and synthetic biology)	Value extraction may occur without physical access; Ethiopia needs policy alignment with evolving global ABS rules.	Potential exclusion from benefits tied to genomic utilization; regulatory uncertainty for users and regulators.	Develop national DSI policy positions and contract clauses; align with CBD/Nagoya decisions; build data governance capacity.

Bio-trade Potential and Implementation Challenges

Biodiversity can be a strategic asset for Ethiopia's development if utilized sustainably and fairly. *Bio-trade* refers to the commercialization of goods and services derived from native biodiversity in line with sustainability and equity principles (UNCTAD, 2012, 2016). Ethiopia's rich ecological diversity; an estimated 6,000 higher plant species (about 12% endemic) alongside diverse ecosystems (Demissew, 2021; Fashing et al., 2022) provides a strong foundation for a biodiversity-based economy. An effective ABS regime can ensure that when biodiversity is used for commercial gain, a share of the benefits supports conservation and local livelihoods.

From a legal and governance perspective, bio-trade potential becomes realizable only when value chains are anchored in ABS instruments: collection and access must be based on PIC; utilization pathways and reporting duties must be specified in MAT; and benefit-sharing must be structured (monetary and non-monetary) with verifiable delivery mechanisms. Without these operational linkages, sectoral "potential" remains economically speculative and legally unenforceable.

Several sectors in Ethiopia have high bio-trade potential:

a) Ethiopia's flora includes many medicinal plants with documented healing properties. For example, *Lippia adoensis* (a traditional antifungal and antimicrobial herb), *Artemisia afra* (used for malaria), and *Moringa stenopetala* (a nutrient-rich tree) have attracted interest from researchers and pharmaceutical companies (Zemede et al., 2024). Compounds and essential oils from *Lippia adoensis* (koseret) have demonstrated antifungal activity in laboratory studies. If commercialization occurs, monetary and non-monetary benefits (e.g., royalties) may be shared with Ethiopia and, where traditional knowledge is involved, with the relevant right-holders through mutually agreed terms in line with the Nagoya Protocol and Ethiopia's ABS framework (Gemeda et al., 2015; Nagoya Protocol, Art. 5).

b) Essential oils, resins, and plant extracts are another promising area. Species like *Aloe* spp. (skincare gel), *Boswellia* (frankincense resin), and *Commiphora* (myrrh resin) have long been harvested in Ethiopia for their aromatic and therapeutic properties and are in demand in global fragrance and wellness markets. Likewise, aromatic herbs like black cumin (*Nigella sativa*) and *Lippia adoensis* (koseret) are used in cosmetics and soaps (Tadesse, W.et al., 2007). By embedding ABS into these value chains; for instance, requiring buyers to obtain permits and agree on benefit-sharing, so that Ethiopia can secure fair compensation for communities cultivating or wild-harvesting these resources. This also encourages sustainable harvesting practices (so that, for example, frankincense trees are not over-tapped) by making local stakeholders direct beneficiaries of long-term resource health.

c) Ethiopia is the center of origin for important food crops such as teff (*Eragrostis tef*) and enset (*Ensete ventricosum*). Teff, a gluten-free grain, has gained international popularity in health food markets, and enset (the “false banana”) is a drought-resilient starch staple with potential for wider cultivation in a climate-stressed future (Kefalew & Sintayehu, 2018; Belete et al., 2020). Ethiopia’s crop genetic diversity (including wild relatives of crops like coffee and sorghum) is of global interest for breeding climate-resilient varieties. For example, wild *Coffea arabica* populations in Ethiopian forests have genes for disease and drought tolerance that major coffee-growing companies might want for developing new coffee cultivars. Through ABS, Ethiopia can allow research on these genetic resources under agreements that, if a valuable new crop variety is developed, Ethiopia and the source communities receive benefits (such as royalties or improved seeds). This turns Ethiopia’s agricultural heritage into an economic opportunity while incentivizing the conservation of crop wild relatives and traditional landraces (Mulesa and Westengen, 2020). Indeed, with climate change threatening agriculture, the global value of Ethiopia’s genetic resources for food security is increasing.

d) When local communities have a stake in bio-trade enterprises, ABS can align economic development with conservation. A study on *Lippia adoensis* in southern Ethiopia demonstrated that local communities depend on this plant for spices, food flavoring, traditional medicine, preservatives, and income generation (Seifu et al., 2019). The valuation showed that 98.3% of respondents were willing to pay for its use values, and over 80% were willing to pay for its conservation. Such findings illustrate that communities recognize both the economic and ecological importance of the species. By informing ABS negotiations with evidence of the plant's direct and indirect use values, valuation studies help ensure that future benefit-sharing arrangements reflect the true contribution of communities to conservation and sustainable use. In this way, biodiversity becomes a managed livelihood asset rather than an undervalued open-access resource.

Despite significant potential, Ethiopia's bio-trade sector faces challenges. Many initiatives are still small-scale pilots; scaling them up requires a supportive ecosystem. Key hurdles include lack of access to finance for bio-entrepreneurs, weak market linkages (e.g. difficulty for cooperatives to directly reach international buyers), and limited technical capacity for product development and quality control (UNCTAD, 2017). Communities venturing into bio-trade often need support to organize effectively (ensuring inclusive governance so benefits are shared fairly within the community) and to navigate regulatory requirements (such as obtaining ABS permits and certifications like organic or fair-trade labels). ABS laws alone cannot address all these issues, but they can be part of a broader strategy by providing legal certainty and by channeling resources (through benefit-sharing funds) into capacity-building.

Another challenge is ensuring that local communities truly benefit. Without strong ABS enforcement, there is a risk that foreign or domestic companies utilize Ethiopian genetic resources through informal channels (biopiracy), and local people receive no compensation. Historical instances of biopiracy such as foreign patents on Ethiopian teff varieties in the 2000s have bred distrust and highlight the need for vigilance (Bernard et al., 2005, as cited in Mulesa & Westengen, 2020). A robust ABS regime, well-publicized among stakeholders, can deter such practices by making legal access the norm and illegal appropriation harder.

In essence, Ethiopia's rich biodiversity presents substantial bio-trade opportunities in pharmaceuticals, cosmetics, agriculture, and other sectors. ABS provides the legal framework to ensure these opportunities are realized in a sustainable and equitable way. However, for ABS to truly facilitate bio-trade, it must be effectively implemented: clear rules for access, reliable enforcement, and genuine involvement of communities as partners. Absent these, bio-trade could degenerate into unsustainable exploitation where communities see little benefit; a scenario Ethiopia must avoid if it wants biodiversity to fuel green development. The next sections delve into the governance and compliance gaps currently hindering Ethiopia's ABS implementation.

Transparency and Monitoring Gaps

Transparency is an ex-ante accountability mechanism: it reduces information asymmetry by making permits, authorized uses, and benefit obligations visible and traceable before harm occurs and before disputes emerge (Fung et al., 2007).

One major weakness in Ethiopia's ABS governance is the lack of transparency and accessible data regarding permits, users, and benefit outcomes. Although the law envisages a public ABS *database* or register, none is operational. Basic figures like how many ABS permits have been issued, for which resources, and the status of benefit-sharing are not published (EBI, 2024). This opacity makes external oversight difficult; Parliament, researchers, and civil society cannot easily evaluate whether ABS is working or whether resources are being misused. It also means local communities have no simple way to find out if genetic resources from their area have been accessed and what was agreed.

Additionally, there is virtually no systematic reporting on benefit-sharing outcomes. When ABS agreements are signed, it remains unclear in practice whether the promised benefits (monetary or non-monetary) have been delivered to the communities. For example, if a company agreed to pay royalties or support a community project, there is no public tracking of those commitments. Without data on benefits, policymakers cannot assess if ABS is achieving its equity goals, and communities may not even be aware of what they are entitled to. The Ethiopian Biodiversity Institute's reports have generally emphasized the number of permits issued rather than the benefits generated (Mihretu, 2018). This focus on the *permit* stage rather than follow-up reflects a broader issue of weak post-access monitoring.

ABS record-keeping also lacks detail that could help adaptive management. Ideally, an ABS database would indicate which types of resources are most accessed (e.g. medicinal plants, agricultural seeds, microbial samples) and from which regions. Such information could highlight patterns for instance, if most permits involve medicinal plants from Oromia, training and enforcement could be prioritized there. At present, however, such granular data is largely confined to internal files and not synthesized for policy use (Jiren et al., 2018). The absence of an organized, transparent information system for ABS is a significant governance gap.

Another transparency issue involves information feedback to the communities themselves. Often, once an ABS permit is granted, local communities do not receive a copy of the agreement or even a summary of its terms (Mihretu, 2018). Community members might only learn that research was conducted or resources collected in their area after the fact, and they may have little idea what was agreed regarding benefits or use of their knowledge. This lack of communication breeds mistrust. In some documented cases, communities have felt "in the dark" about ABS deals supposedly made on their behalf, fueling suspicions that benefits are captured by others (Ameha et al., 2014). Ensuring that communities are given accessible information (in local language) about ABS agreements and follow-up would greatly improve credibility. It would also empower communities to demand their share of benefits if promises are not kept.

Improving transparency is relatively low-hanging fruit in ABS reform. Setting up a publicly accessible ABS registry or online database would not be very expensive and could be modeled on systems in countries like South Africa or India, which post summaries of ABS permits and agreements (including the resource, the user, intended use, and agreed benefits). Ethiopia has started uploading some permit information to the CBD's ABS Clearing-House (an international database) (CBD, 2023), but the coverage is incomplete. A dedicated national ABS portal, updated in real time, would allow customs officials, patent examiners, and others to verify legality quickly. It would also allow communities, journalists, and researchers to scrutinize ABS activities, creating public accountability. In a governance environment where trust is often lacking, "sunlight" can be a powerful disinfectant: if communities see what permits are being issued and what benefits are due, it becomes much harder for corruption or negligence to hide.

In conclusion, the lack of transparency and data in Ethiopia's ABS implementation undermines accountability and stakeholder confidence. Addressing this gap should be a priority. By building a transparent monitoring system from permit issuance through benefit delivery; Ethiopia would not only fulfill its own legal mandate (Regulation 169/2009's registry requirement) but also strengthen compliance (users would know their actions are visible) and community engagement (locals could see ABS working for them). Transparency is fundamental to converting ABS from an abstract concept into a credible contract between the state, communities, and resource users.

Enforcement and Compliance Strategy

Enforcement is an ex-post compliance function triggered when non-compliance is detected and requiring corrective measures (e.g., suspension, sanctions, remedies, or dispute processes). Within this logic, the single most important transparency reform is the establishment of a national ABS information portal. (OECD, 2014). Conceptually, Ethiopia's ABS enforcement gap has three interlocking dimensions: (i) institutional (mandates, staffing, and coordination among EBI, regional bodies, research institutions, and courts); (ii) technical and informational (traceability tools, registries, reporting formats, and identifiers that travel with samples and derivatives); and (iii) international (use of IRCCs, checkpoints, and cooperation with user-country authorities). This framing clarifies why strong legal sanctions alone are insufficient if detection, verification, and cross-border interfaces are weak.

Ensuring compliance with ABS agreements; both within Ethiopia and abroad has been one of the greatest challenges. Ethiopia's ABS laws carry strong penalties for violations, but detection and enforcement mechanisms have been weak. A combination of institutional, technical, and legal factors has contributed to a *compliance gap* where many genetic resource uses are unmonitored and potential benefits go uncollected.

At the heart of enforcement challenges is the institutional setup. EBI, as the central ABS authority, is tasked with everything from permits to follow-up, yet it has limited manpower and resources to monitor what happens after a permit is issued (Jalleta, 2021). Regional and local bodies, who might observe genetic resource collection on the ground, have no clear mandate or authority to enforce ABS rules. This centralization means enforcement is effectively based out of Addis Ababa, far from field sites. Local communities are nominally empowered by law (they are even assigned a role in monitoring access on their lands, Proclamation Art. 28), but in reality they often lack the awareness or legal support to play a watchdog role. Expecting under-resourced rural communities to police bioprospectors is unrealistic (Mihretu, 2018). The result is that unauthorized access can happen with little chance of detection; for instance, a foreign researcher could collect plant samples during fieldwork and take them out of the country without anyone knowing it needed ABS approval.

Customs controls illustrate this weakness. Legally, customs officers should ensure no genetic resource leaves Ethiopia without an ABS permit (Proclamation Art. 30). In practice, without an ABS database or training, customs officials rarely identify such cases (Mihretu, 2018). Biological samples may be misdeclared or simply not recognized as genetic material subject to ABS. For example, seeds or dried plant specimens might pass through airports labeled as "research samples" without scrutiny. The lack of clear guidelines and coordination between EBI and customs means an important line of defense against biopiracy is effectively idle.

Another enforcement gap is post-access monitoring. ABS agreements often require the user to submit periodic reports on research findings or to inform EBI of any commercialization (Proclamation 482/2006, Art. 14). However, Ethiopia does not have a system to track whether users actually comply with these obligations (Mihretu, 2018). Once a permit is given, there is an "information black hole" years may pass and EBI might not know if the research led to a publication, a patent, or a product. Without monitoring or an obligation for users to disclose outcomes (e.g. through a patent disclosure requirement), Ethiopia is unlikely to notice a successful foreign patent based on its resources in time to claim benefits. Many benefits (like royalties) would only accrue *if* a product is developed, often years later, making long-term follow-up essential yet currently absent.

Judicial enforcement has also been negligible. While Ethiopia has the legal provisions to prosecute biopiracy, there have been virtually no court cases. Several barriers explain this. First, detecting a violation in order to prosecute is rare for the reasons above. Second, even when a possible violation is known, bringing a case is complicated by technical evidence issues; linking an end product back to a genetic resource and proving it was obtained without a permit can be difficult without clear documentation or disclosure (Zostiet, 2021). Third, Ethiopia's courts and prosecutors are not specifically trained in ABS, so such cases may not be prioritized or may flounder due to unfamiliarity. As a result, the deterrent effect of Ethiopia's harsh penalties has not materialized; many potential violators likely perceive little risk of being caught or punished.

One of the paradoxes of Ethiopia's ABS enforcement is underutilization of communities. Communities have the most to gain from benefit-sharing and are the eyes and ears on the ground, but current practice gives them minimal role. PIC processes have often been handled through local government surrogates, and communities may not even know the details of permits granted in their area. This disempowerment means a key incentive for enforcement; local interest in ensuring outsiders follow the rules is lost. If communities were more directly involved (for instance, if they co-signed agreements and received copies, and if they had local ABS committees to discuss ongoing uses of their resources), they could be important allies in detecting unauthorized activities or in pressuring authorities to enforce compliance. When communities feel ABS is something done *for* them rather than *with* them, they are less likely to actively engage in monitoring or reporting issues (Ameha et al., 2014). Strengthening community agency in the ABS process (for example, through legal awareness trainings or by establishing community biodiversity registers that log local genetic resources and knowledge) could enhance compliance simply by virtue of more local oversight and pride of ownership.

ABS enforcement inherently has an international dimension, since users of genetic resources (companies, researchers) may operate in foreign jurisdictions. Ethiopia's accession to the Nagoya Protocol in 2014 provides some avenues to address this, but they have yet to be fully exploited. Under the Nagoya Protocol, Ethiopia can issue an Internationally Recognized Certificate of Compliance (IRCC) for each permit it grants, and user countries are supposed to check for IRCCs when resources from abroad are utilized. To date, Ethiopia has not systematically issued IRCCs or registered all its permits in the ABS Clearing-House, which undermines its ability to later track or prove legal access (Greiber, 2012; Lachenmeier et al., 2024). If, for example, a European patent office examines an application on an Ethiopian plant, it will search the ABS Clearing-House for an IRCC. If none is found (because Ethiopia didn't register it), the patent could be granted without any flag, and Ethiopia might miss the window to assert its rights. A straightforward step for Ethiopia is therefore to always post its permits/IRCCs to the international database essentially, “leave a paper trail” that other countries’ checkpoints can find.

The Nagoya Protocol also encourages Parties to designate *checkpoints*; authorities like patent offices or research funders to monitor compliance. Ethiopia itself should designate domestic checkpoints (for instance, requiring its national patent office to screen for ABS clearance in relevant applications, or mandating research institutes to ensure ABS permits for any international collaborations). More importantly, Ethiopia can engage diplomatically so that major user countries of its biodiversity (UK, Canada, US (not a Party to Nagoya), etc.) establish effective checkpoints. Some countries have implemented such measures; India’s patent law, for example, requires proof of NBA approval for biological resources used in patents (Richerzhagen, 2014). Brazil’s system generates certificates that must be presented for product registration. South Africa has liaised with the EU to recognize traditional knowledge rights (Bagley, 2018). Ethiopia could learn from and join these efforts, pushing for a norm that if a company is using Ethiopian genetic resources, it must show an Ethiopian permit. This would greatly extend the reach of Ethiopia’s enforcement beyond its borders.

Bilateral cooperation is another avenue. Ethiopia could seek specific agreements or MoUs with countries where its genetic resources are known to be held or used (such as genebanks or botanical gardens in Europe or the U.S.). These agreements could facilitate information exchange for instance, notifying Ethiopia if a resident company files a patent involving Ethiopian material or even legal assistance in case of disputes. Enforcing ABS across borders is complex, but not impossible especially under the Nagoya Protocol’s framework of cooperation (Secretariat CBD, 2011). Given Ethiopia’s capacity constraints, partnering with international organizations (like the ABS Capacity Development Initiative) or regional bodies (African Union) to pursue violators abroad can amplify its efforts.

Bridging the gap between ABS law and practice will require a multifaceted strategy. Domestically, Ethiopia should establish a dedicated ABS compliance unit (or strengthen EBI's existing team) with the mandate to monitor permits, follow up on benefit-sharing, and investigate any reports of misuse. This unit could liaise with customs (e.g. integrate ABS permits into the customs declaration system) and with the Intellectual Property Office (instituting an internal rule that examiners check with EBI for any patent involving biological materials). Investing in modern tools such as an ABS permit tracking database linked to customs and patent systems would enable automated checks (Lachenmeier et al., 2024). Training a cadre of environmental inspectors or rangers to recognize bioprospecting and ask for permits in the field (perhaps building on wildlife or forestry enforcement networks) could improve on-the-ground surveillance.

Empowering communities is also key strategy. Providing communities with knowledge of their rights and perhaps even legal support (through NGOs or pro bono initiatives) would allow them to act if they suspect illegal access. Something as simple as a community hotline to EBI to report suspicious activities could yield leads. Likewise, if communities know that a share of any benefits must come to them, they have motivation to ensure any researcher in their area is actually authorized.

In the short term, Ethiopia might focus on prevention rather than punitive enforcement; making it easy for well-intentioned users to comply (clear info on how to get a permit, reasonable timelines, etc.), while increasing the likelihood that non-compliance will be detected (through transparency and coordination). Over the longer term, a couple of well-publicized enforcement actions (e.g. catching a illicit exporter or challenging a patent in a foreign jurisdiction) would send a strong signal and set precedents (Ejara, 2022; Mihretu, 2018).

In sum, Ethiopia's enforcement of ABS needs strengthening on multiple fronts: institutional coordination, capacity, community engagement, and international cooperation. By implementing these measures, Ethiopia can transform ABS from a largely theoretical regime into a functional system that deters bio-piracy and ensures that when its genetic resources fuel innovation, Ethiopian communities and conservation efforts benefit in return.

Comparative Lessons and International Strategy

Ethiopia's ABS experience can be contextualized by looking at how other biodiversity-rich countries have addressed similar challenges. Countries like Brazil, India, and South Africa have longer histories with ABS and offer lessons in governance, compliance, and benefit-sharing that is instructive for Ethiopia.

As noted, the Nagoya Protocol provides tools for cross-border compliance. Countries vary in how actively they use them. For example, many EU countries have designated checkpoints (e.g. research funding agencies require grant recipients to declare ABS compliance), and the EU has regulations obliging users to exercise "due diligence" to ensure genetic resources were accessed legally (EU Regulation No. 511/2014). Brazil, after joining Nagoya, set up an electronic system (SISGEN) where all users must register their access to genetic heritage, and it issues certificates automatically (Brazil Ministry of Environment, 2016). This has created a large database that can be cross-checked by authorities when products are developed. Ethiopia could aim to emulate such electronic compliance monitoring to catch violations early. The lesson here is that investing in administrative systems and requiring self-reporting by users can greatly enhance compliance oversight.

Brazil: Historically, Brazil had a complex ABS regime; it reformed its laws in 2015 to reduce bureaucracy and involve stakeholders through a multi-stakeholder council (CGEN) (Cunha, 2019). Brazilian states like Amapá and Amazonas even have their own ABS regulations aligned with the federal law, allowing more local control while feeding into the national system (Laird & Wynberg, 2018). A key takeaway for Ethiopia is the value of decentralization with coordination. Brazil's multi-level approach shows that engaging state governments and local communities in decision-making can improve legitimacy and monitoring, provided national standards are maintained. However, Brazil also learned that overly onerous procedures (lengthy permit processes, too many approvals) can backfire by discouraging compliance; something Ethiopia should be wary of when strengthening its system. The balance to strike is between rigor and user-friendliness.

India: India integrated ABS into its Biological Diversity Act (2002), which established Biodiversity Management Committees (BMCs) at the village level, State Biodiversity Boards, and a National Biodiversity Authority (NBA) (Prip et al., 2010). This three-tier structure empowers communities through BMCs that prepare People's Biodiversity Registers documenting local resources and knowledge. Any application to access Indian biological resources by foreigners requires NBA approval, and benefits (usually monetary) flow into a National Biodiversity Fund, with a significant share directed to the local level.

Moreover, India's patent laws require patent applicants to disclose if they used Indian biological material and, if so, show they obtained NBA clearance (Richerzhagen, 2014). India's model demonstrates robust devolved governance and integration with IP law. The heavy involvement of local committees in ABS decisions could inspire Ethiopia to give a formal role to community institutions (e.g. obligating that a community representative co-sign ABS agreements). India's patent disclosure requirement is a concrete measure Ethiopia could adopt to close the loophole of undetected inventions. On the flip side, India's system is administratively complex and sometimes slow, due in part to the multiple levels of scrutiny (Singh, 2020). Ethiopia, with less capacity, may not replicate the full Indian model but can incorporate elements like community funds and mandatory patent clearance.

South Africa: South Africa's ABS regulations (under its Biodiversity Act) are notable for proactive enforcement and benefit-sharing arrangements in high-profile cases. The Hoodia case (an appetite-suppressant succulent traditionally used by the San people) and the Rooibos tea case involved benefit-sharing agreements with Indigenous communities that were facilitated by government and industry cooperation (Wynberg, 2017). South Africa created community trusts to receive benefit funds and has pushed companies to contribute a percentage of sales to these trusts for broadly-used resources like Rooibos (UNEP, 2020). It also has taken enforcement actions, including seizing illicitly collected biological samples at airports and prosecuting non-compliance. South Africa emphasizes stakeholder engagement: it worked with industry associations (like the South African Rooibos Council) to get buy-in for ABS, turning what could have been conflict into collaboration.

The lesson for Ethiopia is the importance of bringing the private sector and communities to the same table early. By identifying a few key bio-industries (perhaps coffee, herbal medicine, or essential oils in Ethiopia) and developing model ABS agreements with broad participation, Ethiopia could jump-start ABS implementation. South Africa also shows that having electronic permit systems and active inspections can yield compliance dividends. However, one challenge they faced is complexity in distributing benefits when many communities or traditional knowledge holders are involved ensuring fair allocation can be tricky (Wynberg, 2017). Ethiopia, which thus far has few benefit-sharing cases, can prepare by establishing clear guidelines for benefit distribution (for instance, creating community development funds at woreda levels to receive ABS money).

Cross-Cutting Lessons:- Across these country experiences, several common themes emerge:

a) Decentralization and Participation

Engaging local structures (communities, states) in ABS leads to greater legitimacy and compliance. Ethiopia’s highly centralized approach is an outlier; moving toward at least some devolution (e.g. regional ABS liaison offices or community ABS committees) could improve effectiveness and trust.

b) Legal Integration

Tying ABS to other legal processes (particularly patents and research permitting) is critical. India’s patent disclosure and Brazil’s integration of ABS registry with product approval processes underline that ABS cannot function in isolation. Ethiopia should create checkpoints in its IP and export control systems as a matter of priority.

c) Balancing Stringency with Clarity

Users are more likely to comply when rules are clear, processing times are reasonable, and incentives (like access to funding or partnerships) exist. While Ethiopia should tighten enforcement, it should also simplify procedures (perhaps through online applications and clear guidelines) to encourage researchers to go through legal channels rather than avoid them.

d) Benefit-Sharing Implementation

Actually, delivering benefits to communities is just as important as securing them on paper. India's experience shows the need for mechanisms to channel funds to communities, and South Africa's shows the importance of identifying beneficiaries and managing expectations. Ethiopia should establish transparent benefit management systems (such as community trusts or funds) in advance, so that when benefits materialize they can be distributed without delay or dispute.

Comparative lessons should be adapted to Ethiopia's administrative realities. A pragmatic sequencing in sshort-term; establish an operational ABS register/portal; formalize customs and IP checkpoints; standardize MAT templates and reporting; issue IRCCs routinely; and build training for customs, patent examiners, and research institutions.

Medium to long term; deepen decentralization through regional ABS units; embed disclosure and compliance requirements in IP and product-approval laws; strengthen judicial remedies and specialized capacity; and invest in national research and value-add chains to increase non-monetary and domestic benefits.

In conclusion, by learning from others, Ethiopia can accelerate the maturation of its ABS framework. Internationally, leveraging Nagoya Protocol tools will extend Ethiopia's enforcement reach. Domestically, adopting best practices in governance and legal integration will address many current shortcomings. While Ethiopia's context is unique, the fundamental challenges of ABS; aligning conservation with development and national sovereignty with global scientific exchange are shared. The experiences of Brazil, India, South Africa and others provide a menu of strategies that Ethiopia can adapt and implement in its next phase of ABS reforms.

CONCLUSIONS AND RECOMMENDATIONS

Ethiopia's ABS framework, as embodied in Proclamation 482/2006 and Regulation 169/2009, is grounded in laudable objectives: safeguarding the country's genetic resources and associated traditional knowledge, ensuring that communities receive fair benefits, and using those benefits to promote conservation and development. The laws established Ethiopia as a pioneer in Africa in asserting community rights and expanding ABS to derivatives and traditional knowledge. However, the analysis above makes clear that **serious implementation gaps** have prevented Ethiopia from realizing the full potential of ABS.

Nearly two decades since the ABS law was passed, there have been few success stories. Communities who are supposed to be key stakeholders often remain marginal to actual ABS deals. Permits have been issued, but systematic monitoring of what happens afterward is lacking, so Ethiopia may not know if benefits should be forthcoming. Researchers or companies have at times bypassed the ABS system entirely; whether due to unawareness, cumbersome procedures, or willful misconduct; meaning genetic resources leave the country with little or no oversight. Meanwhile, valuable traditional knowledge continues to be recorded in publications or used in product research without clear arrangements to share benefits with the custodians of that knowledge. In short, the current ABS regime is **strong in principle but weak in effect**: it has not yet delivered significant tangible benefits to local communities nor demonstrably contributed to conservation funding. This undermines trust in the system; if ABS is seen as merely a bureaucratic hurdle with no local returns, it will not garner the necessary support among communities and officials.

The good news is that Ethiopia has a solid foundation to build upon. The legal framework does not need to be scrapped; rather, it needs to be *reformed and activated* through a series of strategic interventions. Below are key recommendations for transforming Ethiopia's ABS framework from paper to practice:

1. **Legal clarity and legal integration**

Ethiopia should close key legal loopholes by amending the ABS Regulation (169/2009) or the Proclamation (482/2006) to require disclosure of origin in patent and plant breeder's rights applications (Prip et al., 2010; Richerzhagen, 2014). This would align the mandate of EBI with that of the Ethiopian Intellectual Property Authority (EIPA) to prevent unauthorized commercialization. Furthermore, Article 17 of the ABS Proclamation, which restricts the grant of IP rights on materials accessed unlawfully, needs to be clarified and made operational to enhance enforceability. Ethiopia should also update the legal framework to address Digital Sequence Information (DSI) and other emerging issues in accordance with international best practices (Laird and Wynberg, 2018; Adler Miserendino et al., 2022).

2. **Decentralize ABS Governance**

EBI should initiate decentralization through cooperative arrangements with Regional States by designating accredited regional ABS focal institutions (e.g., regional environment/forest bureaus or local universities) to serve as first-line implementation nodes. Consistent with Proclamation No. 482/2006, these focal institutions can support preliminary application screening, coordinate

PIC facilitation with local communities, and conduct field monitoring and periodic reporting as "relevant institutions". As shown in Yami and Mekuria (2022), local empowerment is crucial to ensure compliance and accountability. Regional units should be trained in ABS procedures and negotiation to act as culturally sensitive and timely entry points, while still reporting to EBI.

3. Strengthen Monitoring and Enforcement Mechanisms

A dedicated compliance and enforcement unit within or parallel to EBI should be established. This unit would maintain a central ABS permit database, conduct follow-ups on benefit-sharing obligations, and coordinate cross-agency alerts with customs and IP authorities (Ejara, 2022; Wynberg, 2017). Regular audits, permit status tracking, and targeted inspections should be institutionalized. Ethiopia should also train a cadre of ABS inspectors from existing enforcement agencies to detect bioprospecting violations and support legal prosecutions.

4. Improve Transparency and Data Management

Establishing a public ABS information portal is essential. This portal should publish non-confidential details about issued permits, accessed species, community participation, and reported benefits. Article 18 of Regulation 169/2009 requires reporting obligations, which should be operationalized via annual public reports. Communities involved in ABS must be informed of their rights and should receive copies of relevant agreements and benefit disbursement updates. Transparent systems create incentives for both users and providers to honor ABS terms.

5. Empower Communities and Recognize Traditional Knowledge Holders

ABS agreements should require documented community consent through representative structures such as Community Biodiversity Committees. These groups, including elders, women, and youth, would formalize community engagement and decision-making. A sui generis system for Traditional Knowledge (TK) protection, as outlined in the African Model Law (OAU, 2000), could supplement contract-based ABS by allowing TK holders to register their knowledge and defend against misappropriation. Ethiopia might also allocate a portion of ABS revenues to community legal and technical capacity-building (Ameha et al., 2014).

6. Leverage International Support and Cooperation

Ethiopia should actively use platforms like the ABS Clearing-House and leverage the Nagoya Protocol's capacity-building funds (UNDP, 2020). Bilateral agreements with major user countries and research institutions can establish shared compliance responsibilities. Engaging in African Union frameworks can further amplify Ethiopia's voice on global forums dealing with disclosure of origin, user compliance, and DSI governance (Nijar, 2011; African Union Commission, 2015).

7. Integrate ABS with National Development and Climate Initiatives

Mainstreaming ABS into Ethiopia's Climate Resilient Green Economy (CRGE) strategy and the Sustainable Development Goals (SDGs) By showing how ABS contributes to poverty reduction (SDG1), industry innovation (SDG9), reduced inequalities (SDG10), life on land (SDG15), etc. It can elevate its political relevance. Specific targets related to benefit-sharing, community adaptation, and biodiversity-based enterprise should be embedded in national development planning. Linking ABS to climate resilience and innovation especially in agriculture and health can unlock international finance and demonstrate ABS as a cross-sectoral development tool.

In conclusion, EBI must spearhead a coordinated, multi-level reform agenda that links policy, law, and practice. By prioritizing decentralized implementation, legal modernization, and robust monitoring, Ethiopia can realize the full value of its genetic resources and reposition ABS as a pillar of sustainable development.

A functional ABS regime will attract more responsible research and bio-investment into the country, as companies and institutions gain confidence in clear rules and streamlined procedures. Ethiopian communities will begin to see real benefits; monetary and non-monetary from the use of their resources and knowledge, incentivizing them to conserve biodiversity and maintain traditional practices. Instances of biopiracy will be deterred or confronted, ensuring Ethiopia's sovereignty is respected. Over time, ABS could evolve from a little-known legal concept into a pillar of Ethiopia's approach to sustainable development, contributing to livelihoods, scientific capacity, and ecosystem health.

Ultimately, an effective ABS regime should be understood as sovereignty-in-action: a practical governance system that translates constitutional and statutory ownership into measurable conservation outcomes, fair economic participation, and accountable utilization of biodiversity. If Ethiopia couples its strong legal foundations with interoperable information systems, domestic checkpoints, credible monitoring, and community-centered benefit delivery, ABS can shift from a compliance obligation to a development instrument that protects national interests while enabling responsible innovation.

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CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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ANALYSIS OF THE ESSENTIAL OIL COMPOSITION AND NUTRITIONAL VALUE OF THE AERIAL PARTS OF *HELICHRYSUM SPLENDIDUM* (THUB.) LESS. FROM THE MENZE GUASSA CONSERVATION AREA, ETHIOPIA

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ABSTRACT:The main objective of this study was to investigate the essential oil composition and nutritional value of *H. splendidum* collected from the Menze Guassa community conservation area. Aerial parts of the target species were collected at the flowering stage through purposive sampling. Three plots, each measuring 10 meters by 10 meters, were randomly placed within dense populations at two different sites. Hydro distillation of the aerial parts yielded 0.6% essential oil, and gas chromatography-mass spectrometry (GC-MS) analysis identified 48 compounds. The GC-MS results indicate that τ-Muurolol (13.49%), β-Pinene (13.21%), naphthalene derivatives (12.95%), and τ-Cadinol (9.16%) are the most prominent compounds. This specific profile suggests a unique chemotype, likely influenced by high altitude and environmental stress. Furthermore, nutritional analysis revealed a crude protein (CP) content of 7.7

5%, and the in vitro organic matter digestibility (IVOMD) result was 51.26%. The concentration of neutral detergent fiber (NDF) was 61.30%, while the metabolizable energy (ME) value was 7.42 MJ/kg. The analysis also indicated a total ash value of 5.30%. The dominance of β-Pinene and τ-Cadinol highlights the significance of antimicrobial and anti-inflammatory potential, while the high level of τ-Muurolol suggests future applications in eco-friendly pest management. The current findings underscore the importance of *H. splendidum* for both pharmacological and ecological uses, serving as an optimal forage resource for ruminants and emphasizing the need to conserve the Menze Guassa community conservation area. Further research should be conducted on bioactive assays and genetic analysis to characterize chemotype variation and ensure the sustainable utilization of this valuable plant resource.

Key words: chemotype,crude protein, forage resource, gas chromatography-mass spectrometry, τ-Muurolol,

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INTRODUCTION

The genus Helichrysum is a highly diversified member of the Asteraceae family, comprising more than 500 species distributed worldwide, including Europe, Africa, Australia, North America, and Madagascar (Cavalli et al., 2001; Mashigo et al., 2015). In Ethiopia, 23 distinct species have been identified and recorded in the Flora of Ethiopia (Hedberg, 1996). Among these, *Helichrysum splendidum* (Thunb.) Less. is a woody shrub of the Afro-alpine ecosystem, occurring at altitudes between 2,500 and 4,300 m above sea level. The shrub is characterized by silvery-gray foliage, fragrant yellow flowers, and a typical height ranging from 20 to 75 cm (Hedberg, 1996). Its competitive growth and nutrient uptake can challenge native grasses, underscoring its ecological significance (Wube et al., 2021).

Globally, Helichrysum species attract considerable scientific interest due to their chemical constituents and medicinal potential. Several studies have shown that the plant contains various bioactive compounds, including flavonoids, terpenoids, and essential oils, which contribute to its antioxidant, anti-inflammatory, and antimicrobial properties (Lourens et al., 2008). Research has demonstrated that the essential oil composition of *H. splendidum* can vary significantly with geographic location and climatic conditions (Komape et al., 2014; Lourens et al., 2004; Mashigo et al., 2015; Mathekga & Meyer, 1998).

Ethiopian scholars have also reported increasing research interest in the chemical composition of essential oils (Abebe et al., 2018; Assefa et al., 2023; Black Solis et al., 2020; Buta & Kinki, 2023; Kebede et al., 2021; Matebie et al., 2023; Shiferaw et al., 2019; Tesfay et al., 2022). However, comprehensive phytochemical and nutritional data on Ethiopian *H.splendidum* populations remain scarce. This knowledge gap limits understanding of the plant's potential applications in diet and health. The lack of information not only concerns essential oil composition but also extends to the plant's traditional uses and nutritional status. Characterizing the chemical constituents could promote the sustainable use of *H.splendidum* in natural health products, cosmetics, and eco-friendly pest control. Similarly, evaluating its nutritional content may create opportunities for its use as a dietary supplement or food additive, providing essential nutrients, minerals, and antioxidants. Assessing the nutritional content of *H. splendidum* is particularly important in the Ethiopian context, as it may enhance its utilization as a dietary supplement. In addition, such evaluations help elucidate plant adaptations in Afro-alpine ecosystems and provide data to inform sustainable management practices under increasing environmental pressures.

Despite its abundance and wide distribution in Afro-alpine ecosystems, *H. splendidum* remains underexploited in Ethiopia, although it is locally used as a fuel source and for home fumigation (Chengere et al., 2022). The motivation for conducting this research on nutritional status and essential oil composition arose during direct field observations of sheep browsing on this species, suggesting its potential as a dietary component within the study area ecosystem.

This research therefore provides a comprehensive analysis, including the chemical profile of essential oil, macronutrients, and nutritional value of the study plant. Understanding the nutritional value of these populations is crucial for assessing their potential as dietary supplements and as forage resources in Afro-alpine ecosystems (Tessema, 2017). The specific focus was supported by standardized methods for evaluating forage quality for ruminants, particularly fiber-based metrics developed by Van Soest (Van Soest, 1994).

We hypothesize that *H. splendidum* from the Menze-Guassa area possesses a distinct and complex chemical profile, with essential oils containing a diverse range of volatile compounds, and that the plant material exhibits significant nutritional value through high concentrations of essential minerals.

The main objective of this study was to identify the chemical composition of *H.splendidum* essential oil using Gas Chromatography-Mass Spectrometry (GC-MS) and evaluate its nutritional properties. Specifically, the study aimed to:

a) Identify the major chemical compounds of *H.splendidum*.

b) Determine the main constituents and assess the nutritional value of the plant.

MATERIALS AND METHODS

Sampling Site

H. splendidum was collected from the Guassa Community Conservation Area in the Menz Gera Midir district of the North Showa zone, Amhara Regional State, Ethiopia. The conservation area's coordinates are between 10°15′–10°27′N and 39°45′–39°49′E, covering an area of 111 km² at altitudes ranging from 2600 to 3560 meters above sea level (m.a.s.l.) (Chengere et al., 2022).

Sample Collection and Preparation

Sampling areas were selected following a reconnaissance survey to represent dense populations of *Helichrysum splendidum* within the study area. In April 2023, 1 kg of aerial plant material was collected at the flowering stage from three independent plots (10 m × 10 m each), labeled AAs-001, AAs-002, and AAs-003, to capture spatial heterogeneity and ensure representative sampling of the study site (Figs. 1–3). Equal amounts of plant material from each plot were pooled to form a single composite, homogenized sample. This composite sample was then subdivided into two portions: one portion (AAs-04) was used for essential-oil extraction and GC–MS analysis, while the second portion (AAs-05) was used for nutritional analysis.

Pooling was adopted to maximize the overall essential-oil yield and to obtain a representative chemical profile of *H.splendidum* across the sampling area. Accordingly, the essential-oil yield was calculated from the pooled composite sample, and plot-specific variation in yield could not be assessed. The objective of the study was to characterize the general chemical composition and major constituents of the species rather than evaluating intra-population chemical variability. Future studies would incorporate true biological replicates and replicate GC–MS analyses to enable quantitative assessment of chemical variability among sampling plots.

The chemical composition of *H. splendidum* essential oil is known to vary significantly in response to environmental factors (Marongiu et al., 2006). To minimize this variability and obtain a comprehensive representation of the plant's chemical profile, aerial parts comprising stems, leaves, and flowers were collected and pooled. These plant parts were selected due to their known richness in essential oils and bioactive compounds. Immediately after collection, samples were packed in plastic bags to minimize the loss of volatile constituents and prepared for subsequent laboratory analyses.

Figure 1.*H. splendidum* with a large canopy due to a recent fire

Figure 2. Dense *H. splendidum* lining the walkway

Figure 3. Expansion of *H. splendidum* overtaking Festuca macrophylla

Essential Oil Extraction

To maintain the integrity of the essential oils, the designated sample (AAS-04) was dried in a shaded, well-ventilated area before being ground. The ground sample was then subjected to hydro-distillation for 3 hours in a Clevenger apparatus with 2 liters of water. The resulting essential oil was dried with anhydrous Na_2SO_4, transferred to sealed vials, and stored at 4°C until chemical analysis.

Chemical Composition Analysis

The chemical composition of the essential oil was analyzed by Gas Chromatography-Mass Spectrometry (GC-MS), following the protocol of Béguin et al. (2006), a common method for analyzing volatile compounds. The GC-MS analysis was carried out on a 7890B GC system connected to a DB-5MS capillary column at Jije Analytical Testing Service Laboratory (Tabel 1). The operating conditions were as follows: inlet temperature 260°C, helium flow 1 ml/min, and a temperature program: 40°C held for 3 min, ramped to 90°C at 4°C/min (held for 3 min), ramped to 170°C at 4°C/min (held for 3 min), ramped to 230°C at 6°C/min (held for 4 min), and finally to 270°C at 10°C/min (held for 1 min). Compound identification was achieved by comparing the mass spectra with the NIST 62 library (McLafferty and Stauffer, 1989)

Nutritional Analysis

Calibration was conducted to develop a spectrochemical prediction model by integrating NIRS spectral data with reference laboratory values to generate predictive equations, following the approach described by Stuth et al. (2003). Samples designated for nutritional analysis (AAS-05) were ground to pass through a 1-mm sieve and pre-dried overnight at 60 °C to standardize moisture content prior to scanning. Visible–near infrared (Vis–NIR) spectra were collected over the wavelength range of 1108–2492 nm at 8-nm intervals, and spectra were averaged for each sample.Because only two samples of *H.splendidum* were available for nutritional analysis, a mixed forage sample population was used for calibration and validation. Calibration equations were developed and validated using stepwise multiple linear regression. Key nutritional parameters, including dry matter (DM), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and metabolizable energy (ME), were predicted to provide a comprehensive assessment of forage nutritive value (Table 2). All analyses were performed using Near Infrared Reflectance Spectroscopy (NIRS) at the Animal Nutrition Laboratory of the International Livestock Research Institute (ILRI), Addis Ababa, Ethiopia.

RESULT

Chemical composition and nutritional values of *H. splendidum* from the two sampling sites are presented in Tables 1 and Tabel 2, respectively. Essential oil extracted from the aerial parts of *H. splendidum* via hydro-distillation yielded a yellow, fragrant oil at 0.6% of dry weight. The GC-MS analysis detected 48 chemical components, accounting for 93.93 % of the oil composition. The main constituents identified were τ-Muurolol (13.49%), β-Pinene (13.21%), naphthalene derivatives (12.95%), τ-Cadinol (9.16%), β-Guaiene (6.25%), and α-Muurolene (5.19%).Near Infrared Reflectance Spectroscopy values for the prediction of DM, Ash, CP, NDF, ADF, ADL, ME and IVOMD (on DM bases) *H. splendidum* samples were presented in Tables,1,2 and 3.

Dry Matter (DM) in the present study indicated moderate predictive results for 1.58 standard deviation (SD) (1.58), standard error of calibration (SEC) (0.72%) and coefficient of determination (R^2) (0.80). while, the highest coefficient of determination for calibration (R2) and coefficient of determination for cross-validation (1-VR) were 0.95 and 0.95 for Ash, 0.99 and 0.98 for CP, 0.98 and 0.97 for NDF and 0.98 and 0.98 for ADF that followed by 0.92 and 0.91 for ME, and 0.92 and 0.91 for IVOMD; and 0.91 and 0.90 for ADL.NDF, and 0.897 and 0.843 for ADL. The chemical composition of H. splendidum from the two sampling sites is presented in Table 1, while the nutritional values are shown in Tables 2 and 3. Near Infrared Reflectance Spectroscopy values for the prediction of DM, Ash, CP, NDF, ADF, ADL,ME and IVOMD (on DM bases) *H.splendidum* samples were presented in Table 2. The analysis of the nutritional profile of the plant showed (Tabel 3) a dry matter (DM) content of 93.88% .

Tabel 1. Chemical Composition Analysis Using Gas Chromatography-Mass Spectrometry (GC-MS)

S/N	Compound Name	Formula	RT	%Area
1	α-Thujene	C10H16	5.59	0.09
2	α-Pinene	C10H16	5.72	1.32
3	Camphene	C10H16	6.00	0.11
4	Sabinene	C10H16	6.36	1.81
5	β-Pinene	C10H16	6.46	13.21
6	α-Phellandrene	C10H16	6.90	0.37
7	Terpinolene	C10H16	7.07	0.14
8	o-Cymene	C10H14	7.20	0.78
9	β-Phellandrene	C10H16	7.31	3.37
10	cis-Sabinene hydrate	C10H18O	7.55	0.12
11	3-Carene	C10H16	7.73	0.29
12	Octanoic acid, methyl ester	C9H18O2	8.25	0.15
13	trans-Pinocarveol	C10H16O	9.11	0.24
14	Pinocarvone	C10H14O	9.43	0.12
15	endo-Borneol	C10H18O	9.59	0.07
16	Terpinen-4-ol	C10H18O	9.69	0.48
17	(-)-Myrtenol	C10H16O	9.93	0.63
18	α.-Cubebene	C15H24	12.03	0.10
19	α.-Muurolene	C15H24	12.37	0.22
20	α.-Copaene	C15H24	12.45	0.78
21	(-)-.β.-Bourbonene	C15H24	12.58	0.40
22	Methyleugenol	$C11H_{14}O_2$	12.77	0.16
23	Caryophyllene	C15H24	13.06	0.29
24	β-Cubebene	C15H24	13.18	0.12
25	(1S,4S,4aS)-1-Isopropyl-4,7-dimethyl-1,2,3,4,4a,5-hexahydronaphthalene	C15H24	13.43	0.22
26	Humulene	C15H24	13.53	0.16
27	Naphthalene, 1,2,3,4,4a,5,6,8a-octahydro-	C15H24	13.59	1.80

S/N	Compound Name	Formula	RT	%Area
	7-methyl-4-methylene-1-(1-methylethyl)-, (1.alpha.,4a.beta.,8a.alpha.)-			
28	γ-Muurolene	C15H24	13.73	1.17
29	Germacrene D	C15H24	13.85	0.31
30	γ-Cadinene	C15H24	14.23	3.31
31	Naphthalene, 1,2,3,5,6,8a-hexahydro-4,7-dimethyl-1-(1-methylethyl)-, (1S-cis)-	C15H24	14.27	12.95
32	α-Cadinene	C15H24	14.51	0.63
33	α-Calacorene	C15H20	14.58	0.21
34	Cubebol	$C15H_{26}O$	14.75	0.23
35	β.-Guaiene	C15H24	15.04	6.25
36	Spirojatamol	$C15H_{26}O$	15.13	1.69
37	Viridiflorol	$C15H_{26}O$	15.28	4.93
38	Globulol	$C15H_{26}O$	15.41	0.69
39	(1S,3aS,4S,5S,7aR,8R)-5-Isopropyl-1,7a-dimethyloctahydro-1H-1,4-methanoinden-8-ol	$C15H_{26}O$	15.45	4.50
40	Di-epi-1,10-cubenol	$C15H_{26}O$	15.63	1.79
41	τ-Cadinol	$C15H_{26}O$	15.80	9.16
42	τ-Muurolol	$C15H_{26}O$	15.97	13.49
43	Jatamansone	$C15H_{26}O$	16.22	1.95
44	γ-Himachalene	C15H24	16.44	0.11
45	(4aS,8S,8aR)-8-Isopropyl-5-methyl-3,4,4a,7,8,8a-hexahydronaphthalen-2-yl) methanol	C15H24O	16.57	0.18
46	(3R,3aR,5R,6R,7aR)-3,6-Dimethyl-5-(prop-1-en-2-yl)-6-vinylhexahydrobenzofuran-2(3H)-one	$C15H_{22}O_2$	17.72	0.72

S/N	Compound Name	Formula	RT	%Area
47	2-Naphthalenecarboxylic acid, 1,2,3,4-tetrahydro-3-hydroxy-8-methoxy-, ethyl ester	C14H18O_4	19.33	1.87
48	Aminoglutethimide	$C_{13}H_{16}N_2O_2$	19.91	0.24
				93.93

The analysis of the nutritional profile of the plant showed a dry matter (DM) content of 93.88% and a total ash content of 5.30%. Key nutritional components included a crude protein (CP) content of 7.75% and a metabolizable energy (ME) value of 7.42 MJ/kg DM. Fibre analysis showed neutral detergent fiber (NDF) of 61.30%, acid detergent fibre (ADF) of 52.53%, and acid detergent lignin (ADL) of 15.65%. Furthermore, the in vitro organic matter digestibility (IVOMD) was determined to be 51.26%.

Tabel 2. Results of the calibration and validation equation

Chemical components	Calibration			Validation	
	SD	SEC(%)	R^2	SECV(%)	1-VR
DM(%)	1.58	0.72	0.80	0.72	0.79
Ash(%)	6.70	1.45	0.95	1.5	0.95
CP(%)	7.00	0.85	0.99	0.88	0.98
NDF(%)	16.80	2.63	0.98	2.75	0.97
ADF(%)	11.85	1.62	0.98	1.69	0.98
ADL(%)	2.345	0.72	0.91	0.75	0.90
ME(MJ/DM Kg)	1.355	0.39	0.92	0.40	0.91
IVOMD(%)	8.75	2.55	0.92	2.64	0.91

R2 = coefficient of determination in calibration SEC = standard error of calibration, 1-VR = coefficient of determination of cross validation SECV = error of cross validation.

Table 3. Descriptive statistics of forage chemical composition of *H.splendidum* (Thunb.) Less

Sample no	DM (%)	Ash (%DM)	CP (%DM)	NDF (%DM)	ADF (%DM)	ADL (%DM)	ME MJ/kg DM	IVOMD (%DM)
1	94.61	4.14	5.26	66.87	61.36	16.97	7.87	53.29
2	93.16	6.45	10.23	55.73	43.69	14.32	6.97	49.22
Mean	93.88	5.30	7.75	61.30	52.53	15.65	7.42	51.26

DISCUSSION

Chemical Content and Chemotype

The essential oil extracted from the aerial parts of *Helichrysum splendidum* via hydro-distillation yielded 0.6% of the plant's dry weight. This value is consistent with results reported for other *Helichrysum* species (Ras, 2013). Gas Chromatography–Mass Spectrometry (GC–MS) analysis identified 48 chemical constituents, representing 93.93 % of the total oil composition. The major components were τ-Muurolol (13.49%), β-Pinene (13.21%), naphthalene derivatives (12.95%), and τ-Cadinol (9.16%).The dominance of β-Pinene, a monoterpene, in this analysis agrees with previous findings in other *Helichrysum* species (Lourens et al., 2008). Moreover, the high proportion of sesquiterpenes such as τ-Muurolol and τ-Cadinol is particularly noteworthy. These compounds are known for their antimicrobial, anti-inflammatory, and antioxidant properties (Lourens et al., 2008; Maroyi, 2019), supporting the traditional medicinal uses of *H. splendidum*.

The relatively high concentrations of τ-Muurolol and τ-Cadinol observed in the Menze Guassa population suggest a unique chemotype. Such chemical diversity is likely influenced by environmental conditions specific to the Afro-alpine ecosystem, including altitude, ultraviolet (UV) radiation, and climatic stress, which can affect essential oil composition (Melito et al., 2016; Shiferaw et al., 2019).
Comparative studies from South African and Madagascan populations have reported considerably lower levels of these sesquiterpenes than those detected in this study (Cavalli et al., 2001; Marongiu et al., 2006; Mashigo et al., 2015). This variation may be attributed to marked intraspecific variability within the *Helichrysum* genus, where chemical composition depends on both environmental and genetic factors (Jafari et al., 2016). According to Melito et al. (2016), high-altitude conditions—characterized by strong UV radiation, temperature fluctuations, and low oxygen levels—can induce the synthesis of protective secondary metabolites, thereby influencing essential oil composition.

Nutritional analysis

The calibration and validation statistics demonstrated that the near-infrared reflectance spectroscopy (NIRS) equations used in this study were robust and exhibited high predictive accuracy for most chemical constituents. The performance of the NIRS calibration and validation models for *H.splendidum* was comparable to previously reported results for forage species (Nigam and Blümmel, 2010).

Dry matter (DM) in animal nutrition refers to the fraction of feed remaining after the complete removal of water or moisture. The determination of DM is fundamental for accurately quantifying other chemical constituents in forage, as moisture content in plant feedstuffs can vary widely. Typically, dried feeds contain less than 15% moisture or more than 80% DM (Musa et al., 2021). Consequently, DM determination is among the most routinely performed analyses in animal nutrition laboratories (Musa et al., 2021).

The DM content of *H. splendidum* observed in the present study was comparable to that reported for *Vachellia seyal* (Delile) P.J.H. Hurter (93.6%) and *Cordia africana* (93.9%) (Belete et al., 2024), as well as *Vachellia nilotica* (L.) (93.5%) (Deraro and Kitaw, 2018) and was higher than the DM content of most multipurpose fodder trees, shrubs, and indigenous browse species previously studied in Ethiopia (Tesfaye et al., 2020; Belete et al., 2024). Similarly, the DM content was comparable to that reported for the leaves of *Helichrysum odoratissimum* (93.9%) (Afuape et al., 2022), as well as the fruits and leaves of *Mussaenda arcuata* (94.11%), *Celosia trigyna* (94.48%), and *Pteridium aquilinum* (94.41%) (Daba et al., 2025).

The high DM content of *H. splendidum* indicates a low moisture level, which may be associated with a more fibrous plant structure. Such a characteristic is advantageous for storage, as it reduces the risk of microbial growth and spoilage (Afuape et al., 2022).

Ash content, which reflects the mineral composition of forage, was moderate in H. splendidum. The ash value recorded in this study was comparable to that of the stem fraction (5.27%) but lower than the leaf fraction (10.07%) of H. odoratissimum (Afuape et al., 2022), and slightly lower than that reported for A. nilotica (5.6%) (Belete et al., 2024).

The crude protein (CP) content of *H. splendidum* met the minimum requirements necessary to support rumen microbial activity and maintenance in ruminants (Van Soest et al., 1991). Its CP content was similar to that reported for the leaves of *H. odoratissimum* (7.75%) but higher than that of the stem fraction (Afuape et al., 2022). In contrast, the neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were higher than those reported for *H. odoratissimum* (45.56% and 32.31%, respectively) (Afuape et al., 2022) and comparable to the NDF (59.14%) and ADF (52.53%) values reported for *Cordia africana* (Debela et al., 2017).

Between the two analyzed samples, sample 2 exhibited higher CP and lower NDF contents than sample 1, which may be attributed to differences in morphological composition, particularly the leaf-to-stem ratio (Aydin et al., 2022; Belete et al., 2024). Overall, the mean CP content of *H. splendidum* was higher, while its NDF content was lower, than the average values reported for several grass species in Ethiopia (Keba et al., 2013).

Furthermore, the in vitro organic matter digestibility (IVOMD) and metabolizable energy (ME) values of H. splendidum were comparable to those of common indigenous browse species such as Acacia tortilis (53.8% IVOMD) and Balanites aegyptiaca (7.3 MJ/kg DM ME) (Belete et al., 2024).

Variations in chemical composition and forage quality among species and sites may be influenced by factors such as soil fertility, seasonal conditions, and stage of harvest. Overall, the laboratory results indicate that *H. splendidum* possesses a favorable nutritive profile for ruminant livestock, with ADF (52.53%) and acid detergent lignin (ADL; 15.65%) values within acceptable limits, and CP (7.75%), NDF (61.36%), ME (7.42 MJ/kg DM), and IVOMD (51.26%) values sufficient to meet maintenance requirements (Van Soest et al., 1991; Kenkel et al., 1989).

Implications for Potential Applications

The unique chemical profile of *H. splendidum* populations from the Menze Guassa conservation area has several practical implications. The dominance of β-Pinene and τ-Cadinol, known for their antimicrobial and anti-inflammatory activity (Lourens et al., 2008), indicates the essential oil's potential use in pharmaceuticals, therapeutics, and the cosmetics industry (Agidew, 2022).

Furthermore, the high concentration of the sesquiterpene τ-Muurolol suggests future applications in eco-friendly pest management, as it has been reported to possess insect-repellent effects (Black Solis et al., 2020). Additionally, it has been recognized that *H. splendidum* is a highly competitive species that challenges endemic grasses like *Festuca macrophylla* (Wube et al., 2021). The findings of this study, which characterize the shrub oil composition and nutritional content, support the sustainable utilization of this plant as it is an underutilized resource, offering a management approach that benefits both conservation efforts and local economic interests.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This research has limitations. First, studying one population restricts our ability to generalize our findings. Comparative studies across different Ethiopian habitats should be conducted to verify the consistency of the chemotype and assess environmental effects on chemical variation. Second, while the GC-MS provided comprehensive chemical identification, it lacks concurrent bioactive tests, and the pharmacological potential currently remains hypothetical.

Future research must include bioactivity analysis of the major constituents, such as antimicrobial, anti-inflammatory, and antioxidant activity, to confirm traditional uses and explore new therapeutic promise (Kebede et al., 2021). Investigating synergistic interactions between compounds is also important, as the combined effect of multiple compounds may enhance overall bioactivity (Zheng et al., 2021). Finally, genetic studies across different altitudes and climatic regimes will help illuminate the role of environmental adaptation in driving chemotypic variation.

CONCLUSION

This research successfully characterized *H.splendidum* from the Menze Guassa area, which has dual significance as both a source of unique bioactive compounds and a critical livestock supplement. Essential oil analysis revealed a distinct chemotype likely influenced by the high altitude, with major constituents including τ-Muurolol (13.49%), β-Pinene (13.21%), and τ-Cadinol (9.16%). The latter two indicate potential for antimicrobial and anti-inflammatory applications.Nutritional analysis of

H.splendidum falls within the optimum threshold values for use in ruminant diets, particularly regarding its ADF (52.53%) and Acid Detergent Lignin (ADL 15.65%) values. This finding confirms the direct field observations of sheep browsing on the plant and validates its role as a critical and viable dietary component within the study area. The detected variation in nutrients between sampling sites, with higher CP and lower NDF, results from factors such as soil fertility or harvest stage, which influence the final nutritional quality and warrant further investigation.

RECOMMENDATION

The findings of this study reveal that *H.splendidum* (Thunb.) Less. essential oil from the Menze Guassa Conservation Area possesses unique chemical constituents and significant nutritional potential, highlighting its ecological and economic importance. It is therefore recommended that further detailed studies be conducted to evaluate its pharmacological and therapeutic properties, as well as to assess variations in chemical composition across different ecological zones and seasons.

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ECONOMIC LOSS OF LIVESTOCK DEPREDATION AND ITS CONSERVATION IMPLICATION IN ETHIOPIA

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ABSTRACT: In Ethiopia human carnivore conflict (HCC) is escalating. Human population expansion, habitat destruction, and increasing disturbance in or around wildlife-inhabiting regions are some of the major drivers of human carnivore conflict (HCC). A large number of literatures and pre reviewed papers were used and SPSS software was used to analyze the number of predated livestock and identify which predator causes more predation per household. Livestock depredation and attacks on predation on managed wild animal species are all regular HCC concerns. This makes the income of the society were condensed and faced food crises in the country. *Canis aureus, Crocuta crocuta, Papio anubis*, *Panthera leo* and *Canis lupaster* are just a few of the animals who have taken part in the HCC and influenced the economy of the country. In Ethiopia, several papers on the human carnivore conflict are published but the presentation is very inconsistent which makes a good picture of main predators, livestock types predated, economic loss of predation per household difficult. The goal of this article is to review vast amount of information on the causes and consequences of HCC, predator–prey patterns across regions, household economic losses, and current conflict-mitigation strategies. Across the reviewed studies, a total of 8,590 livestock individuals were reported lost to carnivore depredation, resulting in an estimated economic loss of USD 90,072. Sheep and cattle emerged as the most heavily depredated livestock species, followed by goats, with losses disproportionately affecting households located near protected areas and community-managed forests. Livestock loss per household ranged from 0.07 to 6.66 animals, while household-level economic losses varied from USD 2.84 to USD 252.27, indicating strong spatial heterogeneity in livelihood impacts. Spotted hyena (*Crocuta crocuta*) and leopard (*Panthera pardus*) were the most frequently reported predators, followed by lions, African wolves, and Ethiopian wolves, with predator assemblages varying across landscapes. As a result, this data is vital in supporting policymakers and ecologists in formulating land use plan strategies to reduce HCC in Ethiopia, as well as developing fruitful and replicable wildlife educational and training activities.

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Key words: carnivore attacks, conflict mitigation, human–carnivore conflict, predator–livestock conflict

INTRODUCTION

Carnivores represent one of the most diverse groups of mammals, with approximately 250 extant species globally (Upham et al., 2019). Most species are primarily predators, and their ecological role depends on the availability of natural prey. However, rapid land-use change, decline of wild herbivore populations, and habitat fragmentation increasingly force carnivores to shift toward livestock as alternative prey (Ripple et al., 2014; Oriol-Cotterill et al., 2015). This shift escalates human–carnivore conflict, particularly in pastoral and agro-pastoral systems, where livestock losses often trigger retaliatory killing of carnivores through spearing, poisoning, or trapping (Kissui, 2008; Lichtenfeld et al., 2015; Carter & Linnell, 2016; Admasu et al., 2022).

Recent studies across Africa and Asia shows that declining natural prey density remains one of the strongest predictors of livestock depredation and subsequent carnivore persecution (Khorozyan & Waltert, 2019; Moghari et al., 2020; Loveridge et al., 2022). Carnivores play a critical role in maintaining ecosystem structure and function by regulating herbivore populations, suppressing mesopredators, and influencing vegetation dynamics (Ripple et al., 2014; Prugh et al., 2009). Their ecological importance is widely recognized in trophic cascade research, where the removal or decline of apex carnivores leads to ecosystem destabilization (Estes et al., 2011; Atkins et al., 2019). Given their ecological significance, conserving carnivore populations requires a clear understanding of human carnivore conflict patterns, including the extent of livestock predation, dominant predator species involved, and the effectiveness of locally used mitigation strategies (Carter & Linnell, 2016; Khorozyan & Waltert, 2019). Recent studies

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emphasize that community-based coexistence approaches, informed by accurate assessments of predation levels and local perceptions, are essential for sustainable carnivore management and for reducing conflict across rangeland landscapes (Lichtenfeld et al., 2015; Loveridge et al., 2022).

Carnivores require high-protein diets and occupy extensive home ranges, which frequently bring them into competition with humans, especially in landscapes surrounding protected areas (Carter & Linnell, 2016; Van Eeden et al., 2018). Many large carnivores are specialized ungulate predators, and when natural prey availability declines, individuals readily shift to depredating livestock, which is energetically profitable and often easier to catch (Khorozyan & Waltert, 2019; Cozzi et al., 2020). Consequently, livestock predation remains the most widespread driver of human–carnivore conflict globally (Inskip & Zimmermann, 2009; Khorozyan et al., 2020). Although less common than livestock losses, attacks on humans do occur and generate intense fear and trauma within affected communities, often leading to retaliatory killing of carnivores (Packer *et al.,* 2019; Loveridge *et al.*, 2022). The identity of conflict-causing carnivores varies regionally: wolves and bears dominate conflicts in Europe and North America, jaguars and tigers in South America and Asia, and leopards, hyenas, lions and jackals in much of sub-Saharan Africa (Ripple *et al.,* 2014; Broekhuis *et al.,* 2020).

In many rural communities in developing countries, human–carnivore conflict imposes substantial but highly variable economic burdens, often representing one of the most significant livelihood risks for households dependent on livestock (Miller *et al.,* 2016; Mkonyi *et al.,* 2017). Frequent livestock losses reduce local tolerance toward carnivores, reinforcing negative attitudes and driving retaliatory killing, which in turn contributes to population declines of threatened

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species (Kansky *et al.,* 2016; Carter *et al.,* 2020). Studies across Africa and Asia show that intolerance increases sharply when economic losses exceed household income thresholds, highlighting the link between financial impacts and conservation outcomes (Khorozyan & Waltert, 2019; Elliott et al., 2020). Preventing further population declines and local extinctions therefore requires improved understanding of the ecological and socio-economic drivers of conflict, as well as the conditions that enable long-term coexistence between humans and carnivores in shared landscapes (Van Eeden *et al.,* 2018; Loveridge *et al.*, 2022).

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METHODOLOGY

This study employed a narrative literature review approach. Relevant studies were retrieved from Google Scholar, Web of Science, Scopus, ScienceDirect, PubMed, and African Journals Online using the keywords ―human–carnivore conflict,‖ ―livestock depredation Ethiopia,‖ ―carnivore attacks,‖ ―predator–livestock conflict,‖ and ―conflict mitigation.‖ Literature published between 2009 and 2024 was considered, with earlier studies included when essential for context. Only studies conducted in Ethiopia and reporting data on carnivore species, livestock losses, human impacts, or community responses were included. In total, 32 publications met the inclusion criteria. Key information such as predator species involved, types of conflict, livestock loss, and mitigation measures was extracted and synthesized thematically to provide an overview of human–carnivore conflict patterns across Ethiopia.

Human carnivore conflict in Ethiopia

Ethiopia is no exception to the widespread challenge of human–carnivore conflict, and livestock losses to hyenas, common jackals, leopards, lions, African wolves and the endemic Ethiopian wolf are well documented across different ecological regions of the country (Aberham *et al.*, 2017; Ayenew Biset et al., 2019; Misganaw *et al.,* 2020). Recent studies further confirm that spotted hyenas remain the predominant livestock predators in many highland and lowland systems, while leopards and African wolves are major threats in forested and Afro-alpine landscapes, respectively (Salahadin & Dereje, 2021; Zelalem *et al.,* 2021; Hailu *et al.,* 2022). In Ethiopia, several papers are published on the human wildlife conflict but their very inconsistent presentation makes it difficult to obtain a good picture of main predators, livestock types predated, economic loss of predation per household difficult (Mesele Yihune *et al*., 2009; Fikirte Gebresenbet *et al*., 2018; Anagaw *et al.,* 2010 and 2017; Misganaw *et al.,* 2020).

Increasing human population which cause habitat encroachment and land-cover changes and reduce the number of natural prey species worsen livestock predation, (Aberham Megaze *et al*., 2017; Ayenew *et al.,* 2019; Yigrem *et al.,* 2016; Gidey and Bauer, 2010; Getahun *et al*., 2021; Fikirte *et al*., 2018). The level of livestock predation varied a lot from different regions depending on the predators' density and livestock management (Soulsbury and White, 2012).

Major factor escalating human carnivore conflict

Population growth

As the world's population continues to grow and technological expansion accelerates, the demand for agricultural and pastoral land has intensified, particularly in developing countries. This expansion often results in habitat degradation, fragmentation, and conversion of natural ecosystems into farmland and settlement areas (Hannah *et al.,* 2020; Song *et al*., 2021). Shifting cultivation, land clearing, and encroachment for crop cultivation and livestock grazing increasingly alter ecological landscapes and reduce habitat availability for wildlife (Goldstein *et al.,* 2020). Human activities have now modified more than half of the Earth's terrestrial surface, with profound ecological consequences for biodiversity and ecosystem functioning (Ellis *et al.,* 2021).

Rapid global population growth currently exceeding 8 billion continues to drive land-use change, resource extraction, and expansion of human-dominated landscapes (United Nations, 2022). Ethiopia mirrors these global trends: with its population increasing from approximately, as indicated in Fig.1,42 million in 1984 to over 120 million in 2023, and is projected to surpass 150 million by 2035 (CSA, 2023). This demographic growth has intensified pressure on forests, rangelands, and protected areas, leading to habitat loss, reduced prey availability, and increased spatial overlap between people, livestock, and wildlife (Tefera *et al.*, 2019; Gashaw & Bekele, 2021). Consequently, expanding agricultural frontiers and settlement areas heighten the frequency of human–wildlife interactions and elevate the risk of conflict, posing a growing threat to biodiversity conservation across Ethiopia (Alemayehu *et al.*, 2022).

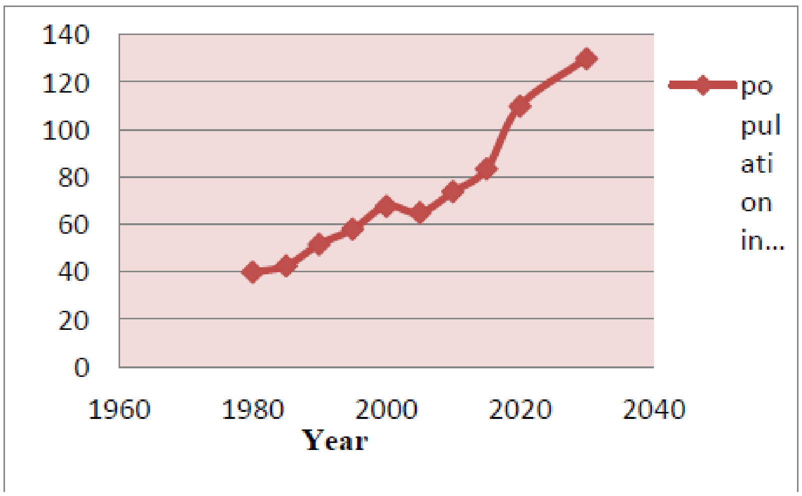

Figure 1. Trends of Human population growth in Ethiopia (Source of data: CSA and ICF International, 2011).

The Bale Mountains National Park, for example, has experienced increasing pressure from a steadily growing population (population is increasing almost linearly). Similarly, the human population in and around the Simien Mountains National Park has increased, and the local community has taken advantage of the park to graze their animals. Those who lived close to the park were able to take advantage of the resources all year (Mesele *et al*., 2009). Similarly, wildlife has been a major source of conflict with local communities due to the proximity of local residents' farmlands to wildlife habitats in various countries in the region (Anagaw *et al*., 2017;

Hailemariam, 2017). Human population growth, insufficient national or municipal land-use plans for districts surrounding the park, a lack of public understanding, and a poor attitude toward wildlife and conservation among the people all contribute to an increase in human-animal conflict.

Habitat Destruction and Disturbance

Habitat destruction refers to the loss or severe alteration of a wild animal's natural environment, which reduces the availability of critical resources such as forage, nesting sites, and breeding areas. Human activities—including tree cutting for charcoal, clearing land for settlement, livestock overgrazing, bush encroachment, regular burning, and obstruction of habitats—are major drivers of habitat degradation in Ethiopia (Getahun Shanko *et al.*, 2020; Mekonen *et al.*, 2020). These disturbances not only reduce plant cover but also fragment landscapes, limiting the space available for wildlife and increasing the likelihood of human–wildlife conflict (Leta *et al.*, 2016; Tefera *et al*., 2019).

Recent assessments indicate that habitat disturbance is among the leading causes of human–wildlife conflict in Ethiopia (Admasu *et al.*, 2022). For instance, increasing settlement and land-use change in Chato Forest, Western Ethiopia, and Gera District, Southwestern Ethiopia, have intensified conflicts with carnivores and other wildlife (Leta *et al*., 2016; Gashaw & Bekele, 2021). Encroachment by growing human populations has exacerbated wildlife habitat loss and fragmentation, elevating the risk of livestock depredation and crop damage (Demeke & Afework, 2013; Alemayehu *et al.*, 2022). Notably, a decade-long (1999–2009) human–leopard conflict near the Borena–Sayint National Park border resulted in seven human fatalities and the retaliatory killing of two leopards, highlighting the direct consequences of habitat disturbance on both people and wildlife (Ayenew Biset *et al*., 2019).

Consequences of Human–Carnivore Conflict

Human–carnivore conflict has particularly severe socio-economic and ecological impacts in Ethiopia, where rural livelihoods depend heavily on agriculture and livestock (Kidane *et al.*, 2025). Low-income households and agro-pastoralists, who rely primarily on livestock and crop production, are especially vulnerable to depredation events and related economic losses (Gashaw & Bekele, 2021; Alemayehu *et al.*, 2022).

A wide range of wild carnivores contribute to livestock predation in Ethiopia. Commonly reported species include spotted hyena (*Crocuta crocuta*), leopard (*Panthera pardus*), common jackal (*Canis aureus*), African wolf (*Canis lupaster*), Ethiopian wolf (*Canis simensis*), bat-eared fox (*Otocyon megalotis*), lion (*Panthera leo*), serval (*Leptailurus serval*), caracal (*Caracal caracal*), and occasionally Anubis baboon (*Papio anubis*) (Belayneh & Tolcha, 2020; Bezihalem *et al.,* 2016; Fikirte *et al.,* 2017, 2018; Misganaw et al., 2020; Yigrem Kebede *et al.,* 2016; Tesfaye & Jatni, 2017; Salahadin & Dereje, 2021; Ayenew *et al.,* 2019). The identity and relative impact of predators vary by region, livestock type, and husbandry practices. For example, in Senkele Swayne's Hartebeest Sanctuary, spotted hyenas are the primary predators of cattle, whereas common jackals target sheep in the Choke Mountains and Simien Mountain National Park (Misganaw *et al.,* 2020; Bezihalem *et al.,* 2016; Mesele *et al.*, 2009).

The consequences of predation extend beyond economic losses. Livestock predation reduces household income, undermines food security, and often triggers retaliatory killings of carnivores, further driving biodiversity decline. Human fatalities and injuries, though less frequent than livestock losses, also contribute to heightened fear and negative perceptions toward wildlife (Ayenew *et al.,* 2019; Hailu *et al.,* 2022). Overall, these dynamics create a feedback loop: economic vulnerability drives intolerance, which leads to predator removal, further destabilizing local ecosystems and reducing coexistence opportunities.

Human deaths and injuries

In Ethiopia, human carnivore interactions have resulted in documented fatalities and injuries. For example, on the border of Borena Sayint National Park, seven people were attacked by leopards between 1999 and 2009, leading to the retaliatory killing of two leopards (Ayenew *et al.,* 2019). Around Chebera Churchura National Park, from 2007 to 2011, seven human attacks by lions, five by hyenas, and six injuries caused by leopards were recorded; local communities retaliated by killing two lions, two leopards, and six spotted hyenas (Alemayehu Acha & Temesgen, 2015). Similarly, in the Kafa Highlands between 2009 and 2013, 17 people were killed due to interactions with lions and leopards, while three human fatalities were reported in Gambella National Park from lion attacks (Fikirte *et al.,* 2018).Retaliatory killings often exacerbate biodiversity loss, as species such as leopards are targeted due to perceived threats to human life and livestock during guarding activities (FAO, 2009; Yirga *et al.,* 2013).

Livestock predation

Livestock predation is the most common form of human–carnivore conflict in Ethiopia, directly affecting household income, food security, and attitudes toward wildlife. Large carnivores, including spotted hyenas, leopards, lions, African wolves, and Ethiopian wolves, prey on cattle, sheep, goats, donkeys, horses, poultry, and occasionally pets (Indris , 2021; Belayneh & Tolcha, 2020). Predatory behavior is influenced by prey availability, habitat conditions, and proximity to human settlements. Farmers and resource collectors who enter wildlife habitats for firewood or water are particularly vulnerable to attacks.

Recent studies demonstrate substantial economic impacts. Hailemariam *et al.* (2017) reported that 590 domestic animals were killed in northeastern Ethiopia, causing a household income loss of USD 41,740 from 250 informants. In Bale Mountains National Park, lions and hyenas accounted for 57% and 18% of 704 documented livestock depredations, respectively (Atickem *et al.*, 2010). In Chebera–Churchura National Park, lions, hyenas, and Anubis baboons killed 221 sheep, 306 goats, 206 cattle, 577 chickens, 36 donkeys, and 103 dogs, resulting in significant economic loss (Aberham *et al*., 2017).

At the household level, livestock loss varies with in the study area , predator species, and husbandry practices. In Borena–Sayint National Park and Guassa Mountain Forest, approximately two sheep and over three cattle per household were lost annually in the surrounding districts of Alage College, Central Rift Valley of Ethiopia, while poultry predation was primarily caused by serval and white-tailed mongoose (Misganaw *et al*., 2020; Table 1–3). Variations in carnivore abundance, livestock management, and the relative availability of prey explain differences in depredation patterns across Ethiopia.

Table 1. Livestock depredation and its economic loss in different localities of Ethiopia

Location	No Live stock	Economic loss $	Livestock loss per household	Loss per household $	year of study	Predators	References
BSNP	511	33,300	3.87	252.27	2016 to 2017 and	spotted hyena and leopard	(Ayenew Biset *et al*., 2019)
BMNP	704	13054	1.94	36.06		spotted hyena, leopards and African wolves	Anagaw *et al*., 2010)
BSNP	233	1173.9	1.01	5.1	(2013-2018	Leopards, Spotted hyena and Papio hamadryas	Salahadin and Dereje, 2021
CCNP	1149		3.25		2012–2014	Lions, Leopards, and Spotted Hyena	Aberham *et al*., 2017
CCNP	1,364		4.55		2007 to 2011	Lions, Leopards, and Spotted Hyena	Alemayehu and Mathewos, 2015
SCMCF	745		2.4		2005 to 2007	spotted hyena, common Jackal, Leopard, and Jackal, African wild Dog, Caracal, and Serval	Yigrem *et al.,* 2016
GNP	31		0.89			lions and leopards	Fikirte *et al*., 2018
EKH (kafa)	412	597	1.96	2.84	2009 to 2013	lions and leopards	Fikirte *et al*., 2018
ACCRV	932		6.66		2018 to 2019	spotted hyena, common Jackal, mongoose,	Zelalem *et al*., 2021
GFA	590	41,740	2.36	166.96	2014 to 2015	Common fox, Hyena and Leopard	Hailemariam *et al*., 2017
GMF	492		1.97		1999 to 2002	spotted hyena, African and Ethiopian wolf, Serval	Anagaw *et al*., 2017

AMNP	334		2.30			spotted hyena and, mongoose	Bizuneh *et al.*, 2018
SSH	1062	207	2.81	77.27	2016–2018	spotted hyena and African wolves	Misganaw *et al.*, 2020
KSNP	31		0.07		2014 to 2015	Atakilt Berihun *et al*., 2016	Atakilt *et al*., 2016
Total	8590	90,072	36	541			

Abbreviation: - BSNP (Borena Sayint National Park), Kafa (kafa highlands of Ethiopia), BMNP (Bale Mountain National Park), CCNP (Chebera Churchra National Park), SCMCF (Sodozuria Community managed conservation forest), SSH (Senkele Swayne's Hartebeest Sanctuary), AMNP (Arsi Mountain National Park), GFA (Gemshat Forest Area), GMF (Guassa mountain forest), Alage College, Central Rift Valley

Table 2. Livestock species predated in different localities of Ethiopia

Area	Sheep	Goat	cattle	Donkey	Horse	Poultry	Mule	HH	Year	References
BSNP	0.54	0.30	0.10	0.05	0.02	0.00	0.00	230.00	(2013-2018	Salahadin and Dereje, 2021
Kafa	0.83	0.17	0.26	0.01	0.36	0.00	0.04	210.00	2009-2013	Fikirte *et al.*, 2017
SCMCF	0.82	0.47	0.60	-	-	0.41	0.00	310.00	2005 to 2007	Yigrem *et al.*, 2016
SSH	0.74	0.39	1.47	0.11	0.10	0.00	0.00	378.00	2016–2018	Misganaw *et al.*, 2020
BMNP	0.27	0.30	0.16	0.03	0.12	0.00	0.00	362.00	1999 to 2002	Anagaw *et al.*, 2010
CCNP	1.19	1.29	2.06	0.00	0.00	0.00	0.00	300.00	2007-2011	Alemayehu and Mathewos 2015
CCNP	0.62	0.86	0.58	0.10	0.00	0.00	0.00	354.00	2012–2014	Aberham *et al.*, 2017
AMNP	0.33	0.00	0.37	0.21	0.00	0.66	0.00	145.00		Bizuneh *et al.*, 2018
BSNP	1.98	1.80	0.03	0.05	0.00	0.00	0.00	132.00	2016 – 2017	Ayenew *et al.*, 2019
GFA	1.10	1.20	0.00	0.00	0.06	0.00	0.00	250.00	2014 -2015	Hailemariam *et al.*, 2017
GMF	1.78	0.14	0.00	0.03	0.01	0.00	0.00	250.00		Anagaw *et al.*, 2017

ACCRV	0.35	0.51	3.54	1.12	0.81	0.07	0.26	140.00	2018 -2019	Zelalem *et al*., 2021
Total	0.75	0.59	0.73	0.06	0.07	0.10	0.02			

Table 3. Livestock predation per house hold with their predators

Area	Livestock	Total loss	Loss per House Hold	Predator type									
				1	2	3	4	5	6	7	8	9	10
SCMCF	Sheep	253	0.82	46	65	48	-	27	18	-			
	Goat	147	0.47	31	37	9	-	15	16	-			
	Cattle	186	0.6	71	55	-	-	-	21	-			
	Chicken	128	0.4		11	-	-	-	-	83			
	Donkey	31	0.1	3	6	-	-	-	10	-			
SSH	Sheep	279	0.74	-	212	-	-	-	-	-		67	
	Goat	147	0.39	-	115	-	-	-	-	-		32	
	Cattle	556	1.47	-	556	-	-	-	-	-		-	
	Donkey	43	0.11		43								
	Horse	37	0.09		37								
Kafa	Sheep	209	0.99	35			174						
	Goat	59	0.28	24			35						
	Cattle	56	0.27	2			54						
	Donkey	3	0.01				3						
	Horse	38	0.18	1			37						
	Mules	8	0.04				8						
BMNP	Sheep	241	0.67	17	121	92				11			
	Goat	238	0.66	105	60	24				49			
	Cattle	120	0.33	5	115								
	Donkey	17	0.05		17								
	Horse	88	0.24		88								
CCNP	Sheep	48			48								
	Goat	106			106								
	Cattle	54			54								
	Donkey	30			30								
AMNP	Chicken	96	0.66								96		
GMF	Sheep	445	1.78		11							351	83
	Goat	35	0.14							1		16	18
	Cattle	1	0.004		1								
	Horse	3	0.012		3								
Total		3702	12		1793	173	311	42	65	144	96	466	101

1 (leopard), 2 (Hyena), 3 (Common Jackal), 4 (Lion), 5 (African wild dog), 6 (Caracal), 7 (Serval), 8 (White-tailed mongoose), 9 (African wolves), 10 Ethiopian wolf

Consequences on Wildlife Conservation

Human–carnivore conflict imposes severe consequences for wildlife populations, particularly species most prone to conflict. Anthropogenic mortality including retaliatory killing and hunting has been reported to threaten survival, local population stability, and even contribute to extinctions (Sintayehu & Merkebu, 2019; Gashaw & Bekele, 2021). Such human- induced mortality not only affects the survival of globally endangered species but also disrupts ecological balance and biodiversity (Leta et al., 2016; Alemayehu et al., 2022).

For instance, the Walia ibex (*Capra walie*) population in Simien Mountains National Park has declined due to habitat loss from agricultural expansion (Mesele Yihune et al., 2008). Similarly, in Senkele Wildlife Sanctuary, the area decreased from 200 km² in 1972 to 54 km², and the Swayne's hartebeest population dropped from over 3,000 to approximately 800 individuals due to human settlement and land conversion (BIDNTF, 2010). In Bale Mountains National Park, over 60% of land above 3,200 m has been converted to farmland, contributing to the decline of the endemic Ethiopian wolf (*Canis simensis*), whose population fell from around 700 individuals(Fig.2) in 1986 to 200 in 2000 (BIDNTF, 2010).

Carnivore populations have also been affected. Lion and hyena densities in Ethiopia are estimated at 2–5 and 4–8 individuals per 100 km², respectively, although these estimates include areas with high human encroachment where lions are unlikely to persist (Yirga et al., 2014). Population data on Ethiopian lions remain scarce, yet declines could have serious implications for regional conservation, as Ethiopia forms a critical corridor connecting East and Central African lion populations (Fikirte Gebresenbet et al., 2009).

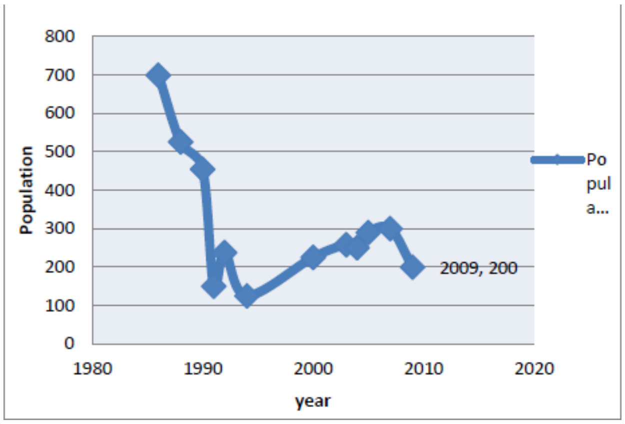

Figure 2. Population trend of Ethiopian wolf in Bale Mountains National Park (Source: BIDNTF, 2010).

Community strategies to mitigate human carnivore conflict

Several proposals for successful human carnivore conflict prevention measures have been offered by researchers from across the country. This section outlines some of the empirical findings of scholars across the countries that have looked into this case. Many Ethiopian farmers use dogs to guard their livestock and livestock enclosures with thorn bush kraals (Yigrem *et al*., 2016; Anagaw Atickem *et al*., 2010; Aberham *et al*., 2017; Getahun *et al*., 2021), voluntary resettlement (Mesele Yihune *et al*., 2009), keeping cattle in houses or fenced fields at night and not grazing livestock in forest (Fikirte *et al*., 2017) and herding their livestock in a herd in the pasture (Alemayehu and Mathewos , 2015) were very effective methods of reducing livestock depredation. Cattle depredation in Southeastern Tigray, Northern Ethiopia, was reduced through habitat burning, killing, and poisoning, according to Gidey and Hans Bauer (2010). Similarly, According to Yigrem *et al.,* (2016) in different villages of around sodo community conservation forest the farmers used different methods, such as guarding with dogs is effective to keep their livestock from predators (Fig.3).

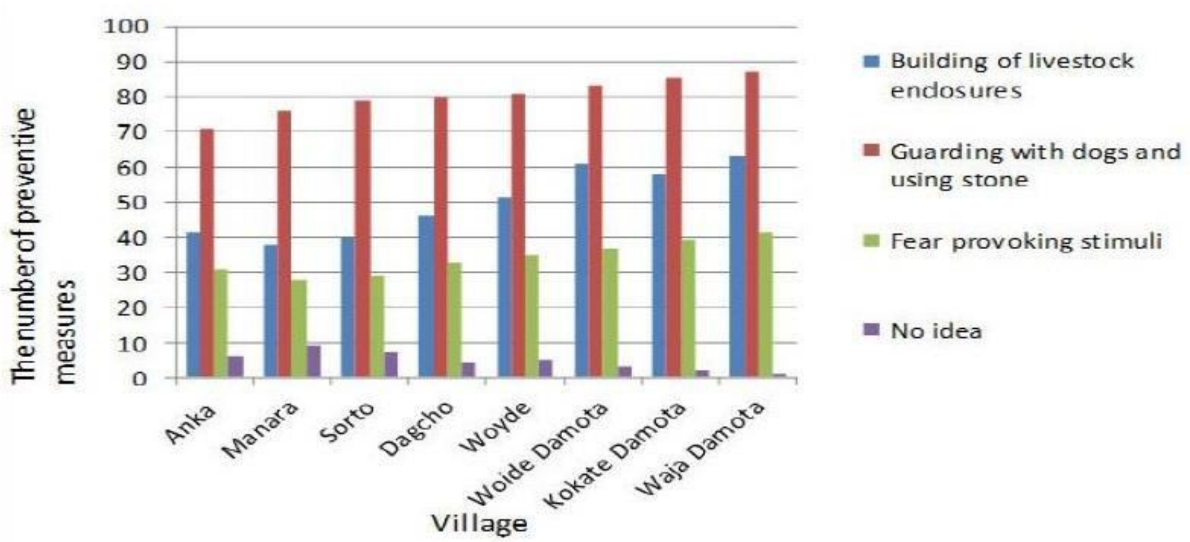

Figure 3. Preventive measures to reduce livestock depredation in relation to distances among different villages around sodo community conservation forest

SUMMARY

The review demonstrated that human-carnivore conflicts in Ethiopia are particularly severe for individuals living within or near protected areas. However, the level of conflict, the source, the effects, and the measures they employed to mitigate the conflict were all different. Spotted hyena, leopard, common jackal, lions, African and Ethiopian wolf, African wild dog, caracal, serval and Common fox are the common carnivores that depredated livestock. Such carnivores were found to cause more losses to the people living in different areas of Ethiopia. The spotted Hyena, leopards and the common Jackal were the most destructive wild carnivores in most areas of Ethiopia. Hyenas prey on more than one cattle per household in Swayne's Hartebeest Sanctuary, and more than two cattle per household were lost in Chebera Churchra National Park.

Around two sheep killed per household in Guasa Mountain forest by Ethiopian wolf, African wolf and hyena. To defend their livestock, they have traditionally used a variety of techniques. Guarding with dogs and building livestock enclosure are the most preventive measures of livestock depredation from predators.

RECOMMENDATIONS

Addressing human–carnivore conflict in Ethiopia requires coordinated efforts between policy makers and local communities. Priority should be given to strengthening locally appropriate mitigation practices, including improved livestock husbandry, construction of secure night enclosures, and strategic use of guarding dogs. Government and conservation agencies should invest in community education programs to raise awareness about carnivore behavior and promote coexistence. Establishing equitable and transparent livestock compensation or insurance schemes is essential to reduce retaliatory killing and build positive community attitudes toward wildlife. In addition, systematic monitoring and research are needed to identify conflict hotspots and evaluate the effectiveness of mitigation interventions.

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Ethiopian Journal of Biodiversity (EthJBD)

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